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Verônica Maurer Tabim

PROPOSAL OF A METHOD TO SUPPORT THE IMPLEMENTATION OF VERTICAL INTEGRATION IN THE CONTEXT OF INDUSTRY 4.0

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Verônica Maurer Tabim

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Orientador: Alejandro Germán Frank, Dr.

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Prof. Alejandro Germán Frank, Dr.
Orientador PPGEP/UFRGS

Prof. Michel José Anzanello, Dr.
Coordenador PPGEP/UFRGS

Banca examinadora:
Professor Giuliano de Almeida Marodin, Dr. (Darla Moore School of Business, University of South Carolina)
Professor Moacir Godinho Filho, Dr. (Departamento de Engenharia de Produção, Universidade Federal de São Carlos)
Professor Michel José Anzanello, Dr. (Departamento de Engenharia de Produção e Transportes, Universidade Federal do Rio Grande do Sul)

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A meus pais, Claudio e Sandra

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RESUMO

Um dos princípios fundamentais da Indústria 4.0 no domínio da manufatura inteligente é a implementação da integração vertical, ou seja, a integração dos sistemas de informação dos diferentes níveis hierárquicos da empresa para fornecer fluxo de dados no tempo e suporte à tomada de decisão. Contudo, a literatura acadêmica ainda não tem apresentado evidências empíricas sobre a forma como a integração vertical e as tecnologias que a compõe podem ser implementadas de maneira a contribuir com os requisitos da Indústria 4.0. Embora integração vertical seja apresentada como uma solução para necessidade de visibilidade de dados que a Indústria 4.0 requer, é sabido que existem diferentes caminhos para implementação da integração vertical que dependem dos objetivos operacionais almejados e das características das empresas. Portanto, os conjuntos tecnológicos da integração vertical podem ter diferentes formas de contribuição para alcançar uma maior visibilidade dos processos de produção. O objetivo desta tese é propor uma metodologia para suportar as empresas na implementação de integração vertical que permita que as empresas avancem na Indústria 4.0. O estudo seguiu uma abordagem mista, combinando métodos qualitativos e quantitativo. Em termos qualitativos, a tese apresenta um estudo multicasos em 10 empresas de manufatura líderes na implantação de tecnologias 4.0, visando entender os principais fatores que influenciam essas empresas na adoção de sistemas de informação para integração vertical. E ainda, um estudo qualitativo multicascos em 3 díades de comprador e fornecedor para compreender as implicações da assimetria da informação na compra de MES que permita a integração vertical na Indústria 4.0. Por outro lado, em termos quantitativos, a tese apresenta uma pesquisa survey conduzida com 134 empresas do setor de máquinas e equipamentos, através da qual se analisa a contribuição de ações em cibersegurança na integração vertical possibilita alcançar maior transformação digital. A presente tese demonstra que, de fato, a implementação da integração vertical é desafiadora para as empresas devido sua complexidade e novidade, mas que as metodologias apresentadas contribuem para o esclarecimento dessa implementação. Além disso, explora as limitações e nuances dessas contribuições em diferentes situações. A principal contribuição deste estudo é fornecer evidências empíricas de metodologias que suportem as empresas na implementação de integração vertical no contexto da Indústria 4.0.

Palavras-chave: Industria 4.0, Manufatura inteligente, Integração vertical.

ABSTRACT

One of the fundamental principles of Industry 4.0 in the field of intelligent manufacturing is the implementation of vertical integration, that is, the integration of information systems at the different hierarchical levels of the company to provide data flow over time and support decision-making. However, the academic literature still needs to present empirical evidence on how vertical integration and the technologies that compose it can be implemented to contribute to the requirements of Industry 4.0. Although vertical integration is presented as a solution to the need for data visibility that Industry 4.0 requires, it is known that there are different ways to implement vertical integration that depend on the desired operational objectives and the characteristics of the companies. Therefore, the technological sets of vertical integration can have different ways of contributing to achieving greater visibility of production processes. This thesis aims to propose a methodology to support companies in the implementation of vertical integration that allows companies to advance in Industry 4.0. The study followed a mixed approach, combining qualitative and quantitative methods. In qualitative terms, the thesis presents a multi-case study of 10 leading manufacturing companies in implementing 4.0 technologies, aiming to understand the main factors that influence these companies in adopting information systems for vertical integration. Furthermore, a multi-case qualitative study in 3 buyer-supplier dyads to understand the implications of information asymmetry in MES purchasing allows vertical integration in Industry 4.0. On the other hand, in quantitative terms, the thesis presents a survey conducted with 132 companies in the machinery and equipment sector, through which the contribution of cybersecurity actions to vertical integration is analyzed, making it possible to achieve greater digital transformation. This thesis demonstrates that the implementation of vertical integration is challenging for companies due to its complexity and novelty but that the methodologies presented contribute to clarifying this implementation. Furthermore, it explores the limitations and nuances of these contributions in different situations. The main contribution of this study is to provide empirical evidence of methodologies that support companies in the implementation of vertical integration in the context of Industry 4.0.

Keywords: Industry 4.0, Smart manufacturing, Vertical integration.

SUMÁRIO

1. INTRODUCTION

The phenomenon of Industry 4.0 can be understood as a result of the increasing digitization of companies, especially concerning manufacturing processes (ISSA et al., 2018; LI et al., 2018). Several authors relate Industry 4.0 with advanced technologies such as the Internet of Things (IoT), Cyber-Physical Systems (CPS), information and communication technology (ICT), Enterprise Architecture (EA), Enterprise Integration (EI), Cloud Computing and Big Data (WANG et al., 2015; LU, 2017; JESCHKE et al., 2017; GIUSTOZZIA et al., 2018). However, the concept is much broader than the simple use of digital technologies (DALENOGARE et al., 2018). Frank et al. (2019) state that Industry 4.0 considers integrating several business dimensions, such as smart products/services, smart supply chain, smart energy, and smart working, with a main concern in production issues, based on “smart manufacturing”. (LIAO et al., 2017; LU, 2017; DALENOGARE et al., 2018).

For Industry 4.0 to be possible in smart manufacturing, the availability of vertically integrated systems with heterogeneous data management is central to the expected efficiency gains (TABIM et al., 2021). Therefore, vertical integration is a principle that allows hierarchical data integration from the factory floor to the middle and upper management levels. Thus, the traditional Enterprise Resource Planning (ERP) corporate system is integrated with the Manufacturing Execution System (MES) manufacturing execution system, which has a direct connection with the entire operational structure of the factory, such as machines, equipment, sensors, PLCs and SCADA (ISMAIL & KASTNER, 2016; PÉREZ-LARA et al., 2018; TAMAS et al., 2019).

In this context, vertical integration has supported manufacturing companies in several ways. In capturing real-time data derived from sensors and actuators, processes, production machines, and the product itself, and also in the availability, traceability, and intelligence of this data in all company layers. Thus, it supports advanced analytical tools to analyze collected data to monitor and predict machine failures and automatically identify product nonconformities. It also complements systems such as ERP with demand forecasting and order fulfillment (FRANK et al., 2019). Vertical integration also allows plant managers to quickly and efficiently analyze datasets to support real-time decision-making applied to predictive maintenance and production planning (COHEN et al., 2019).

The literature has focused on several aspects involving vertical integration, such as definitions, applications, and performance of specific technologies that make up vertical integration (IoT, MES, automation, sensors, etc.), in addition to the communication between these technologies. However, it is still a great challenge to design production systems and their technological infrastructure to achieve efficient vertical integration (DA COSTA DIAS et al., 2021; MORGAN et al., 2021). Ghobakhloo and Ching (2019) considered that due to the innovative characteristics and complexity of vertical integration concepts, it is a challenge that requires a robust technology adoption model suitable for the context of Industry 4.0. To exemplify this challenge, Schuh et al. (2020) evaluated 70 European manufacturing companies striving to enter Industry 4.0 and showed that only 4% achieved data and information visibility through vertical integration. Another series of studies in Brazil showed that most companies engaged in Industry 4.0 initiatives are still concerned with verticalization as a priority investment focus (CNI, 2016; DALENOGARE et al., 2018). Several other reports from consulting firms around the world have reported the priority given by companies to vertical integration, even though ten years have passed since the launch of the Industry 4.0 concept (e.g., McKinsey & Company, The Boston Consulting Group and IBM Institute for Business Value) (BRUNELLI et al., 2017; LIGGESMEYER, 2014; SNYDER et al., 2020). Consequently, there is a need to understand vertical integration in the context of Industry 4.0, aiming to reduce the risks of failure in implementation and optimize the production system (DA COSTA DIAS et al., 2021; PÉREZ-LARA et al., 2018).

However, nowadays, it is not enough to adopt information systems individually; instead, vertical integration requires consideration of the entire suite of technologies involved in that purpose (SCHUH et al., 2020). Consequently, the operational challenges associated with vertical integration objectives strongly depend not only on specific adoptions but also on the use of clear implementation strategies (MORGAN et al., 2021). As stated by Schuh et al. (2020), before Industry 4.0, Information Technologies (ITs) (e.g., ERP, PLM) and Operational Technologies (OTs) (e.g., MES, SCADA, PLCs) sought to achieve their goals independently. This earlier autonomous approach formed closed systems and different communication protocols, creating complex technical obstacles for systems and architectures to achieve smooth data flow between systems (PERUZZINI et al., 2017). In addition, these systems usually have different providers, database structures, and nomenclatures, making their integration challenging (PEREIRA et al., 2020).

Furthermore, in an environment where working machines are connected to the network and each other through smart devices, the chance of cyber-attacks grows exponentially (CORALLO et al., 2020). Due to this new scenario, technology buyers and suppliers must understand how vertical integration should be implemented, generating information asymmetry (NOTHEISEN et al., 2017; ZAVOLOKINA et al., 2021). Thus, achieving an Industry 4.0 level of vertical integration is not trivial, as it involves risky and uncertain decisions (JUNIOR et al., 2019). However, although considered crucial for Industry 4.0, vertical integration still needs to be explored by operations management and technology scholars. Most of the literature refers only to interactions between systems or mentions vertical integration as a general concept along with other Industry 4.0 technologies (BELLINI et al., 2021; Fernandez-Viagas & Framinan,2021; ISMAIL & KASTNER, 2016; PÉREZ-LARA et al., 2018; TAMAS et al., 2019; WANG et al., 2016; XU et al., 2018). Although such studies have been important in elucidating the strategic and operational role of vertical integration, there is a lack of analyses that support companies in implementing vertical integration that allows companies to advance in Industry 4.0. Therefore, more research is needed to propose a vertical integration implementation methodology that supports manufacturing companies that seek an Industry 4.0 level.

Given this context, the research questions that guide this thesis arise. Firstly: **(i) What factors influence the adoption of information systems for vertical integration in the context of Industry 4.0, and how do they influence such adoption?** Secondly: **(ii) How can the KS activities between buyers (manufacturers) and MES technology providers reduce information asymmetry between parties when pursuing different levels of solutions in the Industry 4.0 context?** Finally, given that vertical integration is related to existing cybersecurity actions in the organization: **(iii) What is the role of cybersecurity actions in implementing vertical integration in smart manufacturing?** This thesis proposes to deepen these issues, thus expanding the current state of knowledge on the subject and proposing practical alternatives for decision-making in companies.

1.1 THESIS THEME

Given the above needs, this thesis is concerned with Operations and Technology Management, focused on the principle of Vertical Integration, which allows companies to advance in Industry 4.0. In this sense, this research understands that vertical integration allows production data to be integrated from the factory floor to the intermediate and higher levels of management. In short, the traditional corporate ERP system integrates with the MES system, which has a direct connection to the entire operational structure of the factory, such as machines, equipment, sensors, PLCs, and SCADA (ISMAIL & KASTNER, 2016; PÉREZ-LARA et al., 2018; TAMAS et al., 2019). Finally, it is understood that in the context of intelligent manufacturing in which real-time data are protagonists, Industry 4.0 is only possible with the successful implementation of vertical integration to obtain the flow of operational information (DA COSTA DIAS et al., 2021; DALENOGARE et al., 2018; PÉREZ-LARA et al., 2018; WANG et al., 2016).

1.2 THESIS OBJECTIVES

The general objective of this thesis is to propose a methodology to support companies in the implementation of vertical integration that allows companies to advance in Industry 4.0. In order to achieve this general objective, it is necessary to achieve the following specific objectives:

1. Understand the main factors that influence companies in the adoption of information systems (MES, ERP, PLM, SCADA, etc.) for vertical integration in the context of Industry 4.0
2. Understand how the dynamics of knowledge sharing can reduce information asymmetry between buyers and suppliers for the implementation of MES in the context of Industry 4.0
3. Understand how a high implementation of cybersecurity actions in vertical integration contributes to operational performance in smart manufacturing.
4. Define clear strategies for implementing vertical integration in the context of Industry 4.0 through a descriptive model.

1.3 BACKGROUND TO THE SUBJECT AND OBJECTIVES

This thesis work is justified by identifying theoretical and practical gaps. Related to theoretical aspects, it becomes important because Industry 4.0 is a new paradigm and therefore brings different questions to be researched. In this sense, although in recent years, academic studies on the subject have increased, there are still gaps in the ways to implement Industry 4.0 and what would be way for these technologies to be implemented in companies satisfactorily (GHOBAKHLOO & CHING, 2019; ZHANG et al., 2021). Specifically, this study addresses the adoption of technologies that support the principle of vertical integration to achieve the concept of Industry 4.0. Vertical integration has been considered a key piece for companies that seek to visualize the flow of operational data in real-time to support operational and strategic decision-making.

For this reason, vertical integration in manufacturing is a widely studied topic, and different solutions have been proposed so that the technologies that compose it are deepened when observed together. However, the concept of vertical integration is still considered complex to implement because it is multidimensional and depends on many variables (DA COSTA DIAS et al., 2021). Most of the technologies that form vertical integration already existed before Industry 4.0. Thus, information systems such as ERP, MES, APS, SCADA, and technologies such as IoT and Big Data have a growing consolidation in the literature, but only when seen separately. For vertical integration to be possible, technologies need to be arranged to allow data to flow between hierarchical layers. In this sense, according to several authors, there is a need to support decision-making regarding the adoption of technologies that support vertical integration as a gateway to Industry 4.0 (SCHUH et al., 2020; TAMAS et al., 2019; WANG et al., 2020; WANG et al. al., 2016).

From a practical point of view, although several studies claim that vertical integration is the central objective at the beginning of the Industry 4.0 journey, it still seems to be far from the reality for companies, especially in developing countries like Brazil (Benitez et al., 2020; Dalenogare et al., 2018; Fakhar Manesh et al., 2021). In turn, achieving vertical integration throughout the company still requires great efforts for companies (DA COSTA DIAS et al., 2021; PÉREZ-LARA et al., 2018; TABIM et al., 2021). This may be because companies still do not have enough knowledge to start the journey of implementing vertical integration in Industry 4.0 (FRANK et al., 2019). Another possibility is that companies underestimate vertical integration because it lacks clarity, involves a costly implementation process, and its benefits are difficult to immediately perceive (SREEDEVI; SARANGA, 2017).

1.4 RESEARCH METHOD

According to the nature of the research, this work fits as applied research. This is because it is oriented toward generating knowledge to solve specific problems (GIL, 2008). Regarding the type of approach, this research combines qualitative and quantitative approaches, which are used alternately depending on the work stage under analysis. Regarding the objectives, the first part of the thesis deals with exploratory research (Articles 1 and 2) since it aims to provide greater familiarity with the problem in order to make it explicit through the survey of the main factors that influence the adoption of information systems for vertical integration, and, through the survey of the MES implementation stages that reduce the asymmetry of information between buyers and sellers (GIL, 2008). On the other hand, the third part of the thesis (Article 3) will deal with explanatory research since hypotheses are proposed that explain a reality to be validated through the collection of empirical data (GIL, 2008).

To achieve the objectives, the conduction of this work occurs through three stages presented in three scientific articles. Figure 1 illustrates the evolution of conceptual models through the research stages. Step 1 seeks, through multiple case studies, to explore and understand how manufacturing companies that aim for Industry 4.0 choose information systems for vertical integration in the face of the various solutions on the market. For that, it is considered in a framework (Figure 1) two main aspects to answer the questions above the technology adoption process and the technological, organizational, and environmental aspects that influence its use. Based on this understanding, Step 2 seeks to understand, through qualitative research, which dynamics of knowledge sharing (KS) can reduce information asymmetry between buyers and suppliers to implement MES in an Industry 4.0 context (Figure 2). To shed light on the implementation process, it considers in a framework three levels of MES configurations according to the desired outcome of Industry 4.0. It reveals which KS dynamics and buyer-supplier configurations are needed to increase the potential for success in the implementation of the MES. Finally, the third step seeks to identify the role of cybersecurity in implementing vertical integration in smart manufacturing. Cybersecurity was identified in steps 1 and 2 as the main challenge why companies are not successful in vertical integration. This research uses survey data from the Brazilian Machinery and Equipment Industry Association (ABIMAQ). In this way, it is possible to create a complete understanding of the studied phenomenon.

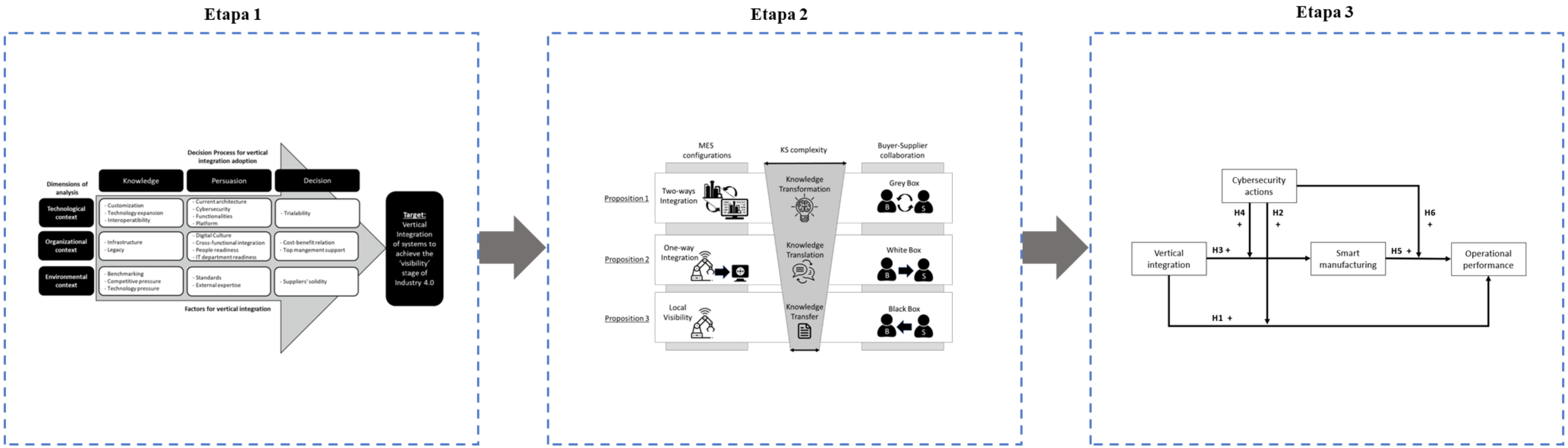

Figure 1: Modelo estrutural da tese (Fonte: elaborado pelo autor)

Table 1. Articles' scope

	Objectives	Research question	Research method
Article 1	Provide a framework that presents the main factors influencing companies in adopting information systems for vertical integration, according to three dimensions: technological, organizational, and environmental.	What factors influence the adoption of information systems for vertical integration in the context of Industry 4.0, and how do they influence such adoption?	Qualitative research: case study in companies (individual interviews).
Article 2	Understand how the dynamics of knowledge sharing can reduce information asymmetry between buyers and suppliers for implementing MES in the context of Industry 4.0.	How can the KS activities between buyers (manufacturers) and MES technology providers reduce information asymmetry between parties when pursuing different levels of solutions in the Industry 4.0 context?	Qualitative research: case study in companies (individual interviews).
Article 3	Understand how a high implementation of cybersecurity actions in vertical integration contributes to operational performance in smart manufacturing.	What is the role of cybersecurity actions in implementing vertical integration in smart manufacturing?	Quantitative research: survey with companies

(a) Article approved for publication in Information Systems Frontiers (Qualis Capes A1);
(b) Article submitted to the International Journal of Production Research (Qualis Capes A1);
(c) Article to be submitted to the International Journal of Production Research (Qualis Capes A1).

Article 1- "*Implementing Vertical Integration in the Industry 4.0 Journey: Which Factors Influence the Process of Information Systems Adoption?".* The objective of this step was to identify the main factors that influence companies in adopting information systems for vertical integration to start the Industry 4.0 journey. This stage had a qualitative character since 22 interviews were conducted, and the analyzed companies adopted information systems with the objective of vertical integration.

Article 2- "*Reducing information asymmetry between buyers and providers of Manufacturing Execution Systems (MES) to unlock the Industry 4.0 doors".* This step took advantage of the analysis of case studies to understand which dynamics of knowledge sharing (KS) can reduce the asymmetry of information between buyers and suppliers for implementing MES in an Industry 4.0 context. As a main result, the article presents a framework that presents three levels of MES configurations according to the desired result of Industry 4.0 and shows which KS dynamics and buyer-supplier configurations are necessary to increase the potential for success in implementing MES.

Article 3: "What is the role of cybersecurity actions in implementing vertical integration in smart manufacturing?" This stage of the thesis aims to understand how a high implementation of cybersecurity actions in vertical integration contributes to the operational performance in smart manufacturing in companies. This stage follows a quantitative approach based on a survey and subsequent statistical data analysis.

1.5 STUDY LIMITATIONS

For the development of the research, the following study limitations are proposed. The study will consider the practical context of Brazil since developing countries often need help in industrializing and having a competitive advantage over others. In this way, with the implementation of Industry 4.0, the country can accelerate its development and digital transformation. However, other countries may have other contexts and different levels of technological development. Therefore, the territorial space is considered a limitation of the work.

Furthermore, the present study focuses on analyzing three technological dimensions identified as relevant for a successful implementation of vertical integration. However, other proposals for dimensions cover a wider range of areas, such as sociotechnical theory. These different proposals contemplate other business dimensions not directly contemplated in this thesis. This is because considering many dimensions leads to a very detailed analysis. Therefore, the work was limited to more generic dimensions for understanding the structure of the vertical integration business.

Finally, the types of configurations of the relationship between the MES buyer company and the MES supplier company are restricted to adapting a model widely disseminated in new product development (White/Grey/Black box model). However, other types of collaboration structures could be evaluated, which is an option for delimiting the analytical structure of the work.

1.6 THESIS STRUCTURE

This thesis proposal is organized into five chapters, including the chapter already presented. The first chapter discussed the research problem, the objectives, and the justifications in addition to the study's method, structure, and limitations. Subsequently, in Chapters 2, 3, and 4, the central articles developed so far that meet each specific objective are presented. The fifth chapter is dedicated to the conclusions, discussing the general objective, theoretical and practical implications, and suggestions for future research.

1.7 REFERENCES

BELLINI, P., CENNI, D., MITOLO, N., NESI, P., PANTALEO, G., & SODERI, M. (2021). High level control of chemical plant by industry 4.0 solutions. Journal of Industrial Information Integration, 100276. https://doi.org/10.1016/j.jii.2021.100276

BENITEZ, G. B., AYALA, N. F., & FRANK, A. G. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. International Journal of Production Economics, 228(July 2019). https://doi.org/10.1016/j.ijpe.2020.107735

BRUNELLI, J., LUKIC, V., MILON, T., & TANTARDINI, M. (2017). Five lessons from the frontlines of industry 4.0. The Boston Consulting Group, November, 1–14. https://www.bcg.com/publications/2017/industry-4.0-lean-manufacturing-five-lessons-frontlines.aspx. Accessed in July 2020.

CNI, N. C. of I. (2016). Industry 4.0: a new challenge for Brazilian industry. CNI Indicators, April, 13. https://static-cms-si.s3.amazonaws.com/media/filer_public/13/e7/13e7e7bd-9b1d-4c16-8099-99b6d844d04e/special_survey_industry_40.pdf. Accessed in July 2020.

CORALLO, A., LAZOI, M., & LEZZI, M. (2020). Cybersecurity in the context of industry 4.0: A structured classification of critical assets and business impacts. Computers in Industry, 114, 103165. https://doi.org/10.1016/j.compind.2019.103165

DA COSTA DIAS, J. E., DE CASTRO FILHO, F. G., DE ANDRADE, A. A., & FACÓ, J. F. B. (2021). The strategic role of MES systems in the context of industry 4.0. Smart Innovation, Systems and Technologies, 198 SIST(June), 52–61. https://doi.org/10.1007/978-3-030-55374-6_6

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, 204(December 2017), 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

FERNANDEZ-VIAGAS, V., & FRAMINAN, J. M. (2021). Exploring the benefits of scheduling with advanced and real-time information integration in Industry 4.0: A computational study. Journal of Industrial Information Integration, 100281. https://doi.org/10.1016/j.jii.2021.100281

FRANK, A. G., AYALA, N. F., GHEZZI, A., & MENDES, G. H. S. (2019). Servitization and Industry 4.0 convergence in the digital transformation of product firms: A business model innovation perspective. Technological Forecasting and Social Change, 141(January), 341–351. https://doi.org/10.1016/j.techfore.2019.01.014

GIL, Antonio Carlos. Métodos e técnicas de pesquisa social. 6. ed. Ediitora Atlas SA, 2008.

GHOBAKHLOO, M., & CHING, N. T. (2019). Adoption of digital technologies of smart manufacturing in SMEs. Journal of Industrial Information Integration, 16. https://doi.org/10.1016/j.jii.2019.100107

ISMAIL, A., & KASTNER, W. (2016). Vertical integration in industrial enterprises and distributed middleware. International Journal of Internet Protocol Technology, 9(2–3), 79–89. https://doi.org/10.1504/IJIPT.2016.079547

ISSA, A., HATIBOGLU, B., BILDSTEIN, A., & BAUERNHANSL, T. 2018. Industrie 4.0 roadmap: Framework for digital transformation based on the concepts of capability maturity and alignment. Procedia CIRP, 72, 973-978.

JESCHKE, S., BRECHER, C., MEISEN, T., ÖZDEMIR, D., ESCHERT, T., 2017. Industrial Internet of Things and Cyber Manufacturing Systems. Springer. https://doi.org/10.1007/978-3319-42559-7_1.

JUNIOR, C. H., OLIVEIRA, T., & YANAZE, M. (2019). The adoption stages (Evaluation, Adoption, and Routinisation) of ERP systems with business analytics functionality in the context of farms. Computers and Electronics in Agriculture, 156(January 2018), 334–348. https://doi.org/10.1016/j.compag.2018.11.028

LI, Q., TANG, Q., CHAN, I., WEI, H., PU, Y., JIANG, H., LI, J., 2018. Smart manufacturing standardization: Architectures, reference models and standards framework. Computers in Industry 101, 91–106. doi:10.1016/j.compind.2018.06.005

LIAO, Y., DESCHAMPS, F., FREITAS, E. DE, LOURES, R., 2017. Past , present and future of Industry 4 . 0 - a systematic literature review and research agenda proposal. International Journal of Production Research 7543, 0. doi:10.1080/00207543.2017.1308576

LIGGESMEYER, P. (2014). Industry 4.0. Informatik-Spektrum, 37(4), 284–285. https://doi.org/10.1007/s00287-014-0809-1

LU, Y., 2017. Journal of Industrial Information Integration Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration 6, 1–10. doi:10.1016/j.jii.2017.04.005

MORGAN, J., HALTON, M., QIAO, Y., & BRESLIN, J. G. (2021). Industry 4.0 smart reconfigurable manufacturing machines. Journal of Manufacturing Systems, 59(February), 481–506. https://doi.org/10.1016/j.jmsy.2021.03.001

NOTHEISEN, B., CHOLEWA, J. B., & SHANMUGAM, A. P. (2017). Trading Real-World Assets on Blockchain: An Application of Trust-Free Transaction Systems in the Market for Lemons. Business and Information Systems Engineering, 59(6), 425–440. https://doi.org/10.1007/s12599-017-0499-8

PEREIRA, R. M., SZEJKA, A. L., & CANCIGLIERI, O. (2020). A Discussion on Current Issues for Semantic Interoperability in an Integrated Manufacturing System, 514–523. https://doi.org/10.3233/ATDE200112

PÉREZ-LARA, M., SAUCEDO-MARTÍNEZ, J. A., MARMOLEJO-SAUCEDO, J. A., SALAIS-FIERRO, T. E., & VASANT, P. (2018). Vertical and horizontal integration systems in Industry 4.0. Wireless Networks, 2. https://doi.org/10.1007/s11276-018-1873-2

PERUZZINI, M., GRANDI, F., & PELLICCIARI, M. (2017). Benchmarking of Tools for User Experience Analysis in Industry 4.0. Procedia Manufacturing, 11(June), 806–813. https://doi.org/10.1016/j.promfg.2017.07.182

SCHUH, G., ANDERL, R., DUMITRESCU, R., KRÜGER, A., & HOMPEL, M. (2020). Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies – UPDATE 2020 – (acatech STUDY).

SNYDER, S., MEEK, D., LEHTONEN, T., & KIRADJIEV, P. (2020). Smart manufacturing. Ai technologies, intelligent insights. Expert Insights, IBM Institute for Business Value, NY. https://www.ibm.com/downloads/cas/ZLKE8R2X. Accessed in March 2021.

SREEDEVI, R.; SARANGA, Haritha. Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. International Journal of Production Economics, v. 193, p. 332-342, 2017.

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? Information Systems Frontiers, 0123456789. https://doi.org/10.1007/s10796-021-10220-x

TAMAS, L., MURAR, M., & TAMAS, L. (2019). Smart CPS: vertical integration overview and user story with a cobot Smart CPS: vertical integration overview and user story with a cobot. International Journal of Computer Integrated Manufacturing, 32(4–5), 504–521. https://doi.org/10.1080/0951192X.2018.1535196

WANG, S., WAN, J., LI, D., & ZHANG, C. (2016). Implementing Smart Factory of Industrie 4.0: An Outlook. International Journal of Distributed Sensor Networks, 2016. https://doi.org/10.1155/2016/3159805

XU, L., DA, 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

ZAVOLOKINA, L., SCHLEGEL, M., & SCHWABE, G. (2021). How can we reduce information asymmetries and enhance trust in ‘The Market for Lemons’? Information Systems and E-Business Management, 19(3), 883–908. https://doi.org/10.1007/s10257-020-00466-4

ZHANG, Q., VONDEREMBSE, M. A., & LIM, J. (2003). Manufacturing flexibility: defining and analyzing relationships among competence, capability, and customer satisfaction. 21, 173–191.

2. ARTIGO 1 – IMPLEMENTING VERTICAL INTEGRATION IN THE INDUSTRY 4.0 JOURNEY: WHICH FACTORS INFLUENCE THE PROCESS OF INFORMATION SYSTEMS ADOPTION? *

Verônica Maurer Tabim[1]

Néstor Fabián Ayala[1]

Alejandro Germán Frank[1]

[1] Organizational Engineering Group (*Núcleo de Engenharia Organizacional – NEO*), Department of Industrial Engineering, Universidade Federal do Rio Grande do Sul, Brazil.

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Abstract

One of the key principles of Industry 4.0 is the implementation of vertical integration, which considers the integration of information systems from different hierarchical levels in a company to support decision-making with real-time data flow. Companies face challenges to implement vertical integration, which is not trivial due to the risks inherent to the decision stages of adoption. We investigate the main factors influencing the different stages of adoption of vertical integration to provide a clearer view of what managers should consider at each stage. We adopt a multi-case study approach based on the investigation of ten companies that followed this adoption process. We develop a framework with 22 factors deployed in the three stages of decision (knowledge, persuasion and final decision) and three main dimensions of analysis: technology, organization, and environment. We analyze the potential tensions between these factors and show how managers should balance such factors during the decision stages.

Keywords: Industry 4.0; Vertical integration; Information Systems; Smart Manufacturing; Technology adoption.

1 INTRODUCTION

After ten years of research, Industry 4.0 has been consolidated as a technology evolution model which integrates several emerging technologies grounded on the Industrial Internet of Things (IoT) to create cyber-physical systems (Khan & Javaid, 2021; Li, 2018; Lu, 2017; Meindl et al., 2021). One of the core concepts of Industry 4.0 is Smart Manufacturing, which is concerned with the way production activities are executed with the support of sensors, computing platforms, communication technology, data-intensive modeling with artificial intelligence (AI), automated control, simulation, and other advanced IoT-based tools, to create transparent, predictive and adaptable manufacturing systems (Dalenogare et al., 2018; Frank et al., 2019; Kusiak, 2018; Liu & Xie, 2020; Peruzzini et al., 2017; Uysal & Mergen, 2021). One of the key principles of Industry 4.0 in the Smart Manufacturing domain is the implementation of vertical integration, i.e., the integration of information systems from different hierarchical levels in the company – from the factory floor to the middle and upper management levels – to provide real-time data flow and support decision-making (Peruzzini & Stjepandić, 2017a; Wang et al., 2016). Vertical integration enables smart machines to form a self-organized system that can be dynamically reconfigured to adapt to different products. Besides, massive information is collected and processed to make the production process transparent, increasing production reliability and factory flexibility (Branger & Pang,2015; Pérez-Lara et al., 2018; Schuh et al., 2020a; Wang et al., 2016). With such integration, companies obtain a transparent, predictive, and adaptable smart manufacturing system, being vertical integration, therefore, considered the first step toward factory-level Industry 4.0 (Schuh et al., 2020a).

However, to implement vertical integration, companies are facing the challenge of integrating several information systems. As stated by Schuh et al. (2020a), before Industry 4.0, Information Technologies (ITs) (e.g., ERP, PLM) and Operational Technologies (OTs) (e.g., MES, SCADA, PLCs) sought to achieve their goals independently. This previous stand-alone approach formed closed systems and different communication protocols, creating complex technical obstacles for systems and architectures to achieve a smooth data flow between systems (Peruzzini & Stjepandić, 2017b). Additionally, each of these systems usually has different providers, database structures, and nomenclatures, making their integration challenging (Pereira et al., 2020). Thus, adopting and integrating information systems to achieve an Industry 4.0 level of vertical integration is not trivial, as it involves risky and uncertain decisions (Junior et al., 2019). According to Janssen et al. (2020), the constant evolution of systems, combined with increased complexity, high costs, and variety, hinders companies' success in adopting vertical integration. However, although considered crucial for Industry 4.0, vertical integration remains little explored by information and technology management scholars. Most of the literature refers only to interactions between systems or mentions vertical integration as a general concept together with other Industry 4.0 technologies (Bellini et al., 2021; Fernandez-Viagas & Framinan, 2021; Ismail & Kastner, 2016; Pérez-Lara et al., 2018; Tamas et al., 2019; Wang et al., 2016; Xu et al., 2018). Although such studies have been important to elucidate the strategic and operational role of vertical integration, there is a lack of analysis on the factors (i.e., details and complexities) of adopting this system in the organizational context. Therefore, further research is necessary to identify the factors that affect the adoption of information systems for vertical integration in manufacturing companies pursuing an Industry 4.0 level. Thus, we approach this problem through the following research question: ***What factors influence the adoption of information systems for vertical integration in the context of Industry 4.0, and how do they influence such adoption?***

Two main aspects must be considered to answer the above questions: the technology adoption process and the technological, organizational and environmental aspects that influence their utilization. First, we use the theory of diffusion of innovation (DOI) by following the innovation-decision process model (Rogers, 2003) to study information systems adoption for vertical integration. We considered the knowledge, persuasion, and decision stages of this process. This theory is mainly based on the characteristics of the technology and users' perceptions of innovation. Secondly, since the adoption of information systems depends not only on factors directly related to them but also on organizational and environmental aspects (Junior et al., 2019), we employ the technology-organization-environment structure (TOE) (Tornatzky, L.G., & Fleischer, 1990) as a basis for the identification of different sociotechnical factors in the adoption of systems for vertical integration. We investigate these main factors influencing the different stages of adoption of vertical integration to provide a clearer view of what managers should consider at each stage. We adopt a multi-case study approach based on the investigation of ten companies that followed a vertical integration implementation process. We develop a framework with 22 factors deployed in the three stages of decision (knowledge, persuasion, and final decision) and three main dimensions of analysis: technology, organization, and environment. We analyze the potential tensions between these factors and show how managers should balance such factors during the decision stages. As the main contribution for theory, our results show how factors related to vertical integration change alongside the different decision stages of the technology adoption process. While the literature has considered general factors for information system integration, we contribute with the particularities of the Industry 4.0 context, emphasizing the integration between information and automation technologies necessary for vertical integration. We show that sociotechnical factors and tensions between them are present and need to be managed to overcome each of the adoption process stages. On the other hand, managers can learn the specific requirements they will need to implement vertical integration. We discuss infrastructure and organizational needs and how they need to manage the potential tensions among the different requirements. In doing so, we propose a structure to guide professionals on their path towards vertical integration, considering the particularities of an Industry 4.0 context.

The remainder of this article is organized as follows. Section 2 reviews the literature on Industry 4.0 and vertical integration and the two theoretical lenses used. Section 3 details the research methodology used and the case studies, data collection, and analysis. Section 4 presents the results, section 5 discusses the results, while section 6 highlights the limitations of this study and future research directions.

2 THEORETICAL BACKGROUND

2.1 Industry 4.0 and vertical integration

The Industry 4.0 concept has been summarized by Frank et al. (2019) as the development and integration of four smart dimensions – smart manufacturing, smart supply chain, smart product service-systems, and smart working – supported by four base technologies, namely the Internet of Things (IoT), cloud computing, big data, and data analytics, including the use of artificial intelligence (AI), which can have several applications in these dimensions, accomplished by the use of advanced technologies such as robotics and additive manufacturing. In this paper, we focus only on Smart Manufacturing, which is the central concept of Industry 4.0 considering the internal industrial activities of companies (Haleem & Javaid, 2019; Iaksch et al., 2021; Meindl et al., 2021). Along with all technologies involved, Industry 4.0 is formed by three key principles: horizontal integration, vertical integration, and end-to-end engineering (Kagermann, 2013). Horizontal integration refers to the integration of different systems to enable communication between all stages in the supply chain. This includes the connection between logistics, production, and design, within and across different companies. Vertical integration, in turn, refers to the integration of systems at different hierarchical levels in an organization, from production to management (Dalenogare et al., 2018). Finally, end-to-end engineering refers to the integration of engineering throughout the value chain, from its development to after-sales (Kagermann, 2013). In this study, we focus on vertical integration, building on previous studies showing it to be an initial and essential step for the implementation of Industry 4.0 internally, at the factory level (Frank et al., 2019; Schlechtendahl et al., 2014; Schuh et al., 2020a; Wang et al., 2016).

The vertical integration of manufacturing companies is widely represented by the ISA-95 standard pyramid model (Tamas et al., 2019). This model specifies the limits and types of data exchange for each level between the systems (ISA, 2020), as described in Table 1: (a) level zero represents the physical production process; (b) level one presents the sensors and other actuators; (c) level two reports the functions of supervision (SCADA), monitoring and control of production processes (PLC); (d) level three presents the manufacturing management layer (MES); (e) level four presents the business management layer (ERP/PLM). As explained in this model, to achieve vertical integration, the first step is to digitalize physical objects on the shop floor with sensors, actuators, and programmable logic controllers (PLC) (Jeschke et al., 2017). Data is then collected with SCADA systems for production control. At the operational layer, the MES obtains data from SCADA to control and optimize manufacturing workflows and provide information about production status to the ERP system at the corporate layer (Frank et al., 2019; Ismail & Kastner, 2016; Wang et al., 2016). Additionally, some firms employ PLM systems at the corporate layer to control product registration at all stages of the development process (Antonio et al., 2017; Pérez-Lara et al., 2018). According to the Industry 4.0 maturity index model from the German National Academy of Science and Engineering (ACATECH), which provides companies with guidelines for implementing Industry 4.0, the path towards Industry 4.0 starts with visibility and transparency, which is precisely the goal achieved by implementing vertical integration (Schuh et al., 2020a).

Table 1. Main information systems that can compose vertical integration.

Levels	Pyramid components	Role
Level 0 and 1	Instrumentation	Source of the data derived from a measurement of the process. The instrumentation measures a specific process variable and can distribute this information to a PLC. The data generated is used only to monitor process variables (raw data).
Level 2	Supervisory Control and Data Acquisition (SCADA)	System used for data acquisition or process control. Thus, the processes communicate with several devices in real-time. In this context, devices called PLC (Programmable Logic Controller) are generally used. SCADA takes raw data from the PLC and transforms it for use only in the production process (allows limited access to the history of information).
Level 3	Manufacturing Execution System (MES)	A system with functions focused on the execution of production activities. MES establishes a direct link between planning and the shop floor. It generates accurate and real-time information that promotes the optimization of all production stages, from the issuance of an order to the shipment of finished products. The MES has data processed for decision-making (allows access to the history of this information).
Level 4	Enterprise Resource Planning (ERP)	An information system with a unified view of the business, covering all departments and their corresponding functions. It covers product design, operations, logistics, sales and marketing, information storage, material planning, human resources, finance, and project management.
	Product Lifecycle Management (PLM)	Business software manages all data associated with a product during its life cycle phases, including design, manufacture, use, maintenance, recycling, and disposal. It is often referred to as a "single registration system" for product data throughout the product's life cycle.

In a typical firm, each of the described systems has its technical particularities (e.g., database and communication protocol), brand, and length of implementation. Before the advent of Industry 4.0, each of these systems was usually acquired and implemented by the companies without regard to the following integration. Consequently, companies currently face a tangle of systems (legacy or not), and the complexity of different software architectures makes the path towards Industry 4.0 more difficult. Therefore, adopting information systems for vertical integration is a challenge that requires a robust model of technology adoption suitable for the context of Industry 4.0. Moreover, due to the innovative characteristics and complexity of the concepts associated with vertical integration, manufacturing companies struggle to define how to select the information systems necessary to achieve this level of integration (Ghobakhloo & Ching, 2019). To exemplify this challenge, Schuh et al. (2020b) evaluated 70 manufacturing companies in

Europe striving to enter Industry 4.0 and showed that only 4% of those companies achieved data and information visibility through vertical integration. Another series of studies conducted in Brazil showed that most companies engaged in Industry 4.0 initiatives are still concerned with vertical integration as a priority focus of investment (CNI, 2016; Dalenogare et al., 2018). Several other reports from consulting companies around the world have reported the priority given by companies to vertical integration, even though ten years have gone by since the Industry 4.0 concept was launched (e.g., McKinsey & Company, The Boston Consulting Group, and IBM Institute for Business Value) (Brunelli et al., 2017; Liggesmeyer, 2014; Snyder et al., 2020). As explained in the following section, we propose that such a struggle to implement vertical integration can be addressed from the innovation diffusion perspective.

2.2 A framework to study the adoption of vertical integration: using the innovation diffusion perspective and Technology-Organization-Environment

While the adoption of innovative technologies is influenced by several factors (Alshamaila et al., 2013; Maduku et al., 2016; Oliveira et al., 2019), the Diffusion of Innovation (DOI) theory, through its innovation-decision process model (Rogers, 2003), allows structuring the analysis of the adoption of vertical integration. The innovation-decision process model comprises five stages: knowledge, persuasion, decision, implementation, and confirmation. The first three stages refer to evaluating the adoption decision, and the last two refer to post-implementation analysis. We focus our study on the first three stages that cover the assessment of whether to adopt or reject an innovation. Before making a decision (adoption or rejection), managers need to gain an understanding of how the innovative technology works (knowledge) and then take a favorable or unfavorable attitude towards it (persuasion).

Nevertheless, due to the broad impacts on organizations of information systems adoption for vertical integration, our research problem requires a more comprehensive view of how adoption should be handled, considering multiple contexts. In this context, the innovation-decision process model shows to be limited since it does not comprise aspects beyond the technology itself. Thus, to have a complete overview on the adoption of vertical integration, we combine this model with the Technology-Organization-Environment (TOE) framework (Tornatzky & Fleischer, 1990) to achieve a perspective that contemplates changes in the organizational structure, as well as in its communication with the external environment (Schuh et al., 2020a). The TOE framework explains that the decision to adopt an innovation, as the development of a new information system, is influenced by factors in three contexts: technology, organization, and environment (Tornatzky & Fleischer, 1990). The technological context includes the internal and external technologies present in an organization's business ecosystem. The organizational context refers to its internal characteristics and resources, including its size, degree of centralization, degree of formalization, management structure, hierarchy, and procedures. Finally, the environmental context is related to the industry, competitors, and the company's relationship with other institutions, including the government.

Thus, the TOE framework allows us to understand the broader scenario in which innovation occurs by integrating the different factors that influence the adoption of technologies (Oliveira et al., 2019). It is among the most commonly employed structures in research on the adoption of technological innovations (Maduku et al., 2016; Yeo & Grant, 2018), including the adoption of information systems (Thong, 1999), IT (Bose & Luo, 2011), RFID (Wei et al., 2015), cloud computing (El-Haddadeh, 2020; Senyo et al., 2016), Enterprise Resource Planning (ERP) (Junior et al., 2019) and Industrial Augmented Reality (IAR) (Masood & Egger, 2020). Although some studies have used the TOE framework to analyze information systems and ERP adoption, our research brings a new perspective. It aims to investigate the vertical integration of these systems. Prior research on Industry 4.0 has acknowledged the importance of considering sociotechnical factors when Industry 4.0-related technologies are implemented (Marcon et al., 2021). By considering this broader perspective, more factors can be identified that influence the adoption of an information system in the new scenario of Industry 4.0. Thus, as presented in Figure 1, the conceptual framework guiding our research combines the innovation-decision process model of the Diffusion of Innovation Theory (DOI) (Rogers et al., 2019) with the Technology-Organization-Environment (TOE) framework (Tornatzky & Fleischer, 1990). This conceptual framework allows us to identify the main factors of each TOE dimension influencing the adoption of information systems for vertical integration across the three innovation-decision process stages. Because these factors may change along the stages, we aim to understand which should be considered in each specific stage of decision.

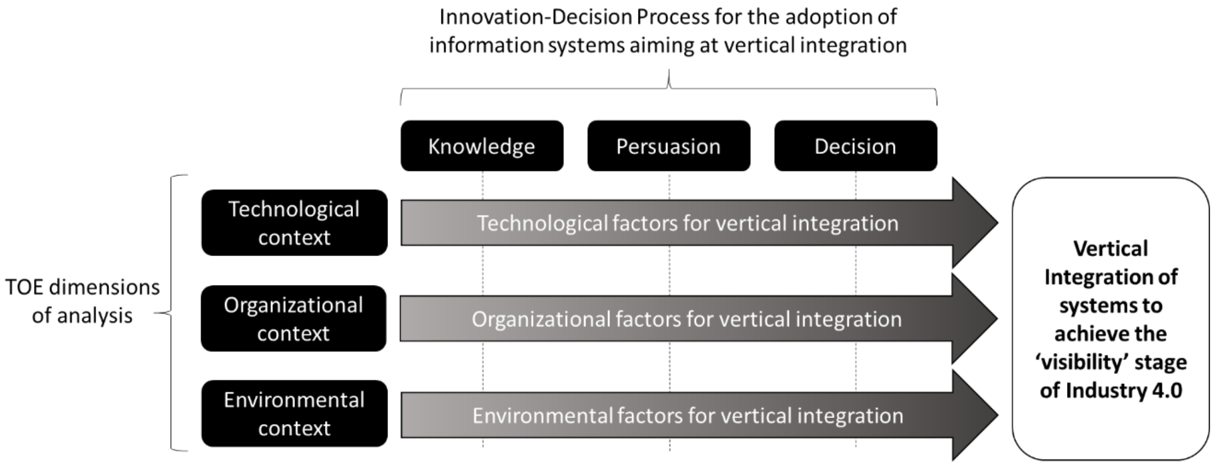

Figure 1. Conceptual framework for the innovation-decision process of adoption of IT systems aiming at vertical integration

3 RESEARCH METHOD

Our study adopts a qualitative approach through a multiple case study to understand the factors that influence the adoption of information systems for vertical integration in manufacturing companies pursuing an Industry 4.0 level. The decision for the qualitative analysis of case studies derives from the recommendations of Voss et al. (2002). They suggest using this approach when the goal is to explore a new phenomenon and build theories based on an in-depth analysis of the field. This approach is based on data collection with several representatives of the studied environment who provide insights and understand the context of the problem (Ayala et al., 2017). Therefore, we conducted an exploratory study grounded on a conceptual literature-based framework (Figure 1) and semi-structured interviews (see Appendix A) with ten manufacturing companies based in Brazil.

3.1 Case study selection

The cases were selected using theoretical sampling; that is, they were selected because they were particularly suitable to shed light on the constructs (Eisenhardt & Graebner, 2007). We intentionally chose companies from different industry segments to produce contrasting results that can offer a broader overview of the phenomenon and facilitate the generalization of results. Following this criterion, we contacted representatives of the Brazilian Chamber of Industry 4.0 and the Southern Brazil Federation of Industries to identify outstanding companies of this country in technology implementation (i.e., high technology intensity) and are currently engaged in digital transformation and Industry 4.0

programs. The associations map these types of initiatives in the country, thus providing a reliable list of potential case studies for our investigation. We obtained a list of 60 potential companies for investigation, contacted them by e-mail, and then made phone calls and video calls to discuss further their interest in participating in this research. From this initial group of companies, we refined our selection only to companies implementing or having already implemented vertical integration to advance in the Industry 4.0 maturity journey. Some companies were not eligible because they were focused on other types of technology implementation, such as intensive use of robotics or artificial intelligence for specific purposes like smart maintenance, which fell out of the scope of this study. Besides, some other companies were considered ineligible because they only implemented specific IT, such as SCADA or MES, but without vertical integration. Thus, we obtained a final list of ten companies that were considered the most suitable to understand the whole decision-making process for implementing vertical integration concepts.

Table 2 provides a brief description of the selected cases. The names of companies and respondents were hidden to preserve anonymity, and we adopted codenames to represent them. Amongst these case studies, ClothingCo, ChemicalCo, TerminalsCo, VehicleCo, PowertoolsCo, ElectronicCo, and AgricultureCo2 reported their process of adopting an MES system aiming at vertical integration with their extant systems. AutomotiveCo reported its recent ERP and MES joint adoption processes, aiming at integration, along with its failed attempt to integrate with PLM. AgricultureCo1 has already employed an MES system for eight years, but there was no integration with other systems. When assessing market options to acquire a new MES for vertical integration, AgricultureCo1 chose to adopt a systems architecture and build its own customized MES, and so did AutomotiveCo2. Each case study company is at the maturity level of obtaining visibility (Schuh et al., 2020a) from the vertical integration.

Table 2. Background of the cases

Case company	Description	Size	Sector	Interviewee's role
AutomotiveCo	Multinational company in road implements	Multinational (+12,000 employees)	Motor vehicles, trailers and semi-trailers	Automation Engineer; Operational Director; Digital Manufacturing

				Engineer
VehicleCo	Brazilian national company in automotive equipment	Medium (+2000 employees)	Machinery and equipment	Industrial IT Specialist
ElectronicCo	Multinational company in electronic materials and components, accessories for data recording and storage.	Multinational (+100.000 employees)	Computers, electronics and optical products	Process Engineer; Industrial Engineer
PowertoolsCo	Multinational company in portable power tools	Multinational (+17,000 employees)	Machinery and equipment	Industrial Planning Specialist; Process Analyst; Production Manager
AgricultureCo1	Multinational company in agricultural equipment	Multinational (+20,000 employees)	Machinery and equipment	IT Manager; Manufacturing Manager; Process Engineer
AgricultureCo2	Brazilian international company in agricultural equipment	Medium (+500 employees)	Motor vehicles, trailers, and semi-trailers	Industrial Director; Process Engineer
TerminalsCo	Brazilian national company in equipment for terminals and handling of solid bulk	Medium (+1000 employees)	Machinery and equipment	Industrial Engineering Supervisor; Engineering Coordinator
ChemicalCo	Multinational company in the chemical and petrochemical sector	Multinational (+10,000 employees)	Chemicals	Automation Engineer; Industrial Engineer
AutomationCo2	Multinational company in automobiles and commercial vehicles	Multinational (+10,000 employees)	Motor vehicles, trailers, and semi-trailers	Industry 4.0 Head; Process Engineer & Industry 4.0;
ClothingCo	Brazilian national company in clothing	Medium (+1600 employees)	Textiles	Industrial Engineer; IT Analyst

3.2 Research instruments and data collection procedures

To identify the factors that influence the adoption of information systems for vertical integration, and their dynamics, semi-structured interviews were used as the primary data collection method. An initial version of the interview script was tested with two participants from different companies and then revised before the main interviews were conducted (see Appendix 1 for the interview script). We then interviewed key representatives who participated in the adoption of information systems for vertical integration, including IT managers and industrial engineers (see Table 2), as well as officers actively involved in the strategic decisions related to Industry 4.0 in the companies. Each interview lasted around 1:30 hour and was conducted by videoconference or in person at the firm.

We recorded the interviews and wrote notes on participants' impressions and comments during data collection. The notes were made by four researchers, which allowed us to confront interview impressions and obtain a complete view of each case while reducing observer bias (Yin, 2009). After analyzing the interview transcripts, we conducted a new round of interviews with the same respondents to clarify details or questions that remained from the first round. Finally, to enable data triangulation, we reviewed documents made available by the companies (internal procedures, business reports, and internal slideshows), information from their websites, past research carried out in these companies by other researchers on Industry 4.0-related subjects. We also visited some firm sites (only for AutomotiveCo, AgriculturalCo1, and AgriculturalCo2, due to COVID-19 pandemic restrictions) to understand how their systems operate in practice. The entire data collection process was carried out from September 2019 to September 2020.

3.3 Data analysis - validity, reliability, and interpretation

For construct validity, the items in the questionnaire script were assessed and complemented with the help of four researchers specialized in Industry 4.0 who did not participate in the data collection process. Additionally, the first round of interviews was conducted with two companies to fine-tune the instrument. In terms of external validity, we conducted multiple case studies and compared the evidence in selecting large companies adopting information systems for vertical integration. As for reliability, a case study protocol was used, and a final report was prepared based on the transcript of the recorded interviews. Some of these procedures have been described in Sections 3.1. to 3.2.

Regarding data analysis, the first step was to transcribe recorded interviews. After transcribing all the interviews, the data were analyzed, looking for evidence of factors influencing the adoption of information systems for vertical integration. The evidence was structured and organized in a final report. After analyzing each interview individually, identifying isolated factors and behaviors, we also performed a cross-case analysis to recognize similarities, contrasts, and patterns between the cases. Finally, we made a second contact with the same interviewees to report our conclusions and collect feedback about our interpretation, as well as new information in cases where divergences existed.

4 RESULTS

The data collected in the interviews provided information to detail the factors that influence the adoption of information systems for vertical integration in manufacturing. In this section, the factors are identified and described following the conceptual research framework presented in Figure 1, i.e., for each context of the Technology, Organization, and Environment (TOE) framework, we analyze the step of the innovation-decision process model.

4.1 Technological context

During the knowledge phase, most of the companies (AutomotiveCo, VehicleCo, ElectronicCo, PowertoolsCo, AgricultureCo1, AgricultureCo2, AutomationCo2, ClothingCo) looked for information systems that could be acquired in modules and assembled according to their individual needs, especially when considering ERP and MES systems. These companies were unwilling to purchase the full information system, but only specific modules that would be useful for their operation aiming to achieve vertical integration in their operations, such as modules for logistics, maintenance, quality, manufacturing control, etc. As expressed by the specialist of VehicleCo: *"We needed an ERP for our vertical integration process that might be customized for the tire production environment, with its particularities in the way it traces, the type of data collection, the type of batch control, etc."*. Therefore, customization was a key factor for these companies.

A second factor was technology expansion capacity. This factor was highlighted by AutomotiveCo, AutomationCo2, ClothingCo, and AgricultureCo2 because the chosen information system had to be robust enough to support the company's long-term expansion plan. For instance, one of the reasons why AutomotiveCo decided to buy a new ERP system for vertical integration was that the old ERP system could not support the company's growth in the following years to accomplish new Industry 4.0 demands like real-data intensity and communication with other information systems. As expressed by the company's Operational Director: *"the two ERPs we had (in different units) would not support our expected growth, as the managers at the time did not consider this. Thus, the IT department has now found that these systems would struggle to support growth in terms of the volume and scale of the company data".* Similarly, ClothingCo reported adopting an MES system to support the plant's growth. *"We needed to grow in our manufacturing field and increase efficiency, and so we needed tools for that (MES) – also to increase production capacity"* (Industrial Engineer). The company expansion achieved by improved vertical integration results in more data from different manufacturing activities. This higher amount of data needs to be processed in real-time to meet the operational requirements of vertical integration systems. Besides, the more a company grows, the more people will need simultaneous access to different information sources and hierarchical layers, which will demand a higher level of accessibility to the systems. Lastly, additional system modules may be required, as expressed by Jain et al. (2012), who highlighted that the company is looking for systems that help integrate the operational activities in real-time with other activities such as supply chain and marketing better prepare its production capacity.

As a third factor, we observed that interoperability highly influenced the companies adopting information systems for vertical integration. Interoperability means providing continuous communication between information systems, devices, and applications. Interoperability features are essential for building integrated business systems. As expressed by the digital manufacturing engineer of AutomotiveCo, *"Since we look for vertical integration, we said no to those providers whose MES was not able to communicate with our ERP. Also, we no longer buy equipment whose builders have restrictions about opening their protocols to connect with the information systems of other brands"*. Similarly, AutomationCo2 reported that it was necessary to adapt much of its machinery to have the same communication protocol to achieve vertical integration: *"We needed to do much work in the standardization of machines and equipment so that everyone can communicate"*. This effort made by the company was considered a negative factor that it wishes to avoid in the following steps of vertical integration.

In the persuasion phase of the adoption process, the company deepens its knowledge of information systems for vertical integration by studying each technology and supplier's pros and cons. At this stage, cybersecurity was mentioned as an important decision factor by the companies ChemicalCo, AutomationCo2, ElectronicCO, and PowertoolsCo for the successful vertical integration of systems. A demand for vertical integration is the integration of Information Technology (IT) and Automation Technology (AT). For a long time, these technologies have been decentralized; they have had different objectives and hierarchies. In this new scenario, cybersecurity is essential to keep data and digital processes safe from cyberattacks that could stun the production lines. As expressed by PowertoolsCo: *"one of the main requirements in adopting MES and integrating it with other systems was the issue of network security due to the integration of the information technology layer with automation technology"*. In this sense, the more verticalized the integration of systems is, the more vulnerable they become to cyberattacks. Therefore, system security is a key element to be considered by the interviewees.

Additionally, the current architecture undoubtedly influences the adoption of specific information systems for vertical integration, as mentioned by all companies interviewed. The architecture defines the software components, their external properties, and their relationships with other software. Each manufacturing company has different applications, tools, and systems, depending on their specific history and needs; thus, there can be a wide range of combinations of these components. Behind each combination, a large organizational structure called software architecture is responsible for carrying out the strategic analysis of these components. To implement vertical integration is necessary to analyze whether the intended new system can be integrated with those existing in the company's current architecture. This strategic analysis can take years, as was the case with AgricultureCo1, which had to redesign its architecture worldwide before adopting a new MES to complete its vertical integration process: *"Software architecture is a real puzzle, and it is necessary to evaluate it carefully for a successful adoption of vertical integration"*.

Another factor is the choice of functionalities for each information system. Different systems, such as ERP and MES, have some functionalities in common, and it is up to the company to choose which one it will use. According to the interviewee from AgricultureCo1, the ERP they had in the company already included some features proposed by the intended MES, so a study was carried out to understand which functionality would be the most suitable for each system: *"we decided that our MES should include all features of four pillars: planning, logistics, quality, and maintenance"*. Similarly, the information system of AutomationCo2 was developed over time for different functions, such as quality and maintenance. Therefore, the MES was developed with only the necessary functions (manufacturing control and process). However, AutomationCo2 also developed its MES to be a "data lake" for the integration of all systems: *"At the manufacturing execution level, we created a data lake to integrate all systems already running in the factory"*.

At this stage, a fourth factor in the technological context is the platform characteristics that information systems require for vertical integration. In recent years, several studies have highlighted the importance of platforms for Industry 4.0 in order to create an ecosystem of solutions for different applications in the company. In this sense, a platform can be defined as a set of subsystems and interfaces that form a common structure. Companies can efficiently develop and produce a line of products derived from these subsystems. Several companies (AutomationCo2, AgricultureCo1, AgricultureCo2, PowertoolsCo, and ElectronicCo) pointed out that the platform factor was influential in adopting information systems for vertical integration. As reported by PowertoolsCo: *"We had four MES solution alternatives. We opted for a platform solution that provides scalability, integration with other systems, and which provides a greater degree of freedom than traditional MES"*. A similar approach can be observed in the statement of ElectronicCo's interviewee: *"the first thing that was taken into account was that it was a platform and not a restricted system because we could grow in the future; the possibility of integrating with other systems, especially with the ERP and its integration with APS , integration with supervision systems and the interface with machines has always been a concern"*.

The last phase is the adoption process. The firms engage in more practical activities to decide whether to adopt or reject the information systems for vertical integration. Since after this phase, the firm will incur in investments, the technology costs should be clear and the supplier. Trialability is another important characteristic that firms should observe. It refers to the ease with which customers can try out a new product or service. The trialability of information systems in small proof of concepts or pilot projects was demanded from technology suppliers by AutomotiveCo, ElectronicCo, ClothingCo, AgricultureCo2, AutomationCo2, ChemicalCo, and AgricultureCo1 to test and learn about the connectivity and integration problems that could arise and could not be predicted in theory. As stated by the Digital Manufacturing Engineer from AutomotiveCo: *"we have a production line that we generally use to test technologies of* *this type. Then, the suppliers present their solutions, and from this experience, we make our final decision".* Similarly, ClothingCo tested its information system for three weeks before deciding for its implementation, and AgricultureCo2 tested the connectivity of IoT with the MES and its functional areas: *"the MES is being tested in 3 sectors of the company and, if successful, we plan to adopt it in one year for the whole company".* In a different strategy, to have less impact on its current activities, AgricultureCo1 tested different parts of the vertical integration in different plants worldwide: *"it gave each region an action for research and development. 'Fail fast, learn faster' is our philosophy for these initiatives. Then, the smart factory committee shares all research and learnings, and then the initiatives become global standards".*

4.2 Organizational context

In the knowledge phase, we observed that the infrastructure factor stood out in most companies (AutomationCo2, AutomotiveCo, VehicleCo, ChemicalCo, ElectronicCo, AgricultureCo1, ClothingCo, AgricultureCo2). In order to adopt an information system for vertical integration, like MES, for instance, much equipment, sensors, and a network structure are required to support it. Besides, depending on the chosen system, it demands a specific infrastructure for integration. For instance, the IT Manager of AgricultureCo1 reported that they needed to adapt the factory's infrastructure to integrate the new systems: *"Every infrastructure modification we made in the site was because we would have to integrate the MES from Brand X with our ERP, which is from the Brand Y, so we would have much integration work to do here by ourselves".*

Additionally, the firms' legacy factor was mandatory when deciding which information system to adopt for vertical integration. None of the companies interviewed is starting their systems implementation from a greenfield; thus, they already have a legacy of previous systems running in their factories. As expressed by AutomotiveCo: *"we did not look for the best MES, but for an MES that we would be able to integrate with the different legacy systems that we have in our many factories".*

In the persuasion stage, firms should observe the relationship of the information system with people. In this sense, the organization's digital culture was identified in our interviews as a factor that influences the adoption of information systems for vertical integration in companies like AutomotiveCo, AutomationCo2, VehicleCo, AgricultureCo1, ClothingCo, andAgricultureCo2. As a counterpoint, ElectronicCo considered that they were unsuccessful in adopting an APS software for their vertical integration process because they neglected aspects such as their employees' culture and readiness to use digital tools. Therefore, they used a different approach for the adoption of MES: *"When we implemented the APS software project, we were very much concerned with the technical part and little mindful of the organizational and cultural part. The system was ready and beautiful, but nobody used it; it was a money pit; until today, they use excel. In the MES project, which was a little later, we did it very differently; when we closed it, we involved many people from various areas in helping us define the requirements."* As this example shows, people's engagement in the company's digital transformation process was considered essential for these companies to integrate the systems of different company layers. Additionally, AutomotiveCo explained that there are difficulties in changing behaviors regarding innovation because they have a long-established tradition in the company. As the interviewee from this company affirmed, *"For people that are used to making decisions based on experience, making decisions based on data or technologies is a challenge".* According to the interviewee, it is necessary to promote the benefits of vertical integration so that everyone will be aware of the whole when acquiring any new technology/equipment. Also, VehicleCo reported that this conservative culture pervades all areas, from IT to the shopfloor: "sometimes we forget that an information system for vertical integration impacts the entire company, and there are divisions within the IT area itself; so, for you to be able to form a team and get it to work and understand certain differences and sometimes even create parallel systems, not necessarily integrated, it is still a very difficult task, especially when managers have more conservative concepts, even about IT… so there is a convincing job to be done. But the greatest difficulty for us to overcome the cultural issue is really on the factory floor". To deal with this factor, AutomationCo2 implemented forums to introduce Industry 4.0 and vertical integration concepts to its employees: *"we held forums with more than 400 employees to show Industry 4.0 and its benefits. We spread a new culture to facilitate adoption"*, affirmed the Industry 4.0 Head. Something similar happened at ClothingCo: *"training was needed to raise awareness of the change and explain what the company is pursuing with the adoption of vertical integration".*

In parallel with the cultural factor that observes people's openness to the change brought by the information system for vertical integration, firms should be aware of people readiness, that is, if employees have the knowledge and capabilities to manage the new information systems and the data they generate. As expressed by AutomotiveCo: *"we put* *our MES to run without giving proper training to our employees. Because of this, the company almost stopped. It was chaos! After one week, we needed to come back to our old system, and the credibility of the project was highly impacted"*. For ClothingCo, more than training the current employees, they needed to hire new professionals to extract results from the data generated by the vertical integration. At ChemicalCo, they created an entirely new department to deal with the data and coordinate projects related to digital technologies. Something similar happened at PowertoolsCo: *"we needed to create a new department when we realized that the MES is not a project with a beginning, middle, and end. The MES project has no end. It is a project that does not belong to any specific sector; it belongs to everyone simultaneously"*. This new department at PowertoolsCo was designed to provide vertical integration systems to the whole company and is mainly composed of IT and production staff. This also brings a new factor into play, the integration between functional areas, which companies should be aware of in this persuasion stage. PowertoolsCo, AgricultureCo1, AutomotiveCo, and ElectronicCo acknowledged that they could implement vertical integration only because they could involve different functional areas and consider each other's demands when building the system. At PowertoolsCo, a key person from each sector was interviewed to determine what exactly the new system would affect.

In addition to the people who will use the information system, IT department readiness was also highlighted by AutomotiveCo, ElectronicCo, PowertoolsCo, ChemicalCo, and AgricutureCo1. Most companies still have their IT departments functioning traditionally, only providing support for the rest of the organization, with standardized solutions for computers, phones, and software. This type of traditional IT department is usually not prepared for large investments in Industry 4.0. The vertical integration demands integrating the IT department with the production and development processes requires knowledge of IT and AT, and specific knowledge regarding other functional areas of the firm to be integrated with the vertical integration. At AgricultureCo1, the IT area was divided into three sectors because of vertical integration: *"we now have an IT area divided in (i) finances and sales, (ii) human resources and supply chain and (iii) manufacturing and engineering. I am responsible for the third. It encompasses all projects involving IT and AT in the areas of manufacturing and engineering"*.

Regarding the persuasion stage, the lack of standards for systems was a factor raised by the companies AutomotiveCo, AutomationCo2, VehicleCo, PowertoolsCo, and

AgricultureCo1. Industry 4.0 is connecting factories, making machines and systems communicate and share data. A standardized form of communication between these systems is desirable to reduce the need to convert data. With a standardized way of defining and communicating data, it would be much easier and faster to adopt the concepts of vertical integration. However, there is currently no industry-wide standard for industrial communication systems. According to AutomotiveCo, communication between new technologies and all existing systems and machines is a complex task, requiring translation of communication protocols between all parties, as mentioned above. The lack of a standard for digital manufacturing systems causes confusion and insecurity when adopting an information system for vertical integration. According to PowertoolsCo, the ISA-95 standard is still insufficient, which presents a benchmark for companies, including integration issues, terminologies, and process models. Although the ISA-95 standard provides a generic map of all processes and their data flows, some activities are not covered by the standard. The project team is responsible for evaluating the company in question and making decisions. In the case of AgricultureCo1, they reported that they needed to carry out an entire study, which took about a year and a half to complete, to define the company's IoT information protocols that would allow data to be collected from any machine or equipment in an organized manner.

A final factor mentioned by the companies AutomotiveCo, VehicleCo, AgricultureCo1, and AutomationCo2 was the need for specialized external expertise to support adopting information systems for vertical integration. AutomotiveCo hired a specialized consultancy to support its ERP system choice due to the firm's know-how, personalized service, and the possibility of frequent iterations in seeking an adequate solution. They also partnered with a university to support a research group and hired a Ph.D. student to dedicate exclusively to the investigation of vertical integration. Although AgricultureCo1 did not hire a consultancy to guide the entire adoption process, they hired a specialized systems architect to design its MES, as mentioned earlier.

In the decision stage, the pilot projects and proof of concepts provide more reliable information to analyze the benefit-cost tradeoff, one of the most important factors in the firms intending to adopt the systems. Eight of the nine firms considered the economic analysis particularly important to make an adopt or reject decision. However, AgricultureCo2, AgricultureCo1, and AutomotiveCo noted several aspects of a cost-benefit analysis that are difficult to measure in monetary terms for vertical integration, as expressed by AutomotiveCo: *"It is complicated to measure the cost-benefit of the systems. We do an extrapolation analysis (technical and financial analysis). For example, in the case of MES: we counted the number of terminals that we would have in this operation, connected machines, televisions, computers, etc. So, we extrapolate, in 5 years we will have more or less than many"*.

Finally, we observed the importance of involving top management in the adopt or reject decision. While most of the analysis in the previous stages was concentrated in lower organizational levels, top management support is a critical factor influencing the adoption of information systems for vertical integration. Top managers should be the supporters and give legitimacy to the many changes people in the organization will need to adapt to during the information system implementation. Thus, all results from the innovation-decision process should be presented to them for approval. For instance, the interviewees from AutomotiveCo pointed out that the adoption decision came as a common agreement between administrative and industrial top managers, even though its president has an innovation and technological bias that is positive for such projects.

4.3 External environment context

In the knowledge phase of the adoption process, the competitive pressure was identified by AutomotiveCo, AutomationCo2, AgricultureCo1, and ChemicalCo, as an important factor for the adoption of information systems for vertical integration. To seek competitive advantage in a competitive global market, organizations strive to adopt innovations, searching for new alternatives to improve their production and face the ‘technological race’ in Industry 4.0 context. ChemicalCo interviewees, for instance, revealed a great concern for the company not to "be left behind" by competitors, considering strategical to invest in Industry 4.0 concepts and technologies. However, this competitive pressure does not come only from competitors but may also come from other units in the company. For example, PowertoolsCo and AgricultureCo1 reported that top local managers feel pushed to adopt information systems for vertical integration since other units implemented them.

Besides, a technology push factor was noticed influencing the adoption of information systems for vertical integration in AutomotiveCo, ElectronicCo, PowertoolsCo, ChemicalCo, and AgricultureCo1. These companies have a constant concern about knowing all innovations available in the market, keeping regular contact with traditional technology suppliers, and startups that develop software or new products that are part of the vertical integration. At AutomotiveCo, they created a prospection team formed by IT and production staff to seek news on digital technologies, visit suppliers, and participate in trade fairs.

In the persuasion phase, interviewees from AutomotiveCo, AutomationCo2, ElectronicCo, PowertoolsCo, AgricultureCo1, ChemicalCo, and TerminalsCo recognized benchmarking as a crucial factor since they needed to monitor their competitors to learn about the technologies they are using. As exemplified by the case of AutomotiveCo: "in the case of PLM and MES, we carry out benchmarking to select potential technology suppliers. We visited four companies to see which brand of information system they were using and get feedback. It was not to check they were using MES or not, because we were already sure that we needed an MES". On the other hand, TerminalsCo reported that they only realized the need for a vertically integrated MES system after benchmarking: *"from visits to other companies, we realized that they were using a vertically integrated MES and reported many benefits from it. So, we decided to go to the market to look for this kind of information system".*

Finally, in the decision stage, suppliers' solidity was mentioned as a crucial factor by AutomotiveCo, ElectronicCo, ClothingCo, and AgricultureCo1. While in the previous stages, the firms were more interested in understanding the characteristics of the information system, at this stage, they are more concerned about receiving adequate support from the systems suppliers during and after implementation. *"The managers have the following vision: Is the supplying company solid? Is it global? Can it serve several plants around the world? Will we be well supported over time?"* (Digital Manufacturing Engineer from AutomotiveCo). Thus, even though AgricultureCo1 and AutomotiveCo tested some vertical integration concepts with startups to understand their pros and cons, in some cases, they ended up choosing another multinational supplier for the information systems implementation. On the other hand, since ClothingCo has only one factory, it has a different opinion about working with small firms: *"Three suppliers met our requirements: two were big, well-established firms and one was a startup. However, the startup cost six times lower than one supplier and three times lower than the other. The startup can offer support only for our region (50km radius). Also, as a smaller company, it was interested in gaining commercial know-how by selling us the MES; so that would benefit both sides"* (Industrial Engineer). However, ClothingCo also demonstrated some concern about its supplier choice: *"small firms have a small structure, and they cannot serve us as quickly as we would like."*

4.4 Summary of the findings

We summarize the main factors identified in the case studies in Figure 2. As shown in this figure, the factors of each TOE dimension change over time according to each stage of the innovation-decision process. The following section discusses the implications of such findings, showing the main patterns behind the adoption process described for vertical integration in the Industry 4.0 context.

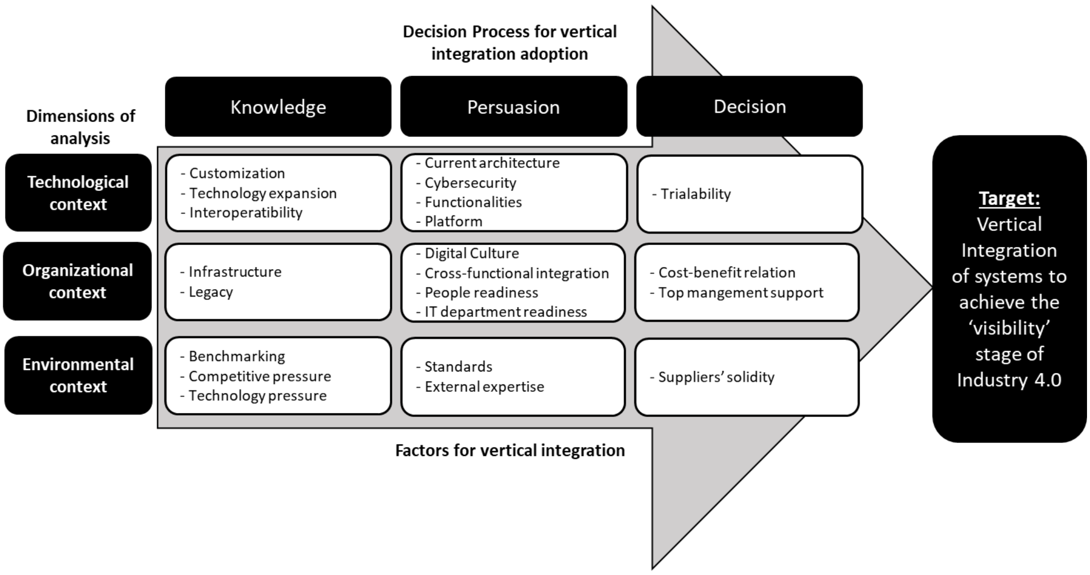

Figure 2. Empirical framework summarizing the factors of the process for adoption of information systems for vertical integration

5 DISCUSSIONS

The results summarized in the consolidated framework in Figure 2 can be analyzed either from the perspective of each TOE dimension along the different stages or from the perspective of each decision stage considering the nuances of the different dimensions analyzed. We opted for the second option (i.e., an analysis of each of the columns of the framework in Figure 1). Our discussion also aims to explore tensions between the different factors identified in our case studies.

The Knowledge stage (Figure 1) shows that the implementation of vertical integration is strongly dependent on the resources currently available in a company's manufacturing activity, meaning that it is a kind of incremental innovation process for the information system adoption (Pérez-Lara et al., 2018). This is evidenced by the fact that even when the environmental context presents external pressures for the advancement in the Industry 4.0 implementation, the internal condition of the information systems layers plays a key role in the vertical integration process. Our results evidenced that companies strongly depend on a fragmented technological legacy and look for customized technologies and systems interoperability because they already have several parts of the technology solution when they decide to advance towards vertical integration. The innovation literature has suggested that this is the usual approach taken by companies with consolidated resources: they tend to rely on what they already have and take a new step toward a more innovative approach (Cortimiglia et al., 2016). This is also understandable since Industry 4.0 solutions frequently come from different providers, which must be interconnected to configure an integrative solution. Therefore, it is easier for companies to start from the already established systems in their companies (Benitez et al., 2021). However, such an approach can also present some challenges for vertical integration in the Industry 4.0 domain. As shown by Frank et al. (2019), many companies face difficulties in implementing a flexible manufacturing system during the Industry 4.0 journey because they rely too strongly on an internal legacy of systems and structures established before the company aimed to advance in the Industry 4.0 concept. Therefore, while the organizational context can limit the company's expansion due to the legacy and infrastructure, companies pursuing vertical integration should balance this with the environmental context, which brings the external needs and trends. In such a scenario, factors of the technological dimension in this stage can play a moderating role since the look at future expansion, customization, and interoperability can help better connect the external needs with the already established resources (Ali et al., 2021; Javidroozi et al., 2020).

At the Persuasion stage (Figure 2) in the decision process, we could observe another type of concern regarding the factors identified for vertical integration. These factors consider operational concerns companies may have for the implementation of the technological solution. Cybersecurity was already observed in the literature as a factor limiting firms' willingness to advance in the vertical integration of systems because of concerns about being hacked and suffering impacts on their production activities (Qian et al., 2012). Furthermore, functionalities and platform issues must be constantly managed by companies to ensure that the information system will operate correctly (Jain &

Bhattacharyya, 2012). Similarly, human-related concerns like culture, integration between sectors, people readiness, and external parties' support also represent operational characteristics of information systems adoption (Javidroozi et al., 2020). These factors also reinforce the highly relevant role of people in the path of firms towards Industry 4.0 (Meindl et al., 2021; Romero et al., 2020), suggesting that companies can make mistakes when they implement technology programs without putting people at the center of this process. Such factors can be observed in adopting any information system, but they become particularly relevant in the Industry 4.0 context. In this sense, it is important to bear in mind that vertical integration represents a major integration of different layers of systems, including SCADA, MES, ERP, and sometimes also APS, PLM, and other applications, that are used in the most diverse firm departments, not only in the manufacturing sites (Antonio et al., 2017; Longo et al., 2017; Rossit et al., 2019). In this sense, any problem related to factors like cybersecurity or unsuitable functionalities (Technological context), or lack of workers' engagement in their use (Organizational context), or lack of external partners' support in the event of a problem (External context), can become a systemic information problem for the company. Kahle et al. (2020) demonstrated that the creation of digital ecosystems with the participation of several stakeholders for the provision of expertise, standards, and cybersecurity rules for companies that adopt Industry 4.0 technologies could help to advance faster in this kind of adoption, which is consistent with this stage of our framework. Moreover, external support is essential at this stage because most companies may not have all the internal skills and resources to implement advanced systems due to a lack of people and IT readiness for digital transformation (Benitez et al., 2020). Consequently, while the previous stage was marked by the tensions between internal and external demands for vertical integration, this new stage needs to balance vertical integration's technology and social requirements.

At the third stage, Decision, our findings point to fewer yet not less important factors. We show that some companies are more willing to prove concepts and testbeds before implementing the full, costly solution (Technological context). As the literature highlights, investments in Industry 4.0 are hard to assess because of their complexity (Margherita & Braccini, 2020), and therefore proofs of concepts are essential to visualize the real cost and investments of a broader implementation of vertical integration systems. Many of such proofs of concepts can be performed through the involvement of startups in the Industry 4.0 development (Alam & Khan, 2020). However, as shown in our findings, this can also be challenging for the future scalability of the solution since startups may not have the necessary operational capacity to extend the solutions to the whole company, especially when the company is a large one (Marcon & Ribeiro, 2021). Therefore, suppliers' solidity is equally important since the vertical integration journey can be long and demand much energy from both the company and the provider for integration of processes and systems that will provide a real-time data flow across the different hierarchical layers of the company (Saghiri & Wilding, 2021; Salam, 2019). In such a scenario of costs and demands, implementing vertical integration information systems can be a 'painful' process that firms will resist for as long as possible (Matyoqubov et al., 2020). Besides, losing the support of a technology provider during this journey can jeopardize the entire project. In such a case, suppliers' solidity is usually associated with larger companies and more costly technology solutions for the Industry 4.0 context (Benitez et al., 2020). Therefore, companies may have to deal with a trade-off between smaller and cheaper solutions for testing vertical integration concepts in specific parts of the process and acquiring broader, more robust solutions that will be more expensive and fit for the long journey of a full vertical integration process.

We summarize our discussion above in Figure 3, where we represent the main tensions between the different factors and dimensions that managers may have to deal with during the adoption of systems for vertical integration. As shown in this figure, in the Knowledge stage, managers will face a tension between the demand for new digital solutions in the factory, especially pushed by external competition, and the internal concern of preserving and prioritizing the legacy of information systems already in place. Then, in the Persuasion stage, managers need to balance between the several technical requirements for the digital transformation and the social factors that need to be prepared to follow this transformation. Lastly, at the Decision stage, from a technological and organizational perspective, the investment in small, low-budget trials, usually available from startups, can be a good option for companies to start the Industry 4.0 vertical integration journey. On the other hand, even this journey will be long and challenging, making larger suppliers a sounder source to support the companies' expectations in the long run.

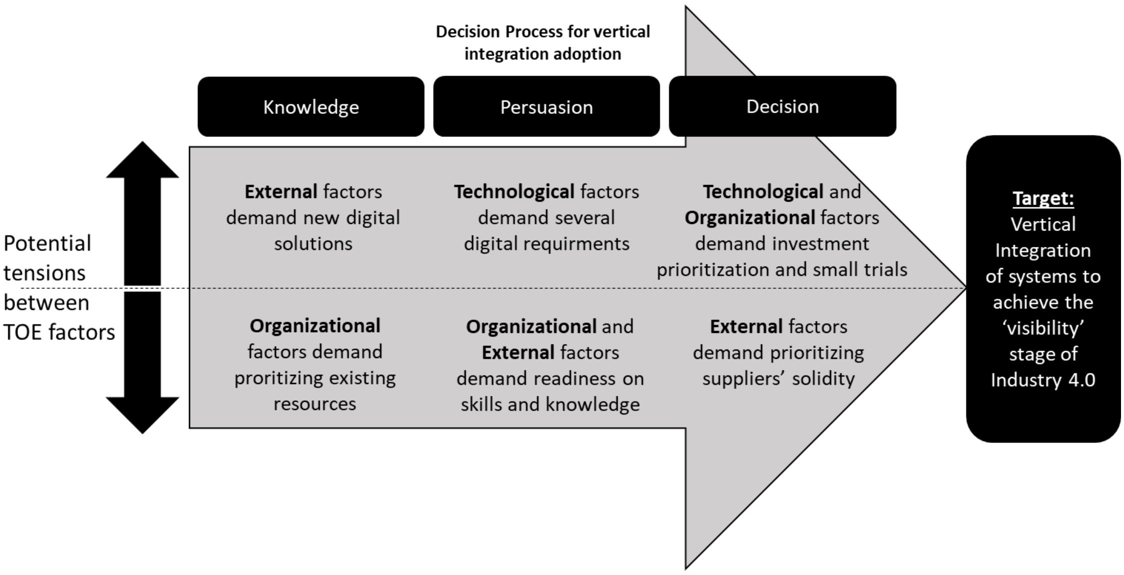

Figure 3. Main tensions between the factors identified in the study for the vertical integration of systems

6 CONCLUSIONS

Our findings provide the big picture of different factors that managers should consider during the decision-making process. Our study adopted the innovation-decision process view and the TOE framework to provide a conceptual understanding of what companies consider to adopt systems for vertical integration, aiming to achieve the visibility stage of Industry 4.0. Using data from the case studies analysis, we developed a framework that describes the main factors involved in the decision-making process for adopting systems aiming for vertical integration. We showed these factors deployed in three main stages of decision: knowledge, persuasion, and decision, and in three main dimensions of analysis: technology, organization, and environment. We summarized 22 main factors distributed along these stages and dimensions of analysis (Figure 1).

6.1 Theoretical contributions

The information systems literature has largely discussed technical and organizational factors for the adoption of information technologies. However, this is the first attempt to provide understanding in a specific type of information system which considers the integration of different technologies such as SCADA, MES, APS, PLM, and ERP to implement vertical integration in the Industry 4.0 context, i.e., when real-time data flow based on IoT systems is used. The novelty of this view is that we considered an interrelated and complex system of different information technologies that demands a broader set of requirements than in the study of single technology adoption, including various technical, organizational, and environmental factors. Moreover, this study demonstrates that such diversity of factors must be considered alongside the technology adoption process' stages. While previous studies have considered Industry 4.0 implementation factors from a static perspective (e.g., Sony and Naik, 2019; Hoyer et al., 2020; Nimawat and Gidwani, 2020; Lin et al., 2019), this is the first study investigating the dynamic aspect of the implementation that information system managers need to consider. This combination of the technology adoption process with the TOE framework is a novel contribution to the literature. It provides a conceptual framework that scholars can adopt for any other type of information system analysis. Thus, our study clarifies vertical integration factors and provides a broader conceptual contribution related to these factors for the general information system literature. Another contribution of this study is that such complex integration of different information technologies creates tensions between the factors alongside the adoption process. We showed which are these tensions and how they relate with each other, highlighting factors from different sociotechnical dimensions that can conflict to each other. Information management scholars can find in this analysis of tensions opportunities for future research since the origins and approaches to manage such different tensions can be investigated to create more theory on the sociotechnical aspects for the adoption of vertical integration.

6.2 Practical contributions

Our results also provide practical contributions for managers, and we provide some guidelines regarding these contributions in this section. Our study showed that, at the knowledge stage of adoption, there is a need for new digital solutions demanded by external factors. In contrast, the company's need to prioritize its internal organizational resources creates tensions between what the company has and what the company needs. In this sense, managers need to balance the use of legacy systems and the reengineering of the company's infrastructure. This is more important in vertical integration because it considers several information technologies that have been acquired in different moments of the company's evolution. Therefore, practitioners must consider the feasibility of such integration between the legacy systems and the new technologies and the resulting flexibility or rigidity of the resulting vertical integration. Since Industry 4.0 requires more flexibility, managers need to take care about verticalizing systems that will result in organizational rigidity due to the lack of functionalities for Industry 4.0 demands.

Secondly, we showed a tension between digital technological requirements and the need for readiness in terms of organizational skills and knowledge in the persuasion stage. Although they are not necessarily in tension, managers can easily focus only on the technological aspects and dismiss social factors. As our results showed, vertical integration in the Industry 4.0 context is a multidimensional and multifunctional implementation of information systems and needs a coherent balance between such sociotechnical factors. Thus, managers need to develop training programs, digital culture development programs, and skilled human resources recruitment as the vertical integration advances in its implementation.

Finally, in the decision stage, there is a tension between the need to develop small trials and prioritize investments and the company's need for technology suppliers' solidity, which is usually associated with large companies offering large technology platforms. Prior studies (e.g., Benitez et al., 2020, 2021; Kahle et al., 2020) suggested that one of the options for managers in such case is to orchestrate a group of companies through an ecosystem approach, which is one of the most prominent approaches in the Industry 4.0 domain. Such an approach allows integrating the complexity of the demands around several small and medium-sized actors that can help create the required environment for small trials. At the same time, there is still solidity due to the ecosystem architecture in which the company does not depend on a single supplier for such an implementation.

6.3 Limitations and future research

Our study also has limitations and opportunities for future research. We did not analyze any of the companies after the vertical integration process was completed. Since Industry 4.0 presents an interrelated set of technologies and solutions, success in the future stages of implementation could be a good measure of how vertical integration was adopted and implemented. For instance, the quality of the data analyzed or the ability of a company to make good predictions depends on how well its systems were integrated to provide the data that will support decision-making. Therefore, future studies could analyze the post-implementation stage of vertical integration to make a backward analysis and assess how successful the vertical integration was and the potential weaknesses in such implementation. Another point is that we only analyzed the adoption stage without regard to the final financial process involved in choosing the best possible systems and their form of implementation. Future studies can provide tools and elements that will facilitate decision at that stage since the Industry 4.0 literature still lacks clear guidelines to help select vendors considering the various subjective factors involved and potential paybacks and returns on investment of some cutting-edge projects. Moreover, as pointed out in our practical contributions (Section 6.2), the implementation of vertical integration through the development of an ecosystem of technology providers working around Industry 4.0 solutions is a field that deserves more attention in the future. Prior studies have considered the development of ecosystems for testbeds and integrated solutions (e.g., Benitez et al., 2020; 2021), but they have not addressed details on the information system requirements and how this can be built around platforms and different companies working in an ecosystem. This can provide future avenues for the study of information systems in the Industry 4.0 field.

7 REFERENCES

ALAM, M., & KHAN, I. R. (2020). Business 4.0-A New Revolution. November. https://doi.org/10.6084/m9.figshare.14369636

ALI, O., SHRESTHA, A., GHASEMAGHAEI, M., & BEYDOUN, G. (2021). Assessment of Complexity in Cloud Computing Adoption: a Case Study of Local Governments in Australia. Information Systems Frontiers. https://doi.org/10.1007/s10796-021-10108-w

ALSHAMAILA, Y., PAPAGIANNIDIS, S., & LI, F. (2013). Cloud computing adoption by SMEs in the north east of England: A multi-perspective framework. Journal of Enterprise Information Management, 26(3), 250–275. https://doi.org/10.1108/17410391311325225

ANTONIO, G. D., MACHEDA, L., BEDOLLA, J. S., & CHIABERT, P. (2017). PLM-MES Integration to Support Industry 4 . 0. 1, 129–137. https://doi.org/10.1007/978-3-319-72905-3

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, 193(August), 538–553. https://doi.org/10.1016/j.ijpe.2017.08.019

BELLINI, P., CENNI, D., MITOLO, N., NESI, P., PANTALEO, G., & SODERI, M. (2021). High Level Control of Chemical Plant by Industry 4.0 Solutions. Journal of Industrial Information Integration, xxxx, 100276. https://doi.org/10.1016/j.jii.2021.100276

BENITEZ, G. B., AYALA, N. F., & FRANK, A. G. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. International Journal of Production Economics, 228(July 2019). https://doi.org/10.1016/j.ijpe.2020.107735

BENITEZ, G. B., FERREIRA-LIMA, M., AYALA, N. F., & FRANK, A. G. (2021). Industry 4.0 technology provision: the moderating role of supply chain partners to support technology providers. Supply Chain Management, November 2020. https://doi.org/10.1108/SCM-07-2020-0304

BOSE, R., & LUO, X. (2011). Integrative framework for assessing firms' potential to undertake Green IT initiatives via virtualization - A theoretical perspective. Journal of Strategic Information Systems, 20(1), 38–54. https://doi.org/10.1016/j.jsis.2011.01.003

BRANGER, J., & PANG, Z. (2015). From automated home to sustainable, healthy and manufacturing home: a new story enabled by the Internet-of-Things and Industry 4.0. Journal of Management Analytics, 2(4), 314–332. https://doi.org/10.1080/23270012.2015.1115379

BRUNELLI, J., LUKIC, V., MILON, T., & TANTARDINI, M. (2017). Five Lessons from the Frontlines of Industry 4.0. The Boston Consulting Group, November, 1–14. https://www.bcg.com/publications/2017/industry-4.0-lean-manufacturing-five-lessons-frontlines.aspx

CNI, N. C. of I. (2016). Industry 4.0: a new challenge for Brazilian industry. CNI Indicators, April, 13. https://static-cms-si.s3.amazonaws.com/media/filer_public/13/e7/13e7e7bd-9b1d-4c16-8099-99b6d844d04e/special_survey_industry_40.pdf

CORTIMIGLIA, M. N., GHEZZI, A., & FRANK, A. G. (2016). Business model innovation and strategy making nexus: Evidence from a cross-industry mixed-methods study. R and D Management, 46(3), 414–432. https://doi.org/10.1111/radm.12113

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, 204(December 2017), 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

EISENHARDT, K. M., & GRAEBNER, M. E. (2007). Theory building from cases: Opportunities and challenges. Academy of Management Journal, 50(1), 25–32. https://doi.org/10.5465/AMJ.2007.24160888

EL-HADDADEH, R. (2020). Digital Innovation Dynamics Influence on Organisational Adoption: The Case of Cloud Computing Services. Information Systems Frontiers, 22(4), 985–999. https://doi.org/10.1007/s10796-019-09912-2

FERNANDEZ-VIAGAS, V., & FRAMINAN, J. M. (2021). Exploring the benefits of scheduling with advanced and real-time information integration in Industry 4.0: A computational study. Journal of Industrial Information Integration, 100281. https://doi.org/10.1016/j.jii.2021.100281

FRANK, A. G., DALENOGARE, L. S., & AYALA, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. International Journal of Production Economics, 210(September 2018), 15–26. https://doi.org/10.1016/j.ijpe.2019.01.004

GHOBAKHLOO, M., & CHING, N. T. (2019). Adoption of digital technologies of smart manufacturing in SMEs. Journal of Industrial Information Integration, 16. https://doi.org/10.1016/j.jii.2019.100107

HALEEM, A., & JAVAID, M. (2019). Additive Manufacturing Applications in Industry 4.0: A Review. Journal of Industrial Integration and Management, 04(04), 1930001. https://doi.org/10.1142/s2424862219300011

HOYER, C., GUNAWAN, I., & REAICHE, C. H. (2020). The Implementation of Industry 4.0–A Systematic Literature Review of the Key Factors. Systems Research and Behavioral Science, 37(4), 557-578. https://doi.org/10.1002/sres.2701

IAKSCH, J., FERNANDES, E., & BORSATO, M. (2021). Digitalization and Big data in smart farming–a review. Journal of Management Analytics, 8(2), 333–349. https://doi.org/10.1080/23270012.2021.1897957

ISA. (2020). ISA - International Society of Automation. https://www.isa.org

ISMAIL, A., & KASTNER, W. (2016). Vertical integration in industrial enterprises and distributed middleware. International Journal of Internet Protocol Technology, 9(2–3), 79–89. https://doi.org/10.1504/IJIPT.2016.079547

JAIN, V. K., & BHATTACHARYYA, B. (2012). Advanced manufacturing processes. In Journal of Manufacturing Technology Research (Vol. 4, Issues 1–2).

JANSSEN, M., WEERAKKODY, V., ISMAGILOVA, E., SIVARAJAH, U., & IRANI, Z. (2020). A framework for analysing blockchain technology adoption: Integrating institutional, market and technical factors. International Journal of Information Management, 50(April 2019), 302–309. https://doi.org/10.1016/j.ijinfomgt.2019.08.012

JAVIDROOZI, V., SHAH, H., & FELDMAN, G. (2020). A framework for addressing the challenges of business process change during enterprise systems integration. Business Process Management Journal, 26(2), 463–488. https://doi.org/10.1108/BPMJ-03-2019-0128

JUNIOR, C. H., OLIVEIRA, T., & YANAZE, M. (2019). The adoption stages (Evaluation, Adoption, and Routinisation) of ERP systems with business analytics functionality in the context of farms. Computers and Electronics in Agriculture, 156(January 2018), 334–348. https://doi.org/10.1016/j.compag.2018.11.028

KAGERMANN. H. (2013). Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Acatech, April, 4–7.

KAHLE, J. H., MARCON, É., GHEZZI, A., & FRANK, A. G. (2020). Smart Products value creation in SMEs innovation ecosystems. Technological Forecasting and Social Change, 156(November 2019), 120024. https://doi.org/10.1016/j.techfore.2020.120024

KHAN, I. H., & JAVAID, M. (2021). Role of Internet of Things (IoT) in Adoption of Industry 4.0. Journal of Industrial Integration and Management, 6(2), 2150006. https://doi.org/10.1142/s2424862221500068

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

LI, L. (2018). China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0." Technological Forecasting & Social Change, 135(February 2017), 66–74. https://doi.org/10.1016/j.techfore.2017.05.028

LIGGESMEYER, P. (2014). Industry 4.0. Informatik-Spektrum, 37(4), 284–285. https://doi.org/10.1007/s00287-014-0809-1

LIN, B., WU, W., & SONG, M. (2019). Industry 4.0: Driving factors and impacts on firm's performance: An empirical study on China's manufacturing industry. Annals of Operations Research, 1-21. https://doi.org/10.1007/s10479-019-03433-6

LIU, Z., & XIE, K. (2020). A paradigm of safety management in Industry 4.0. 632–645. https://doi.org/10.1002/sres.2706

LONGO, F., NICOLETTI, E., & PADOVANO, A. (2017). Smart operators in industry 4.0: a human-centered approach to enhance operators' capabilities and competencies within. Computers & Industrial Engineering. https://doi.org/10.1016/j.cie.2017.09.016

LU, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. Journal of Industrial Information Integration, 6, 1–10. https://doi.org/10.1016/j.jii.2017.04.005

MADUKU, D. K., MPINGANJIRA, M., & DUH, H. (2016). Understanding mobile marketing adoption intention by South African SMEs: A multi-perspective framework. International Journal of Information Management, 36(5), 711–723. https://doi.org/10.1016/j.ijinfomgt.2016.04.018

MARCON, A., & RIBEIRO, J. L. D. (2021). How Do Startups Manage External Resources in Innovation Ecosystems? a Resource Perspective of Startups' Lifecycle. Technological Forecasting & Social Change, 171(June), 120965. https://doi.org/10.1016/j.techfore.2021.120965

MARCON, É., SOLIMAN, M., GERSTLBERGER, W., & FRANK, A. G. (2021). Sociotechnical factors and Industry 4.0: an integrative perspective for the adoption of smart manufacturing technologies. Journal of Manufacturing Technology Management, in press. https://doi.org/10.1108/JMTM-01-2021-0017

MARGHERITA, E. G., & BRACCINI, A. M. (2020). Industry 4.0 Technologies in Flexible Manufacturing for Sustainable Organizational Value: Reflections from a Multiple Case Study of Italian Manufacturers. Information Systems Frontiers. https://doi.org/10.1007/s10796-020-10047-y

MASOOD, T., & EGGER, J. (2020). Adopting augmented reality in the age of industrial digitalisation. Computers in Industry, 115, 103112. https://doi.org/10.1016/j.compind.2019.07.002

MATYOQUBOV, M., SAIDOV, A., KAZAKOV, O., & RUSTAMOVA, O. (2020). Enterprise systems data integration. 2020 International Conference on Information Science and Communications Technologies, ICISCT 2020, 2020–2022. https://doi.org/10.1109/ICISCT50599.2020.9351423

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(November 2020). https://doi.org/10.1016/j.techfore.2021.120784

NIMAWAT, D., & GIDWANI, B. D. (2020). Prioritization of important factors towards the status of industry 4.0 implementation utilizing AHP and ANP techniques. Benchmarking: An International Journal. https://doi.org/10.1108/BIJ-07-2020-0346

OLIVEIRA, T., MARTINS, R., SARKER, S., THOMAS, M., & POPOVIČ, A. (2019). Understanding SaaS adoption: The moderating impact of the environment context. International Journal of Information Management, 49(June 2018), 1–12. https://doi.org/10.1016/j.ijinfomgt.2019.02.009

PEREIRA, R. M., SZEJKA, A. L., & CANCIGLIERI, O. (2020). A Discussion on Current Issues for Semantic Interoperability in an Integrated Manufacturing System. 514–523. https://doi.org/10.3233/ATDE200112

PÉREZ-LARA, M., SAUCEDO-MARTÍNEZ, J. A., MARMOLEJO-SAUCEDO, J. A., SALAIS-FIERRO, T. E., & VASANT, P. (2018). Vertical and horizontal integration systems in Industry 4.0. Wireless Networks, 2. https://doi.org/10.1007/s11276-018-1873-2

PERUZZINI, M., & STJEPANDIĆ, J. (2017a). Editorial to the special issue “Enterprise modelling and system integration for smart manufacturing.” Journal of Industrial Information Integration, 7, 1–3. https://doi.org/10.1016/j.jii.2017.05.001

PERUZZINI, M., & STJEPANDIĆ, J. (2017b). Editorial to the Special Issue Information Integration for Innovative Design and Smart Manufacturing. Journal of Industrial Integration and Management, 02(04), 1702003. https://doi.org/10.1142/s2424862217020031

PERUZZINI, M., GREGORI, F., LUZI, A., MENGARELLI, M., & GERMANI, M. (2017). A social life cycle assessment methodology for smart manufacturing: The case of study of a kitchen sink. Journal of Industrial Information Integration, 7, 24–32. https://doi.org/10.1016/j.jii.2017.04.001

QIAN, Y., FANG, Y., & GONZALEZ, J. J. (2012). Managing information security risks during new technology adoption. Computers and Security, 31(8), 859–869. https://doi.org/10.1016/j.cose.2012.09.001

ROGERS, E. M. (2003). Diffusion of innovations. In New York, NY: Free Press. ((5th ed.).). https://doi.org/10.4324/9780203710753-35

ROGERS, E. M., SINGHAL, A., & QUINLAN, M. M. (2019). Diffusion of innovations. In An Integrated Approach to Communication Theory and Research, Third Edition ((5th ed.)., pp. 415–433). https://doi.org/10.4324/9780203710753-35

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

ROSSIT, D. A., TOHMÉ, F., & FRUTOS, M. (2019). A data-driven scheduling approach to smart manufacturing. Journal of Industrial Information Integration, 15(December 2018), 69–79. https://doi.org/10.1016/j.jii.2019.04.003

SAGHIRI, S., & WILDING, R. (2021). On the effectiveness of supplier development programs: The role of supply-side moderators. Technovation, 103(January), 102234. https://doi.org/10.1016/j.technovation.2021.102234

SALAM, M. A. (2019). Analyzing manufacturing strategies and Industry 4.0 supplier performance relationships from a resource-based perspective. Benchmarking, 28(5), 1697–1716. https://doi.org/10.1108/BIJ-12-2018-0428

SCHLECHTENDAHL, J., KEINERT, M., KRETSCHMER, F., LECHLER, A., & VERL, A. (2014). Making existing production systems Industry 4.0-ready: Holistic approach to the integration of existing production systems in Industry 4.0 environments. Production Engineering, 9(1), 143–148. https://doi.org/10.1007/s11740-014-0586-3

SCHUH, G., ANDERL, R., DUMITRESCU, R., KRÜGER, A., & HOMPEL, M. (2020a). Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies – UPDATE 2020 – (acatech STUDY).

SCHUH, G., ANDERL, R., DUMITRESCU, R., KRÜGER, A., & HOMPEL, M. (2020b). Using the Industrie 4.0 Maturity Index in Industry.

SENYO, P. K., EFFAH, J., & ADDAE, E. (2016). Preliminary insight into cloud computing adoption in a developing country. Journal of Enterprise Information Management, 29(4), 505–524. https://doi.org/10.1108/JEIM-09-2014-0094

SNYDER, S., MEEK, D., LEHTONEN, T., & KIRADJIEV, P. (2020). Smart manufacturing. Ai technologies, intelligent insights. Expert Insights.

SONY, M., & NAIK, S. (2020). Critical factors for the successful implementation of Industry 4.0: a review and future research direction. Production Planning & Control, 31(10), 799-815. https://doi.org/10.1080/09537287.2019.1691278

TAMAS, L., MURAR, M., & TAMAS, L. (2019). Smart CPS : vertical integration overview and user story with a cobot Smart CPS : vertical integration overview and user story with a cobot. International Journal of Computer Integrated Manufacturing, 32(4–5), 504–521. https://doi.org/10.1080/0951192X.2018.1535196

THONG, J. Y. L. (1999). An integrated model of information systems adoption in small businesses. Journal of Management Information Systems, 15(4), 187–214. https://doi.org/10.1080/07421222.1999.11518227

TORNATZKY, L.G., & FLEISCHER, M. (1990). The Process of Technological Innovation. Lexington Books.

UYSAL, M. P., & MERGEN, A. E. (2021). Smart manufacturing in intelligent digital mesh: Integration of enterprise architecture and software product line engineering. Journal of Industrial Information Integration, 22(February), 100202. https://doi.org/10.1016/j.jii.2021.100202

VOSS, C., TSIKRIKTSIS, N., & FROHLICH, M. (2002). Case research in operations management. In International Journal of Operations and Production Management (Vol. 22, Issue 2). https://doi.org/10.1108/01443570210414329

WANG, S., WAN, J., LI, D., & ZHANG, C. (2016). Implementing Smart Factory of Industrie 4.0: An Outlook. International Journal of Distributed Sensor Networks, 2016. https://doi.org/10.1155/2016/3159805

WEI, J., LOWRY, P. B., & SEEDORF, S. (2015). The assimilation of RFID technology by Chinese companies: A technology diffusion perspective. Information and Management, 52(6), 628–642. https://doi.org/10.1016/j.im.2015.05.001

XU, L. DA, 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

YEO, B., & GRANT, D. (2018). Predicting service industry performance using decision tree analysis. International Journal of Information Management, 38(1), 288–300. https://doi.org/10.1016/j.ijinfomgt.2017.10.002

Appendix A

Presentation: Thank you for accepting to be a part of our research on the adoption of information systems for vertical integration. We intend to understand the process of adoption these systems, from the emergence of their need to the decision to adopt them. We would like to point out that there are no right or wrong answers, and all the information provided is completely confidential and anonymous. Company data will be hidden under codenames.

i. Introduction

a. Ask about the company's Industry 4.0 view

b. Ask about the interviewee activities in the company

ii. Level of adoption of Information Systems (IS) for Vertical Integration (VI)

a. Does the company aim to gain visibility from vertical integration systems?

b. Explain your involvement with IS and actions aimed at VI of systems in the company.

c. What are the IS adopted by your company? (e.g., ERP, PLM, MES, PLM, etc.)

d. What challenges does the company face in VI?

iii. Adoption strategies for Information Systems (IS) for Vertical Integration (VI)

a. Which IS have you had experience in adopting?

b. What was your role in this adoption?

c. Considering the IS you've had experience with (e.g., participated in adopting an MES in the company), explain how the demand for this system came about.

d. Explain the selection process for this new IS within the company, considering the diverse range of options on the market.

e. Explain the process to make the final decision to adopt that information system.

iv. Impact of Technology-Organization-Environment structure framework (TOE) factors in the adoption of Information Systems (IS) for Vertical Integration (VI)

a. What technological factors (relative advantage, uncertainty, compatibility, complexity, connectivity, expansion) do you think may impact the adoption of information systems in the context of I4.0 in your company? Why?

b. What organizational factors (company size, top management support, innovation capacity, culture, IT change) do you think might affect the adoption of information systems in the context of I4.0 in your company? Why?

c. What environmental factors (competitive pressure, industry, market scope, partnerships with suppliers) do you think may affect your company's adoption of information systems in the context of I4.0? Why?

3. ARTIGO 2 – REDUCING INFORMATION ASYMMETRY BETWEEN BUYERS AND PROVIDERS OF MANUFACTURING EXECUTION SYSTEMS (MES) TO UNLOCK THE INDUSTRY 4.0 DOORS

Verônica Maurer Tabim [1]

Néstor Fabian Ayala [1]

Giuliano Almeida Marodin 2

Guilherme Brittes Benitez [3]

Alejandro G. Frank [1]

[1] Organizational Engineering Group (*Núcleo de Engenharia Organizacional – NEO*), Department of Industrial Engineering, Universidade Federal do Rio Grande do Sul, Brazil.

[2] Darla Moore School of Business, University of South Carolina (USC), United States.
[3] Industrial and Systems Engineering Graduate Program, Polytechnic School, Pontifical Catholic University of Parana (PUCPR), Brazil.
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Abstract

Manufacturing Execution Systems (MES) have been considered the 'entrance door' to the Industry 4.0 journey. MES 4.0 must work in real-time and be integrated with several other systems, resulting in modular adaptation and customized implementation of this solution. This increased complexity underscores the importance of the relationship between companies and their technology providers, requiring intensive knowledge-sharing (KS) activities between the parties. In particular, information asymmetry between buyers and MES 4.0 providers may be critical for the successful implementation of the system, but little is known about this issue, which has a high impact on the first stage of the Industry 4.0 journey. Our objective is to understand how knowledge sharing affects information asymmetry between buyers and technology providers for MES 4.0 implementation. To achieve this, we first conducted qualitative interviews with 56 key experts from 33 companies, which allowed us to identify MES configurations for Industry 4.0. Then, we conducted a multiple case study with three buyer-provider dyads in pre- and post-contract phases of purchasing MES to analyze KS dynamics. We propose a model that explains the relationship between MES 4.0 complexity and KS intensity and discuss buyer-provider configurations to increase the success of MES 4.0 implementation.

Keywords: Industry 4.0; Vertical integration; Manufacturing Execution System; MES; Information asymmetry; Knowledge Sharing.

1 INTRODUÇÃO

Industry 4.0 has been one of the strongest industrial trends in the past decade (Meindl et al., 2021). The vast range of new applications of digital technologies in industrial activities has provided many opportunities for companies to invest in Industry 4.0 technologies and concepts to increase productivity, quality, flexibility, and other operational performance metrics (Enrique et al., 2022). The Industry 4.0 journey toward a digitally-enabled factory starts with increasing visibility capability on the shop floor (Benitez et al., 2023). This capability allows companies to visualize what is happening in the factories in real time and combine this information with others for better decision-making (Dalenogare et al., 2018).

In practice, Manufacturing Execution System (MES) plays an essential role in visibility capability since it has a direct connection to the operating structure of the shop floor, such as machines, equipment, sensors, and other systems, such as Supervisory control and data acquisition (SCADA) systems and Programmable logic controller (PLCs) (Ismail & Kastner, 2016; Pérez-Lara et al., 2018; Tamas et al., 2019). MES allows data management and recording of the history of production data to be used in decision-making (Tabim et al., 2021). There are also more advanced levels of I4.0 maturity, such as autonomous systems, where machines in the production lines make their own decisions based on real-time data (Acatech, 2020). This capability demands vertically integrated systems that allow the integration of hierarchical data from the shop floor, gathered by the MES, to intermediate and upper management levels, known as the traditional Enterprise Resource Planning (ERP) corporate system (Frank et al., 2019). Thus, MES can become a central platform to connect different technologies in a smart manufacturing environment (Benitez et al., 2023). As such, there is a growing interest in implementing and using MES more efficiently to achieve real-time visibility and vertical integration. Although MES has been around since the 1990s (MESA, 2011) – two decades before the term Industry 4.0 was coined – implementing MES in the Industry 4.0 era (MES 4.0) presents new challenges. This is due to the need for customization to accommodate the characteristics of each production process. Downstream, achieving real-time visibility requires integration with shop floor equipment, which typically consists of a mix of old and new equipment with varying technologies (Tabim et al., 2021). Upstream, I4.0 vertical integration requires connecting with ERP and other systems, but many companies still rely on older legacy systems (Benitez et al., 2023).

Due to the numerous functionalities of the new MES 4.0, effective information and knowledge sharing between technology providers and buyers is essential (Tabim et al., 2021). Information asymmetry can cause a mismatch between the two parties, leading to difficulties in implementation, usability, and system performance (Chattopadhyay & Aundhe, 2021). Technology providers may market MES solutions as Industry 4.0 technologies without fully explaining their capabilities, limitations, and integration complexities with other systems. In contrast, buyers may overestimate the ease of integration and the range of automated solutions provided by the MES. Asymmetric information during the purchasing process can lead to incorrect implementation and poor performance, damaging the trust and reputation of technology providers (Chattopadhyay & Aundhe, 2021). Therefore, successful MES implementation in the context of Industry 4.0 requires a level of knowledge sharing that goes beyond just technology. Due to the system's complexity and multiple functionalities, companies need a certain level of Knowledge Sharing (KS) to prevent information asymmetry during system negotiations and purchases (Carlile, 2004; Tabim et al., 2021). For example, a simple MES 4.0 implementation that only requires production scheduling without real-time upstream and downstream integration would need less KS than a full MES 4.0 integration operating as a platform with all shop floor equipment and ERP systems interconnected (Benitez et al., 2023). Recent literature recognizes MES as the initial and essential step in the Industry 4.0 journey (Tabim et al., 2021) and the central platform or "brain" in the integration of operational technologies for creating smart manufacturing (Benitez et al., 2023). However, little is known about the challenges involved in integrating different levels of solutions through interactions between buyers and providers. Thus, the following research question is proposed: ***How can the KS activities between buyers (manufacturers) and MES technology providers reduce information asymmetry between parties when pursuing different levels of solutions in the Industry 4.0 context?***

Our objective is to propose a framework that determines the type of KS necessary to reduce information asymmetry between buyers and technology providers for MES implementation in an Industry 4.0 context based on the functionalities of the system. To achieve this aim, we first applied the information asymmetry perspective (Akerlof, 1978) and combined it with the KS dynamics (Carlile, 2004) to identify the type of KS and related dynamics that would reduce information asymmetry problems, leading to a successful implementation project. With this theoretical framework in place, we conducted qualitative interviews with 56 key experts from 33 companies to identify MES configurations for Industry 4.0. We then conducted a multiple case study with three buyer-provider dyads in pre- and post-contract phases of purchasing MES to analyze the KS dynamics. Our results indicate that MES 4.0 can have different combinations of functionalities, which depend on the firms' Industry 4.0 maturity and strategic objectives. Accordingly, the innovativeness and complexity of MES vary, demanding different KS dynamics between buyer and provider that can evolve from simple knowledge transfer to knowledge translation and finally to the highest complexity of knowledge transformation. Moreover, these different types of KS dynamics will require different buyer-provider collaboration configurations (Petersen et al., 2003). By illuminating the nuances of buyer-provider relationships for MES implementation, this study makes a valuable contribution to the scarce academic literature on the topic. It also provides practical guidance for practitioners who want to advance on their Industry 4.0 journey.

2 THEORETICAL BACKGROUND

2.1 Manufacturing Execution System (MES) for Industry 4.0

The Manufacturing Execution System (MES) concept was coined in 1990 to unify the information system layers operating on the shop floor, including machinery, equipment, sensors, PLC, and SCADA, with the ERP system of the traditional automation pyramid (Chen & Voigt, 2020). In 1992, the Manufacturing Execution Systems Association (MESA) was created. This association the MESA model, which considered a set of 11 functionalities necessary for an information system to be classified as an MES. These functionalities include resource allocation and status, operations/detail scheduling, dispatching production units, document control, data collection/acquisition, labor management, quality management, process management, maintenance management, product tracking, and genealogy and performance analysis. The MESA initiative aimed to fill the gap in the MES layer with all the potential functionalities that could be implemented for commercial purposes. However, many scholars claim that this definition of MES is too general, making it difficult to understand the main objective of the MES solution and causing confusion in successful implementation within companies. This scenario worsened after the emergence of Industry 4.0, which put the MES in the spotlight due to its key role for vertical integration (Benitez et al., 2021; Tabim et al., 2021).

In the context of Industry 4.0, MES 4.0 utilizes basic technologies such as IoT, Big Data, and Cloud Computing to obtain vertical integration and historical production data in real-time (Jaskó et al., 2020). Therefore, the MESA functionalities should consider data gathering and processing within this new real-time premise. It is expected for the MES 4.0 system to be a protagonist in integrating the Information Technology (IT) and Operations Technology (OT) layers, making its implementation even more complex. However, the definition of concepts, standards, and specifications for integrating Industry 4.0 technologies with MES is still under development, although the Industry 4.0 concept has been around for over a decade. Tabim et al. (2021) showed that adopting MES for vertical integration is a challenging decision that involves critical factors for the success of the implementation. Defining and purchasing an MES in this new scenario requires buyers and technology providers to be aligned with the system's concepts, expectations, and purposes, as it will become a manufacturing platform (Benitez et al., 2023). Therefore, the existence of any information asymmetry between the buyer and the technology provider during the process of MES purchasing and implementation could harm both firms and become a barrier for the advancement of Industry 4.0 maturity of the buyer.

2.2 Asymmetry of information and knowledge sharing activities

Aligning the decisions of different actors, such as buyers and providers, who have independent objectives, is a critical challenge (Shao et al., 2021; Ayala et al., 2019). Industry 4.0 has brought even more difficulties to this context due to the need for integration of multiple technologies. This complexity demands specific technical knowledge from the actors, which can increase the information asymmetry between them (Vosooghidizaji et al., 2020). Information asymmetry is a concept rooted in economics (Akerlof, 1978). In the case of a buyer-provider relationship, it assumes that buyers are at a disadvantage when they cannot distinguish between high- and low-quality products during the purchasing process. This purchasing transaction can be separated into pre-contract and post-contract stages. To ensure the successful implementation of technology in a buyer-provider relationship, the information asymmetry throughout the entire transaction should be minimized (Zavolokina et al., 2021).

Asymmetric information is present in buyer-provider relationships for various reasons, such as the fear of losing competitive advantage, gaining extra benefits or bargaining power, ensuring information system compatibility, and difficulty in expressing ideas (Vosooghidizaji et al., 2020). Information asymmetry is also widely studied in the field of information systems (Fernández-Barcala et al., 2010; Notheisen et al., 2017; Preikschat et al., 2021; Son et al., 2021; Woods & Simpson, 2018; Zavolokina et al., 2021) where product quality assessment is challenging due to the inability to physically examine products (Zavolokina et al., 2021). The complexity of assessing information quality is further amplified in an Industry 4.0 environment that requires heterogeneous integrated technologies. One example of this complexity is the buyer-provider relationship during the purchasing process of a Manufacturing Execution System (MES) compatible with the vertical integration requirements (Büchi et al., 2020; Dalenogare et al., 2018; Tabim et al., 2021). Tabim et al. (2021) identified several factors in the adoption of systems for vertical integration in Industry 4.0 that must be considered for successful implementation in this new technological scenario. They also reported numerous cases of MES implementation failure due to wrong purchasing decisions resulting from information asymmetry.

A common issue in the market is that providers may not fully disclose the challenges and limitations of MES regarding its implementation and effectiveness (Tabim et al., 2021). Therefore, it is crucial to establish a collaborative relationship between technology providers and buyers, where information and knowledge are shared and processed to minimize information asymmetry (Vosooghidizaji et al., 2020). By exploring information asymmetry, it is possible to clarify the implementation of an MES that allows vertical integration in Industry 4.0. Thus, based on the findings of Tabim et al. (2021), it is evident that this is not solely a technological problem, but also an issue of information and knowledge sharing.

To address the challenge of information asymmetry, we propose to use the knowledge-sharing framework introduced by Carlile (2002), which suggests three types of knowledge sharing - transferring, translating, and transforming - to facilitate knowledge exchange between actors and create different dynamics of knowledge sharing (see Figure 1). Previous studies, such as Le Dain and Merminod (2014) and Ayala et al. (2017), have applied this framework to analyze buyer-supplier relationships, and we use their insights to analyze the process of purchasing and implementing an MES system for vertical systems integration in Industry 4.0. In this context, knowledge sharing is viewed as a process of moving knowledge from a source to a recipient, followed by absorption and use, building on previous experience (Ayala et al., 2017; Razak et al., 2016). In our case, the MES providers possess knowledge about the system's functionalities, while the manufacturing companies seek to purchase the MES to align with their Industry 4.0 strategy. Figure 1 illustrates the three levels of knowledge-sharing complexity across the boundaries between the buyer and the provider. As the parties engage in a digital transformation through the implementation of the MES, the complexity of knowledge sharing grows from knowledge transfer to knowledge translation and, finally, to knowledge transformation. Depending on the MES's complexity in terms of functionalities needed for the Industry 4.0 journey, the actors may exhibit different knowledge-sharing dynamics, moving up or down across the levels of cross-knowledge complexity.

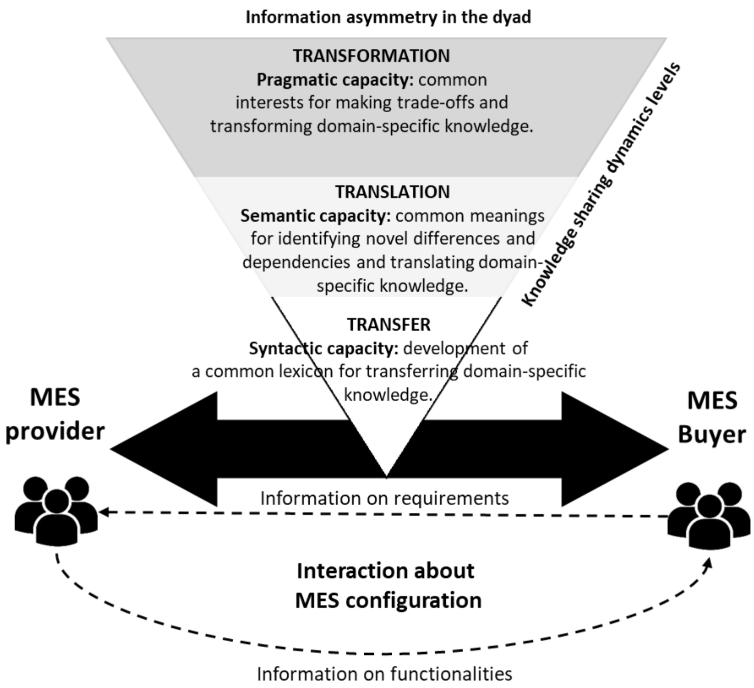

Figure 1. Knowledge sharing dynamics between buyer and provider (Adapted from Ayala et al., 2017)

At the level of knowledge transfer, knowledge is considered to be external, explicit, and storable. The primary concern at this level is the syntactic capability required to develop a common lexicon that can be used to facilitate communication across boundaries. However, as the level of innovation increases, transferring knowledge may no longer be sufficient because the existing lexicon may no longer be adequate to represent differences and dependencies (Carlile, 2004). In practice, knowledge transfer can be identified when there is an exchange of boundary objects between actors. Boundary objects are objects or documents created and used during communication, such as requirements, prototypes, design drawings, information on a website, and emails (Carlile, 2004; Le Dain and Merminod, 2014).

At the level of knowledge translation, as innovation (in our case, digital transformation) and complexity increase, so does the complexity of knowledge sharing. Thus, a transition from a syntactic boundary to a semantic or interpretative boundary becomes necessary, as some differences and dependencies become obscure, and meanings can become ambiguous. At this level, the complexity of knowledge sharing naturally leads to different interpretations, requiring the use of mechanisms to create shared meaning between the buyer and the provider to cross this new frontier. The creation of common meanings can become more than just a translation process; it can be a process of negotiating interests between actors that may result in learning costs for some of them (Carlile, 2004; Le Dain and Merminod, 2014).

In the highest level of innovation and complexity, which is the knowledge transformation level, a pragmatic frontier replaces the semantic frontier. At this stage, divergent interests and realities of the actors need to be resolved. Actors not only need to learn to accept new knowledge, but they also have to transform their domain-specific and common knowledge to effectively share and evaluate knowledge across the border (Carlile, 2004). This level poses the most complex frontier, as the cost of transforming existing knowledge can negatively impact the actor's willingness to make the necessary changes. (Le Dain and Merminod, 2014).

Given the innovative nature of MES implementation in the context of Industry 4.0 and the varying degrees of complexity of MES 4.0 solutions in the market (Tabim et al., 2021b), it is essential to prioritize knowledge management to advance in Industry 4.0 (de Bem Machado et al., 2022; Fakhar Manesh et al., 2021). We propose that different levels of knowledge sharing dynamics may be necessary to avoid information asymmetry between buyers and providers. Several authors have highlighted the importance of such dynamics, including Le Dain and Merminod (2014) for new product development, and Ayala et al. (2017, 2021) for service innovation. To achieve the desired output from an innovative project, buyers and providers must collaborate in different configurations, as proposed by Petersen et al. (2003): White Box, where the buyer drives solution design; Grey Box, where there is joint solution design; and Black Box, where the provider drives solution design. We propose that a combination of these perspectives could shed light on the MES purchasing and implementation processes towards Industry 4.0, as we discuss in the following sections.

3 METHOD

Our research method consisted of three steps. Firstly, we developed a conceptual framework using the perspective of information asymmetry (Akerlof, 1978) and knowledge sharing theory (Carlile, 2004). We used them to elucidate which knowledge sharing dynamic could effectively reduce information asymmetry problems, thereby leading to a successful MES implementation project. Secondly, we conducted interviews with 56 key experts from 33 companies who had experience with purchasing and implementing MES to gain insight into how specific MES functionalities and characteristics could be related to knowledge sharing dynamics. Lastly, we analyzed the problem through three in-depth case studies of MES purchasing and implementation, covering both pre- and post-contract phases and each related to a different level of knowledge sharing dynamics. We employed a multiple case study research approach that utilized qualitative data collection and analysis. We chose this approach to enhance external validity and mitigate potential observer bias (Voss et al., 2002). We followed the guidelines of Voss et al. (2002) for case study research, as described in the following subsections. Additionally, we adopted the methodological procedures of previous works by Benitez et al. (2020) and Son et al. (2021), which analyzed technological and Industry 4.0 environments. Our unit of analysis was the buyer-provider relationship. To capture the two-fold behavior, Galletta (2013) recommends using semi-structured interviews. Therefore, we conducted interviews with both buyers and providers involved in each MES implementation. Our analysis focused on the collaboration configuration between the buyer and provider, using knowledge sharing theory (Carlile, 2004) and the framework proposed by Le Dain and Merminod (2014) for the MES purchasing and implementing processes.

3.1 Interview with experts

To gain a deeper understanding of the phenomenon, we conducted semi-structured interviews with 56 key experts from 33 companies who have experience with purchasing and implementing MES. Our sample included 27 buyers and 9 providers who met our criteria. Table 1 provides a summary of the interviewees' characteristics. Through these interviews, we gained insights into the different MES configurations that exist in Industry 4.0, which allowed us to pre-select dyads to analyze each of these configurations. Based on the interviews, we identified three types of MES configurations in the Industry 4.0 context which have not been previously described in the literature.

Table 1. Summary of the 56 experts interviewed

Industries	%	Company Size	%
Services	30%	Small (less than 99 employees)	15%
Automotive	15%	Medium (between 100 and 500)	39%
Furniture	12%	Large (more than 500 employees)	45%
Beverage	9%		
Automation/Equipment	9%		
Electronic	6%	Job Position	%
Chemical	6%	Director	23%
Transportation	3%	Manager	13%
Houseware	3%	Engineer	43%

Clothes	3%	Analyst/Specialist	21%
Agricultural	3%		

3.2 Multiple case study selection

Based on the insights from the expert interviews, we selected three dyads (three buyers and three providers) using the following criteria: (i) one dyad for each type of MES configuration identified, (ii) a direct relationship between the buyer and provider, without intermediaries, (iii) access to both actors for interviews, and (iv) completion of both pre-contract and post-contract implementation phases. Table 2 provides an overview of each buyer and provider in the dyadic relationships that were studied.

Table 2. Background of the buyers from multiple case study method

Dyad	Case company	Description	Size	Data Sources	Segment
1	AutomotiveCo	Multinational company from road implements	Multinational (+12,000 employees)	Automation Engineer; Operational Director; Digital Manufacturing Engineer.	Automotive
	Digitalization Co	Startup from digitalization	Small (+40 employees)	CEO; COO; MES business analyst	Software and IT
2	FurnitureCo	Company from furniture	Large (+1000 employees)	Operational Director; Head of innovation; Industrial Engineer; Process Engineer.	Furniture
	SoftwareCo	Company from automation and software solutions for manufacturing	Small (+10)	Automation Engineer; System Engineer	Software and IT
3	AgriculturalCo	Multinational company from agricultural equipment	Multinational (+20,000 employees)	IT Manager; Manufacturing Manager; Process Engineer	Machinery and equipment
	SystemsCo	Multinational company from industrial systems	Large (+1200 employees)	Industrial Engineer; Business Analyst	Software and IT

3.3 Data collection procedures

We first employed semi-structured interviews with MES buyers, then providers were interviewed. This was necessary to cross the information and match what happened before and after the MES purchasing. The interviews were conducted from September

2020 to October 2021. To achieve the main goal and properly answer the research questions, we used the knowledge sharing perspective to identify information asymmetry problems. We split our analysis into two stages: (i) the first was related to the period before the buyer signed the contract for MES purchasing, and (ii) the second was after the contract.

For the first stage, we considered aspects of information asymmetry, such as when and what providers had more information than the potential buyers and vice-versa. This analysis helped us better understand how the dyadic relationship led to information asymmetry and misalignment among providers and buyers. Furthermore, these points supported our knowledge about what buyers understand as MES in I4.0, its functionalities, what providers were selling, and which buyer-provider collaboration configuration was expected.

In the second stage of our analysis, we observed the actual collaboration between buyers and providers in supporting the MES implementation project after the technology was purchased. By examining this stage through a knowledge sharing theoretical lens, we were able to identify which pieces of information were missing during the MES negotiation process for buyers and how the dyadic relationship between buyers and providers evolved during the implementation phase. This enabled us to draw connections between the different elements and conclude what is necessary for firms to successfully implement MES technology and achieve their Industry 4.0 goals.

Moreover, we contrasted and complemented statements from buyers and providers to understand both parties during MES purchasing before and after the buyer signed the contract. The purpose was also to review and validate evidence, which is important to avoid misinterpretations or bias in reviewers' analyses (Goffin et al., 2019). We performed at least two interviews per dyad (provider and buyer), which lasted around two each. At least two research assistants took notes of the main comments while the main researchers conducted interviews. The interviews were also recorded and later transcribed.

3.4 Data analysis – validity, reliability, and interpretation

To ensure construct validity, we followed Voss et al.'s (2002) recommendation and utilized data triangulation, using multiple sources of evidence within each part of the dyad. Our research consisted of four stages: (1) Identifying buyers and providers; (2)

Analyzing dyads' information asymmetry and knowledge sharing before signing the contract, focusing on adverse selection; (3) Integrating and validating data using a data triangulation approach; and (4) Analyzing dyads' information asymmetry and knowledge sharing after signing the contract.

During Stage 1, we aimed to understand how MES technology was dealt with in the market and why buyers purchased it in an Industry 4.0 scenario. We organized all data from interviews to capture how buyers and providers behaved during negotiations of MES technology, utilizing adverse selection from information asymmetry to understand how firms dealt with information during MES negotiations. Stage 2 allowed us to conclude how MES was sold and which functionalities for Industry 4.0 were important. In Stage 3, we cross-checked interview data to validate our results, identifying similarities and patterns in the answers. Finally, in Stage 4, we considered the implications of MES purchasing for both sides of the dyadic relationship, analyzing the main results for buyers after purchasing.

To ensure reliability, we utilized independent analyses by all researchers and assistants and discussed differences in codification and interpretation. We also checked for divergences between understandings by crossing data and information between providers and buyers who had a relationship. To validate our insights, we used secondary data such as websites and news and visited all buyers to obtain a deeper understanding of MES implementation.

To ensure external validity, we presented our results in seminars with other researchers and companies with expertise in Industry 4.0 and information systems. These seminars helped us to collect impressions, correct interpretations and discuss the meanings of our findings. Overall, our study employed a rigorous research design and utilized multiple sources of evidence to ensure construct and external validity, and reliability.

4 RESULTS AND DISCUSSIONS

4.1 Types of MES configuration for Industry 4.0

In the context of Industry 4.0, MES plays a critical role in the information technology infrastructure of manufacturing companies. It is imperative that MES addresses the challenges of decentralization, vertical integration, advanced analysis, and cloud computing. The communication paradigm of smart products and features creates new data flows, and integrating these autonomous entities is essential to ensure efficient cooperation between the company and its systems. The Business Director of SoftwareCo2 provided his insights on the role of MES in the Industry 4.0 landscape, stating that "Now MES needs to exchange information in real-time with all hierarchical layers, and no longer act as an independent system forming an information island." According to the interview with ChemicalCo's Automation Engineer, joining the IT and OT teams is essential to support the I4.0 MES initiatives. Vertical integration of MES is crucial for the entire system to operate as expected in the Industry 4.0 context. A study by Jaskó et al., (2020) demonstrated how MES can meet new integration requirements and highlighted the current status of implementation of these requirements in MES solutions.

To address the information asymmetry issue related to MES, we sought to gain a better understanding of the various configurations that MES can offer in the context of Industry 4.0. Through an analysis of 56 interviews with key experts involved in the purchasing and implementation of MES, we identified three types of MES configurations in this context. This approach of categorizing MES into distinct configuration types allowed us to delve deeper into the issue and analyze the knowledge transfer between buyers and providers in the subsequent section. Table 3 presents our findings on the different MES configurations.

Table 3. Types of MES configuration for Industry 4.0

Types of MES configuration for Industry 4.0	**Description**	**Example cases**
Local visibility	When MES delivers only local visibility, such as data collection, production monitoring (e.g., OEE), product tracking, or quality.	"We expected an MES capable of bringing visibility to a specific line, not yet to the entire plant." (MetalmechanicsCo) "We bought an MES that was installed in our production line in a simple way by our provider." (ClothesCo)
One-way integration	When MES delivers general visibility of the factory. The firms must vertically integrate their systems. The one-way flow of information is enough.	"We needed an MES capable of receiving information directly from the ERP system, for example batch and product expiration information to print on the label. " (CosmeticsCo) "We are working to achieve communication between our MES and the ERP, we still have a way to go. " (BeverageCo)
Two-way integration	When MES has a focus on a complete vertical integration to leverage digital twins or	"We aim to have an MES that not only sends information to SAP but also receives it, allowing SAP to issue commands to MES." (TechnologyCo)

	autonomous processes. The information must have a two-way flow.	"We are seeking an MES that has fully integrated IT layer with AT." (PowertoolsCo)

The first configuration of MES delivers only local visibility and being usually employed by firms starting their I4.0 path (Acatech, 2020). Firms at this configuration implement some specific MES modules, such as data collection, production monitoring (e.g., OEE), product tracking, or quality management (Jaskó et al., 2020). The information is then visualized on dashboards to trigger continuous improvement activities such as root cause analysis, control charts, and PDCA cycles (Telukdarie et al., 2018). These functionalities are usually reached by plug-and-play IoT solutions, with a simple installation, in which the data from the sensors is sent to the cloud and visualized in online software provided by the same provider.

The second configuration of MES delivers general visibility of the factory. To reach this level, the firms must vertically integrate their systems through the different layers: IoT sensors, MES, and ERP (Tamas et al., 2019). Nevertheless, a one-way flow of information could be enough to reach the visibility stage, as proposed by the I4.0 maturity index (Acatech, 2020). This means that indicators from the production line can be combined with administrative information to support decision-making, e.g., to reorganize production orders based on the real efficiency of equipment, based on raw material purchasing schedule, or based on sales (Jaskó et al., 2020).

The third configuration of MES has a focus on a complete vertical integration to leverage digital twins or autonomous processes (Cimino et al., 2019). In addition to the integration of systems at the layers of IoT sensors, MES and ERP, the information must have a two-ways flow. This is necessary because the information will be processed in the digital twin, and it must be downloaded in real-time to the equipment to an autonomous adjustment according to the defined variables.

Our interviews also revealed dissatisfaction among some companies with their relationship with their providers, and vice versa, due to a lack of understanding regarding customer needs versus MES functionalities or configurations. Most customers were unaware of the existence of different MES configurations and treated the technology as a single entity, leading to information asymmetry between actors in several cases. To address this issue, we selected three dyads, one for each configuration type identified, to analyze in-depth how information and knowledge exchange occurred between the actors, and how it could be improved to avoid asymmetry and increase the chances of project success. The details of these cases will be presented in the following section.

4.2 Case studies for each MES configuration

Dyad 1 – MES 4.0 for local visibility

In this case, the provider, DigitalizationCo, is a startup specializing in IoT solutions. One of its main products is an MES system that offers some basic functionalities for process visibility. The buyer, AutomationCo, is a multinational manufacturer of trailers and semi-trailers and railcars. AutomationCo frequently invests in various innovative I4.0 technologies and has a functional sector of five people dedicated to bringing new technological solutions to improve productivity. In this case, the buyer-provider configuration was a *black box*, as the solution was developed entirely in a closed manner without the buyer's participation.

In the pre-contract phase, AutomotiveCo approached DigitalizationCo, intending to purchase the MES system to monitor all critical equipment in real-time, covering features such as data acquisition, quality management, process management, and performance analysis. Then, DigitalizationCo offered its on-shelf MES kit, composed of IoT hardware that captures equipment stops and production volume, together with online software that shows the main indicators for production management, such as OEE, equipment downtime, and main causes. The functionalities of the MES kit were shared with AutomotiveCo through a brochure available on DigitalizationCo website. DigitalizationCo's CEO said that AutomotiveCo personnel *"asked for many other indicators not provided by the standard solution. Then I said, 'let's go with the basic indicators and, after, if you really miss these others, we can add it'. I knew that the KPIs included in our solution would be enough for their needs"*. Because of his experience, DigitalizationCo was confident that the visibility demanded by AutomotiveCo was at the beginning of the Industry 4.0 maturity index (Acatech, 2010), the same that many satisfied customers with the characteristics of AutomotiveCo demanded.

In the post-contract phase, AutomotiveCo charged DigitalizationCo for the entire installation of the IoT kit for data collection. As proof of concept (POC), five equipment in the production site were monitored with this solution. Every time equipment stopped, the time was computed automatically, and the operator was demanded to declare in an HMI the cause. The same happened when quality problems were detected. The software calculated the main KPIs using this data and provided them on online dashboards. AutomotiveCo used these dashboards to understand the main productivity problems, investigate root causes and promote continuous improvement programs. After the POC, the solution was implemented on all critical equipment. The statement of the Digital Manufacturing Engineer reflects the satisfaction with the solution: *"we have all the information we need, with a solution very easy to install and use and for a very low price"*.

In the local visibility configuration case study, can be observed that a ‘knowledge transfer’ dynamic can be enough when the objective of the MES is to reach only local visibility. The complexity of this type of solution is very low, and written information is sufficient since the buyer is buying an MES as a fixed package with standard functionalities that are similar to many companies. Thus, there is a low risk of information asymmetry. However, it is important to highlight that DigitalizationCo solution is stand-alone, so no integration was made in this case with AutomotiveCo’s legacy systems, which justifies the simplicity.

Due to its simplicity, the provider sells these solutions with standard configurations, usually through e-commerce. In other words, a black box buyer-provider configuration occurs since the buyer does not need to know how the technology works. He only uses the outputs of the solution. For the buyer, the information provided on the website is enough to understand the scope of the solution, and no information asymmetry is expected. Thus, a 'knowledge transfer' dynamic is usually enough, originating our first proposition:

PROPOSITION 1: When the MES configuration is intended solely for local visibility purposes, a buyer-provider configuration at the black box level that involves knowledge transfer may suffice to prevent information asymmetry.

Dyad 2 – MES 4.0 one-way integration

In this case, SoftwareCo is a technology provider focused on developing software solutions for the furniture industry. It has consolidated solutions in the design, production, and management software market that serve customers in several countries. The buyer, FurnitureCo, is a large company that manufactures highly customized furniture. This company stands out in the high-end furniture segment, serving customers in several countries. FurnitureCo constantly seeks to invest in technologies in its plant to increase production flexibility. In this scenario of high product customization and the consequent search for flexibility in the factory, FurnitureCo's Industrial Director explains that he seeks to implement I4.0 at the factory to gain data visibility in real-time and with wireless communication. *"I want real-time data visibility so I can know exactly what's happening in the factory at any given time"*. Thus, a one-way vertical integration through MES implementation may be enough to give the firm the aimed stage of Industry 4.0 maturity, i.e., visibility (Acatech, 2020). The buyer-provider configuration employed in this case was a *white box*, evidenced by the fact that solution was developed without the participation of the provider.

According to FurnitureCo's Industrial Engineer, the MES system was purchased from SoftwareCo because they were already a partner providing software for furniture design. Analyzing the pre-contract phase, it was possible to observe a clear knowledge sharing failure that led to an information asymmetry from the beginning of the buyer-provider relationship. FurnitureCo expressed his desire for an MES implementation, and SoftwareCo shared only a website link with his MES software for furniture companies, promising that this MES would give the needed plant visibility. During the negotiation, SoftwareCo's MES functionalities were explained only generically and superficially. However, influenced by the trust of the existing dyad relationship and due to a shallow knowledge of MES, FurnitureCo decided to purchase the software.

In the post-contract phase, FurnitureCo demanded SoftwareCo with the entire plant's visibility based on the vertical systems integration principle, as defined by I4.0. However, according to FurnitureCo's Head of innovation, the scope of the software was unclear: *"Everyone thinks the SoftwareCo system will solve all plant problems with real-time data visibility, but no one understands how it's going to happen"*. SoftwareCo needed help understanding FurnitureCo needs to define how (and if) his software could reach it. After months of misunderstandings between the actors, FurnitureCo hired a management consultancy company to define his needs clearly and to verify if SoftwareCo system would meet them. This consultancy defined the architecture of the MES system, i.e., which functionalities it would have, from which equipment it would take data, to which legacy systems it would be connected and how. Only after the architecture was wrote down, SoftwareCo realized that the complexity of FurnitureCo's needs was greater than what its system could offer. The SoftwareCo system only worked as a viewer of production data, that is, SoftwareCo did not have the expertise or the system to extract data directly from production equipment. Finally, after one year, FurnitureCo decided to cancel the contract and look in the market for an MES with the functionalities needed.

Reflecting on the one-way configuration case study, it can be observed that the MES was sold and bought only through a 'knowledge transfer' interaction between the actors, with both actors interpreting on their own what an MES must do. Because of this, many problems arose, and the MES implementation was unsuccessful. Due to the complexity demanded by the MES for vertical integration in the Industry 4.0 context, the correct interaction would be 'knowledge translation', as expressed by the system engineer of SoftwareCo: *"we only understood what FurnitureCo needed after we sat at the table with them in the meeting mediated by the consultancy company"*. The MES functionalities were discussed in this meeting, and the MES architecture was written down. Only then both actors reached common knowledge.

PROPOSITION 2: When the objective of the MES configuration is one-way integration, a buyer-provider configuration at the white box level, involving knowledge translation, can be sufficient to prevent information asymmetry.

Dyad 3 – MES two-ways integration

In this case, the provider, SystemCo, is a software company founded in 2005 that provides solutions for big companies. According to SystemCo's Industrial Engineer, the company positioned itself early in the concept of Industry 4.0. *"We started with Industry 4.0, big data, and other concepts before these terms even existed, and we've become well known today"*. The buyer, AgriculturalCo, is a multinational manufacturer focused on developing, manufacturing, and distributing agricultural equipment to 140 countries and is headquartered in the US. Our case study at AgriculturalCo was carried out in a factory located in South America, which was relatively well advanced on its Industry 4.0 journey. The firm then realized that implementing an MES for vertical integration of systems based on real-time data must be essential to continue with this journey towards the last level of the Industry 4.0 maturity index, i.e., autonomous factory (Acatech, 2020). The buyer-provider configuration employed in this case was a *grey box*, evidenced by the fact that solution was developed with joint participation of the buyer and provider.

In the pre-contract phase, there was the MES negotiation process in which AgriculturalCo aimed to buy the MES from SystemCo to improve the production flow, find faults, record OEE and manage material movements and systems integration considering what was happening in real-time on the shop floor. The information provided by SystemCo about the MES solution was in line with Industry 4.0 concepts that promise to connect the factory floor to the company's management systems, as expected by

AgriculturalCo. During the negotiation, there was a discussion between the actors to have a common understanding of the MES architecture. On the one hand, SystemCo demonstrated expertise in machine and system integration, communication development, and IoT-related technologies. With that, on the other hand, AgriculturalCo understood that SystemCo would be able to meet its MES needs with systems integration, enabling the start of its 4.0 journey.

In the post-contract phase, AgriculturalCo charged SystemCo with developing the MES system following MES functionalities and Industry 4.0 concepts. Despite SystemCo's MES having a competitive solution in the market with constant software updates aimed at Industry 4.0, AgriculturalCo could not use the system as promised during the pre-contract phase. According to the AgriculturalCo's IT manager interviewed: *"apparently, SystemCo has a fantastic solution, but we could only use 10% of it. We only used a production display, which shows forecasted against real production and losses over time".* According to AgriculturalCo's IT manager, one of the main reasons for the failure was the lack of maturity and adequate infrastructure to support the system. As complemented by the Business Analyst of SystemCo: *"we only realized the complexity of the operation and legacy systems after starting the project. [...] The full integration of systems is a very challenging task".*

After realizing that integrating all systems through the MES was not a task that could be just delegated, both firms started to work together on the project. People from IT, OT, and process engineering from AgriculturalCo were involved in developing together with SystemCo the architecture of MES. However, more than just the architecture, they needed to create a roadmap of steps to reach the desired full vertical integration for autonomous factory feasibility. These steps included improving connectivity infrastructure to support all equipment, communicating with different equipment protocols, and integrating all legacy systems employed to gather and analyze data from equipment, among other critical aspects. As stated by AgriculturalCo's IT Manager: *"things only become clear and begun to advance after we started to work together".*

Therefore, in the two-ways configuration case, it can be seen that the MES was only sold through a 'knowledge translation' dynamic, where the provider thought his MES could do what the customer expected. This was true, but then they realized that in the context of I4.0, the MES software was only one part of the vertical integration journey. Therefore, it was observed that to achieve the MES system demanded by AgriculturalCo, the actors needed to be involved in a 'knowledge transformation' dynamic since, due to the complexity of the solution, neither the buyer nor the providers would be able to develop the complete MES architecture alone.

PROPOSITION 3: "When the MES configuration aims to achieve two-way integration, it is necessary to establish a buyer-provider configuration at the gray box level, which involves knowledge transformation, to prevent information asymmetry."

4.3 Summary of the case study propositions and resulting framework

Based on the aforementioned results from our multiple case study observations and propositions, it is possible to extract many relevant insights. First, different buyer-provider relationships are demanded to develop MES configurations that fit buyers' needs in an Industry 4.0 context. However, both actors must know that different knowledge sharing dynamics must be employed to diminish information asymmetry. Figure 2 summarizes these findings in a framework. From the perspective of I4.0, this figure presents MES complexity growing bottom-up and the knowledge sharing dynamics. In parallel, from a perspective of a buyer-provider collaboration (Le Dain & Merminod, 2014), the increasing complexity of MES and KS demands an evolution from a black box to a white box and, then, to a grey box configuration. Following, we present the discussions for each level of this framework.

From a buyer-provider relationship perspective, reaching this level of MES is challenging due to the complexity of the integration of legacy systems (Calderón Godoy et al., 2018). As observed in the case studies, a knowledge transfer dynamic between the actors is not enough. To avoid information asymmetry, the buyer and provider must be involved in a ‘knowledge translation’ dynamic using the MES architecture as a boundary object (Carlile, 2002). On the one side, the buyer must involve its IT team to present the systems and hardware and its manufacturing team to establish the modules of MES that would be needed to reach the desired visibility. On the other side, the provider must present the functionalities of its MES and integration restrictions. As highlighted by (Ayala et al., 2017b; le Dain & Merminod, 2014), this complexity can hardly be transcribed and demands at least a White box buyer-provider configuration. In this collaboration configuration, the buyer needs to clearly understand his needs and how the solution will work to give it only then to be developed by the provider.

As observed in the case studies, this highest maturity level of industry 4.0 (Acatech, 2020) demands a high complexity of MES configuration that can only be tackled by a joint development between buyer and provider, i.e., a Grey box buyer-provider collaboration. During this collaboration occurs a 'knowledge transformation' since neither the buyer nor the provider knows the final MES architecture, but they develop it together based on the IT and OT demands. At this level, the complexity demands a tailor-made MES or a high customization in order to integrate it to the many software legacy of the buyer and to the different protocols of the equipment on the shopfloor.

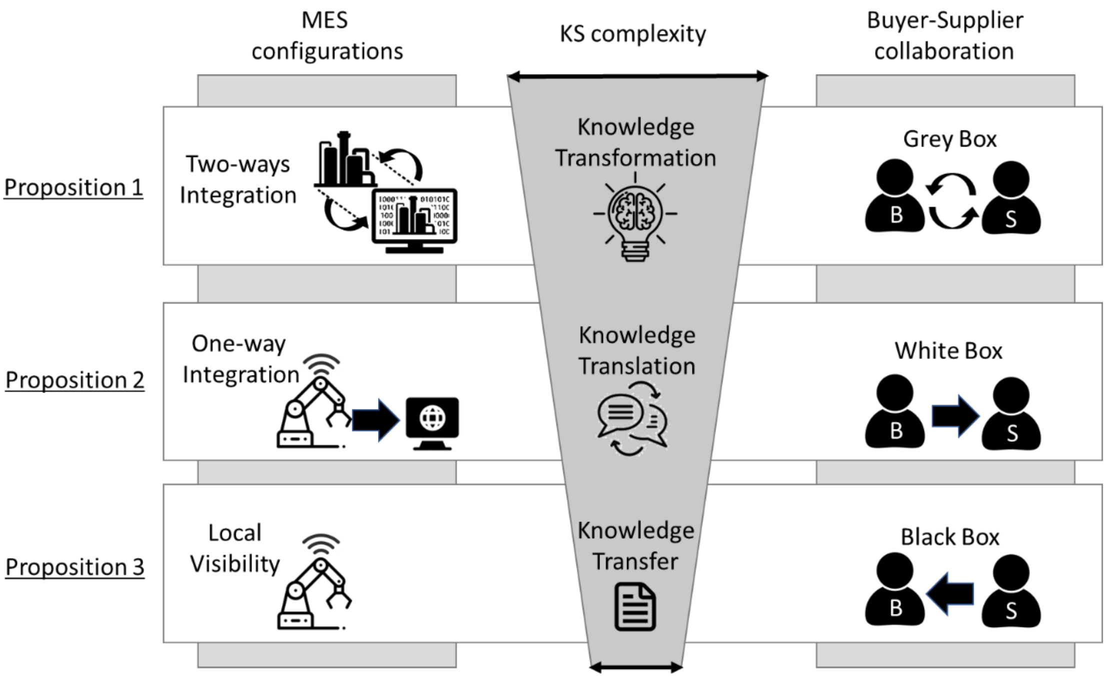

Figure 2. Framework for MES functionalities, KS dynamics and Buyer-Provider collaboration

5 CONCLUSIONS

5.1 Theoretical contributions

Many contributions of this study to academics. First, the information systems literature has widely discussed technical and organizational factors for adopting MES. However, this is the first attempt to provide a broad qualitative understanding of MES implementation in the context of Industry 4.0, i.e., an MES that considers the integration of different technologies, such as automation technologies, sensors, SCADA, and ERP to implement vertical integration and real-time data stream based on IoT. The novelty of this perspective is that we consider an interrelated and complex system of different information technologies that requires a broader set of requirements than in studying the adoption of a single information system. Additionally, this study demonstrates that technological complexity can cause MES buyers and sellers to understand the system characteristics differently. Thus, using the information asymmetry lens (Akerlof, 1978), we demonstrate that a successful purchasing and implementation of MES for I4.0 starts from the pre-contracting stage, a stage usually sub-estimated or not considered by academics and practitioners.

Third, although previous studies have considered MES implementation challenges in Industry 4.0 from a static transactional perspective (e.g., Antonio et al., 2017; Chen & Voigt, 2020; Costa Dias et al., 2021; Jaskó et al., 2020; Kletti, 2015; Tamas et al., 2019), this is the first study that investigates the dynamic aspects of implementation that information systems managers need to consider. Also, information management scholars may find this analysis of tensions along the purchasing and implementation MES processes as an opportunity for future research approaches to create more theory about the socio-technical aspects of adopting Industry 4.0 technologies. Finally, by using the knowledge sharing (Carlile, 2004) and buyer-provider configuration (Petersen et al., 2003) perspectives, we show that different levels of complexity of MES demand different types of knowledge sharing dynamics to overcome the boundaries between the actors and different types of buyer-provider collaboration. This combination of theories culminated in a conceptual framework that scholars can adapt to other types of analysis of adopting complex information systems.

5.2 Managerial contributions

In previous research, Tabim et al. (2021) observed that the same provider of MES was found to be a good provider for one buyer and a bad provider for another. This happened because the buyer's needs were different, but the provider offered the same software configuration and service. Thus, while MES are sold in the market as a unique product, actually, it has different configurations of functionalities. Consequently, our study can guide buyers and providers in deciding on MES implementation as an entrance door for Industry 4.0.

First, small firms with few human and financial resources to invest in I4.0 technologies can find off-the-shelf solutions with only some MES functionalities and plug-and-play hardware in the market. These solutions will offer only equipment visibility, but it would be enough for productivity improvement and could have affordable prices (Mittal et al., 2018). Second, more mature firms that want to reach a vertical integration need to internally develop knowledge on how the MES works and how its functionalities and systems will be integrated. Thus, they will need a specialized internal IT team that will outsource and supervise the MES development in the hands of the provider. This may be a big barrier for manufacturing firms to reach an advanced level of I4.0 (Chen & Voigt, 2020). Usually, these firms have a strong automation team but not a well-developed IT team (Marcucci et al., 2022), and it is pointed as one of the main causes of firms failing on their I4.0 journey (Tabim et al., 2021a).

Third, firms that are already advanced on their I4.0 journey and want to reach the advanced level of I4.0 with 'live' digital twins (Costello et al., 2019) or autonomous processes (Frank et al., 2019) need to go deeper into their MES and vertical integration implementation (Tabim et al., 2021). However, due to the complexity and innovative characteristic of this MES for I4.0, firms cannot buy it off the shelf or internally develop its architecture to be outsourced. In this case, the success of the project will be associated, on the one hand, with finding a provider open to developing a customized MES solution to reach the specificities to integrate buyer's systems completely. Nevertheless, on the other hand, the buyer needs to have well-prepared IT and OT teams that understand the firm's current systems and what is necessary to reach the desired digital twins and autonomous processes.

Concluding, our study collaborates with practitioners to be successful on their Industry 4.0 journey. Many manufacturing firms fail on their MES implementation projects because they are not prepared in terms of internal capabilities or because they do not know clearly what to expect from this implementation (Queiroz et al., 2019). Also, many MES providers have failed in their relationship with buyers, unable to reach their expectations, not because of a lack of capacity but due to an information asymmetry. Thus, we provide support and shed light on the different types of MES implementations and the knowledge sharing dynamics necessary to reach a fruitful buyer-provider relationship.

5.3 Limitations and future research

As common in academic research, although rigorous methodological procedures were followed, this study has limitations. First, we studied only three case studies that were enough to observe different levels of MES complexity and knowledge sharing dynamics. However, future research can expand this study, analyzing more case studies and other technologies than MES. Second, as highlighted, researchers can apply the framework for MES functionalities, KS dynamics, and Buyer-Provider collaboration, proposed in Figure 2, to other technologies. If its generalizability is proved, this framework may guide IT and OT managers on the purchasing and implementation processes of the many I4.0 technologies. Finally, because of the integration of systems demanded by the I4.0, the many functionalities of MES are blurring with those from other systems, such as ERP or PLM. This also can create misunderstandings between buyers and providers. Thus, future research can analyze more deeply the roles of each system in this new I4.0 era.

6 REFERENCES

AKERLOF, G. A. (1978). The Market for “Lemons”: quality uncertainty and the market mechanism. In Uncertainty in Economics (Vol. 84). ACADEMIC PRESS, INC. https://doi.org/10.1016/b978-0-12-214850-7.50022-x

ANTONIO, G. D., MACHEDA, L., BEDOLLA, J. S., & CHIABERT, P. (2017). PLM-MES Integration to Support Industry 4 . 0. 1, 129–137. https://doi.org/10.1007/978-3-319-72905-3

AYALA, N. F., GAIARDELLI, P., PEZZOTTA, G., LE DAIN, M. A., & FRANK, A. G. (2021). Adopting service suppliers for servitisation: which type of supplier involvement is more effective? Journal of Manufacturing Technology Management, ahead-of-p(ahead-of-print). https://doi.org/10.1108/JMTM-09-2020-0374

AYALA, N. F., GERSTLBERGER, W., & FRANK, A. G. (2019). Managing servitization in product companies: the moderating role of service suppliers. International Journal of Operations & Production Management, 39(1), 43–74. https://doi.org/10.1108/IJOPM-08-2017-0484

AYALA, N. F., PASLAUSKI, C. A., GHEZZI, A., & FRANK, A. G. (2017a). Knowledge sharing dynamics in service suppliers’ involvement for servitization of manufacturing companies. International Journal of Production Economics, 193(August), 538–553. https://doi.org/10.1016/j.ijpe.2017.08.019

AYALA, N. F., PASLAUSKI, C. A., GHEZZI, A., & FRANK, A. G. (2017b). Knowledge sharing dynamics in service suppliers’ involvement for servitization of manufacturing companies. International Journal of Production Economics, 193(November), 538–553. https://doi.org/10.1016/j.ijpe.2017.08.019

BENITEZ, G. B., AYALA, N. F., & FRANK, A. G. (2020). Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation. International Journal of Production Economics, 228(July 2019). https://doi.org/10.1016/j.ijpe.2020.107735

BENITEZ, G. B., FERREIRA-LIMA, M., AYALA, N. F., & FRANK, A. G. (2021). Industry 4.0 technology provision: the moderating role of supply chain partners to support technology providers. Supply Chain Management, November 2020. https://doi.org/10.1108/SCM-07-2020-0304

BÜCHI, G., CUGNO, M., & CASTAGNOLI, R. (2020). Smart factory performance and Industry 4.0. Technological Forecasting and Social Change, 150(June 2019), 119790. https://doi.org/10.1016/j.techfore.2019.119790

CALDERÓN GODOY, A. J., & GONZÁLEZ PÉREZ, I. (2018). Integration of sensor and actuator networks and the scada system to promote the migration of the legacy flexible manufacturing system towards the industry 4.0 concept. Journal of Sensor and Actuator Networks, 7(2), 23. https://doi.org/10.3390/jsan7020023

CARLILE, P. R. (2002). View of Knowledge and Boundaries : Boundary Objects in New Product Development. Organization Science, 13(4), 442–455. https://doi.org/10.1287/orsc.13.4.442.2953

CARLILE, P. R. (2004). Transferring, Translating, and Transforming: An Integrative Framework for Managing Knowledge Across Boundaries. Organization Science, 15(5), 555–568. https://doi.org/10.1287/orsc.1040.0094

CHATTOPADHYAY, S. P., & AUNDHE, M. DAS. (2021). Vendor boundary spanning in Indian Information Technology (IT) companies. Asia Pacific Journal of Management, 38(3), 1139–1177. https://doi.org/10.1007/s10490-019-09696-8

CHEN, X., & VOIGT, T. (2020). Implementation of the Manufacturing Execution System in the food and beverage industry. Journal of Food Engineering, 278(January), 109932. https://doi.org/10.1016/j.jfoodeng.2020.109932

CIMINO, C., NEGRI, E., & FUMAGALLI, L. (2019). Review of digital twin applications in manufacturing. Computers in Industry, 113, 103130. https://doi.org/10.1016/j.compind.2019.103130

COSTELLO, K., & OMALE, G. (2019). Gartner survey reveals digital twins are entering mainstream use. Gartner Inc.) Retrieved April, 30, 2020.

COSTA DIAS, J. E., DE CASTRO FILHO, F. G., DE ANDRADE, A. A., & FACÓ, J. F. B. (2021). The strategic role of mes systems in the context of industry 4.0. Smart Innovation, Systems and Technologies, 198 SIST(June), 52–61. https://doi.org/10.1007/978-3-030-55374-6_6

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, 204(December 2017), 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

DE BEM MACHADO, A., SECINARO, S., CALANDRA, D., & LANZALONGA, F. (2022). Knowledge management and digital transformation for Industry 4.0: a structured literature review. Knowledge Management Research and Practice, 20(2), 320–338. https://doi.org/10.1080/14778238.2021.2015261

FAKHAR MANESH, M., PELLEGRINI, M. M., MARZI, G., & DABIC, M. (2021). Knowledge Management in the Fourth Industrial Revolution: Mapping the Literature and Scoping Future Avenues. IEEE Transactions on Engineering Management, 68(1), 289–300. https://doi.org/10.1109/TEM.2019.2963489

FERNÁNDEZ-BARCALA, M., GONZÁLEZ-DÍAZ, M., & PRIETO-RODRÍGUEZ, J. (2010). Hotel quality appraisal on the Internet: A market for lemons? Tourism Economics, 16(2), 345–360. https://doi.org/10.5367/000000010791305635

GALLETTA, A. (2013). Mastering the semi-structured interview and beyond. New York University Press.

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

ISMAIL, A., & KASTNER, W. (2016). Vertical integration in industrial enterprises and distributed middleware. International Journal of Internet Protocol Technology, 9(2–3), 79–89. https://doi.org/10.1504/IJIPT.2016.079547

JASKÓ, S., SKROP, A., HOLCZINGER, T., CHOVÁN, T., & ABONYI, J. (2020). Development of manufacturing execution systems in accordance with Industry 4.0 requirements: A review of standard- and ontology-based methodologies and tools. Computers in Industry, 123. https://doi.org/10.1016/j.compind.2020.103300

KLETTI, J. (2015). MES – Manufacturing Execution System: Moderne Informationstechnologie unterstützt die Wertschöpfung.

LE DAIN, M. A., & MERMINOD, V. V. (2014). A knowledge sharing framework for black, grey and white box supplier configurations in new product development. Technovation, 34(11), 688–701. https://doi.org/10.1016/j.technovation.2014.09.005

MARCUCCI, G., ANTOMARIONI, S., CIARAPICA, F. E., & BEVILACQUA, M. (2022). The impact of Operations and IT-related Industry 4.0 key technologies on organizational resilience. Production Planning and Control, 33(15), 1417–1431. https://doi.org/10.1080/09537287.2021.1874702

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(November 2020). https://doi.org/10.1016/j.techfore.2021.120784

MESA INTERNATIONAL. (2011). MESA White Paper# 39: MESA Model Evolution.

MITTAL, S., KHAN, M. A., ROMERO, D., & WUEST, T. (2018). A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). Journal of Manufacturing Systems, 49(June), 194–214. https://doi.org/10.1016/j.jmsy.2018.10.005

NOTHEISEN, B., CHOLEWA, J. B., & SHANMUGAM, A. P. (2017). Trading Real-World Assets on Blockchain: An Application of Trust-Free Transaction Systems in the Market for Lemons. Business and Information Systems Engineering, 59(6), 425–440. https://doi.org/10.1007/s12599-017-0499-8

PÉREZ-LARA, M., SAUCEDO-MARTÍNEZ, J. A., MARMOLEJO-SAUCEDO, J. A., SALAIS-FIERRO, T. E., & VASANT, P. (2018). Vertical and horizontal integration systems in Industry 4.0. Wireless Networks, 2. https://doi.org/10.1007/s11276-018-1873-2

PETERSEN, K., HANDFIELD, R., & RAGATZ, G. (2003). A Model of Supplier Integration into New Product Development. Journal of Product Innovation Management, 20(4), 284–299. https://doi.org/10.1111/1540-5885.00028

PREIKSCHAT, K., BÖHMECKE-SCHWAFERT, M., BUCHWALD, J. P., & STICKEL, C. (2021). Trusted systems of records based on Blockchain technology - a prototype for mileage storing in the automotive industry. Concurrency and Computation: Practice and Experience, 33(1). https://doi.org/10.1002/cpe.5630

QUEIROZ, M. M., PEREIRA, S. C. F., TELLES, R., & MACHADO, M. C. (2019). Industry 4.0 and digital supply chain capabilities: A framework for understanding digitalisation challenges and opportunities. Benchmarking: an international journal. https://doi.org/10.1108/BIJ-12-2018-0435

SHAO, XUE-FENG, et al. "Multistage implementation framework for smart supply chain management under industry 4.0." Technological Forecasting and Social Change 162 (2021). https://doi.org/10.1016/j.techfore.2020.120354

SILVA, G., GASPAR, R., FACÓ, J. F. B., & DE ANDRADE, A. A. (2021). The positive impacts of using the service design approach for expanding the innovative potential on business. In Smart Innovation, Systems and Technologies: Vol. 198 SIST. https://doi.org/10.1007/978-3-030-55374-6_13

SON, B. G., KIM, H., HUR, D., & SUBRAMANIAN, N. (2021). The dark side of supply chain digitalisation: supplier-perceived digital capability asymmetry, buyer opportunism and governance. International Journal of Operations and Production Management, 41(7), 1220–1247. https://doi.org/10.1108/IJOPM-10-2020-0711

STAKE, R. E. (2013). Multiple case study analysis. Guilford press.

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? Information Systems Frontiers, 0123456789. https://doi.org/10.1007/s10796-021-10220-x

TAMAS, L., MURAR, M., & TAMAS, L. (2019). Smart CPS : vertical integration overview and user story with a cobot Smart CPS : vertical integration overview and user story with a cobot. International Journal of Computer Integrated Manufacturing, 32(4–5), 504–521. https://doi.org/10.1080/0951192X.2018.1535196

TELUKDARIE, A., & SISHI, M. N. (2018). Enterprise definition for Industry 4.0. In 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) (pp. 849-853). IEEE.

VOSOOGHIDIZAJI, M., TAGHIPOUR, A., & CANEL-DEPITRE, B. (2020). Supply chain coordination under information asymmetry: a review. International Journal of Production Research, 58(6), 1805–1834. https://doi.org/10.1080/00207543.2019.1685702

VOSS, C., TSIKRIKTSIS, N., & FROHLICH, M. (2002). Case research in operations management. In International Journal of Operations and Production Management (Vol. 22, Issue 2). https://doi.org/10.1108/01443570210414329

WOODS, D. W., & SIMPSON, A. C. (2018). Cyber-warranties as a quality signal for information security products. In International Conference on Decision and Game Theory for Security. Springer, Cham.

ZAVOLOKINA, L., SCHLEGEL, M., & SCHWABE, G. (2021). How can we reduce information asymmetries and enhance trust in 'The Market for Lemons'? Information Systems and E-Business Management, 19(3), 883–908. https://doi.org/10.1007/s10257-020-00466-4

4. ARTIGO 3 – WHAT IS THE ROLE OF CYBERSECURITY ACTIONS IN IMPLEMENTING VERTICAL INTEGRATION IN SMART MANUFACTURING?

Verônica Maurer Tabim[1]

Néstor Fabián Ayala[1]

Alejandro Germán Frank[1]

[1] Organizational Engineering Group (*Núcleo de Engenharia Organizacional – NEO*), Department of Industrial Engineering, Universidade Federal do Rio Grande do Sul, Brazil.

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Abstract

While vertical integration allows manufacturing systems to become self-aware, self-predictive, self-optimizing, and self-configuring, the integration of operating technologies with information technology makes it vulnerable to cyberattacks. Furthermore, in many cases, companies still have limited knowledge about the vulnerabilities that affect manufacturing systems; thus, they are unprepared to deal with the resulting cyber threats. Thus, cybersecurity is expected to become an integral part of the strategy, design, and operations of companies that adopt the Industry 4.0 paradigm in search of operational performance. However, the implementation of vertical integration is still recent, and there is no evidence regarding the contribution that cybersecurity actions can bring to companies that wish to advance in Industry 4.0. Therefore, this study aims to understand how a high implementation of cybersecurity actions in vertical integration contributes to operational performance in smart manufacturing. The regression results indicate that smart manufacturing plays a partial mediating role in the relationships between vertical integration and firm performance, as well as between cybersecurity actions and firm performance. Additionally, cybersecurity actions positively moderate the association between vertical integration and smart manufacturing. Our findings shed light on cybersecurity actions, defining the activities that encompass this concept and demonstrating their role in vertical integration within smart manufacturing.

Key Words: Keywords: Industry 4.0; Vertical integration; Cybersecurity actions

1 INTRODUCTION

One of the core concepts of Industry 4.0 is Smart Manufacturing, which is concerned with the way production activities are executed with the integration of advanced technologies such as the Internet of Things (IoT), cloud computing, big data, digital twins, augmented reality, 3D printing, artificial intelligence, and next-generation cyber-physical systems (CPS) (Dalenogare et al., 2018; Frank et al., 2019; Kusiak, 2018; Liu & Xie, 2020). This integration allows for the creation of self-aware, self-predictive, self-optimized, and self-configurable manufacturing systems through vertical integration. The integration of these heterogeneous equipment in the industrial cyber environment makes cybersecurity considerations mandatory in the design strategy of companies seeking to embrace the Industry 4.0 paradigm. Despite the improvements brought by Industry 4.0 in manufacturing efficiency, cybersecurity violations would involve negative impacts on business performance (Dawson, 2019).

As proof of the negative impact on businesses, a study conducted by the Engineering Employers' Federation (EEF) (2018) on cybersecurity shows that of the 48% of manufacturers who reported being affected by cyber-attacks, about half of them suffered financial losses or other business losses. Studies by Prinsloo et al. (2019) shed light on some recent cyber security attacks observed in various manufacturing factories worldwide that resulted in financial disasters. The authors also propose countermeasures to address a wide range of cybersecurity risks. A more specific recent survey reviewed 262 articles on all aspects of Industry 4.0 security and its negative impacts on production (Tange et al., 2020).

Despite the literature proving the negative impacts regarding cybersecurity in vertical integration, research shows that only 16% of companies are ready to face cybersecurity challenges (Mullet et al., 2021). Among the reasons cited is the lack of accurate reference standards and the lack of managerial and technical skills to understand and implement them. Several organizations that work on guidelines and standards help companies understand which scheme they should use to reinforce their security and make it compatible. Although the impacts of the lack of cybersecurity in the integration across digital information systems that operate in each organizational hierarchical level - namely vertical integration - are still relatively recent, there is little evidence on the contribution that cybersecurity actions can bring to companies seeking to advance in Industry 4.0. Therefore, more research is needed to identify the role of implementing cybersecurity actions in vertical integration in manufacturing companies seeking an Industry 4.0 manufacturing model. Thus, we address this problem through the following research question: ***What is the role of cybersecurity actions in implementing vertical integration in smart manufacturing?***

To answer this question, we present an quantitative analysis of 132 manufacturing companies in the machinery and equipment sector. We analyze the relationship between vertical integration and smart manufacturing and the moderating role of cybersecurity actions. Our goal is to understand the role of cybersecurity actions in vertical integration in smart manufacturing. Such analysis helps us understand what is necessary for effective implementation of vertical integration in manufacturing companies.

The remaining sections of this article are divided as follows: First, in Section 2, we provide the theoretical foundations of cybersecurity in vertical integration (Section 2.1). We also discuss cybersecurity actions as a way to avoid negative performance impacts (Section 2.2). In Section 3, we present the hypotheses of our study. Section 4 presents the research method. Section 5 presents our results, which are discussed in Section 6. Finally, we present our conclusions in Section 7.

2 THEORETICAL BACKGROUND

2.1 Cybersecurity actions in Vertical integration

The concept of Industry 4.0 is much broader than just the use of digital technologies (DALENOGARE et al., 2018). Frank et al. (2019) argue that Industry 4.0 considers the integration of various different dimensions of the business, such as smart products/services, smart supply chain, smart energy and smart working, with a primary focus on production issues, based on smart manufacturing (LIAO et al., 2017; LU, 2017; DALENOGARE et al., 2018). For Industry 4.0 to be possible within smart manufacturing, the availability of vertically integrated systems with heterogeneous data management is central to the expected efficiency gains (TABIM et al., 2021). Therefore, vertical integration is a principle that allows for the integration of hierarchical data from the factory floor to intermediate and upper management levels. Thus, the traditional Enterprise Resource Planning (ERP) corporate system integrates with the Manufacturing Execution System (MES) manufacturing execution system, which has a direct connection to the entire operational structure of the factory, such as machines, equipment, sensors, PLCs and SCADA (ISMAIL & KASTNER, 2016; PÉREZ-LARA et al., 2018; TAMAS et al., 2019).

In this context, vertical integration has supported manufacturing companies in various ways. It captures real-time data derived from sensors and actuators, processes, production machines, and the product itself, and provides availability, traceability, and intelligence of this data across all layers of the company. It supports advanced analytical tools that can analyze collected data to monitor and predict machine failures, automatically identify non-conformities of products, as well as complement systems such as ERP, with demand forecasting and order fulfillment (FRANK et al., 2019). Vertical integration also allows factory managers to make quick and efficient data analytics to support real-time decision making applied to predictive maintenance and production planning (COHEN et al., 2019).

The literature has focused on various aspects that involve vertical integration, such as definitions, applications, and performance of specific technologies that make up vertical integration (IoT, MES, automation, sensors, etc.), as well as the communication between these technologies. However, it is still a major challenge to design production systems and their entire technological infrastructure in a way that achieves efficient vertical integration (DA COSTA DIAS et al., 2021; MORGAN et al., 2021). Ghobakhloo and Ching (2019) considered that due to the innovative characteristics and complexity of vertical integration concepts, it is a challenge that requires a robust technology adoption model suitable for the Industry 4.0 context. As stated by Schuh et al. (2020), prior to Industry 4.0, Information Technologies (ITs) (e.g., ERP, PLM) and Operational Technologies (OTs) (e.g., MES, SCADA, PLCs) sought to achieve their objectives independently. This previous autonomous approach formed closed systems and different communication protocols, creating complex technical barriers for systems and architectures to achieve a smooth flow of data between systems (PERUZZINI et al., 2017). Additionally, in an environment where working machines are connected to the network and to each other through the use of smart devices, the chance of cyberattacks grows exponentially (CORALLO et al., 2020). Therefore, interest in security within the digital context has increased, although it still needs more clarity.

2.2 Cybersecurity actions in Vertical integration

The implementation of vertical integration and adoption of the Industry 4.0 paradigm present a critical security challenge for companies. The presence of vertically integrated systems in industrial environments can be highly vulnerable to cyber threats, as most of these systems were not originally designed with cybersecurity in mind. In the past, manufacturing systems were isolated and physically controlled to ensure security, but nowadays modern manufacturing machines have intelligent devices such as sensors and actuators and are connected via wireless or wired Ethernet networks to other machines and data processing systems. Although manufacturing components communicate over private industrial networks, these connections do not provide adequate protection against cyber threats, making manufacturing systems highly vulnerable to attacks.

Lezzi et al. (2018) indicate that cyber-attacks on manufacturing systems can have serious negative impacts on businesses, including sabotage of critical infrastructure, denial of service to networks and computers, theft of commercial secrets and intellectual property, violation of safety and pollution regulations, and even endangering workers' safety. As a result, companies face significant economic losses to restore normal working conditions and lose competitive power in the relevant market. In summary, cybersecurity is a critical factor that must be taken into consideration by companies implementing vertical integration and adopting Industry 4.0, in order to minimize risks and protect their businesses.

An alternative to cyberattacks is investing in actions to improve cybersecurity in companies. These cybersecurity actions can include: (i) having a clear cybersecurity strategy; (ii) training employees in cybersecurity; (iii) creating rules and processes for employees (e.g. password generation, use of private storage, backups, network access, etc.); (iv) imposing technical solutions such as software updates, backups, communication encryption, and rules for network access; and (v) having certifications according to Information Security standards (e.g. ISO-27000). However, it is still unclear in the literature what role these actions play in implementing vertical integration in smart manufacturing.

3 HYPOTHESES DEVELOPMENT

In the management literature, vertical integration has been considered as the fundamental principle for the successful implementation of Industry 4.0 in manufacturing (BENITEZ et al., 2023; MEINDL et al., 2021; TABIM et al., 2021) and as an antecedent of Smart Manufacturing (FRANK et al., 2019). We follow this stream of studies, which assumes that we can only obtain visibility and transparency of manufacturing data with vertical integration. Then, from this connected data, we will obtain greater performance in the other technologies that are part of Industry 4.0. We explore vertical integration as a structural condition that affects Smart Manufacturing, as shown in our conceptual model presented in Figure 1 and discussed below.

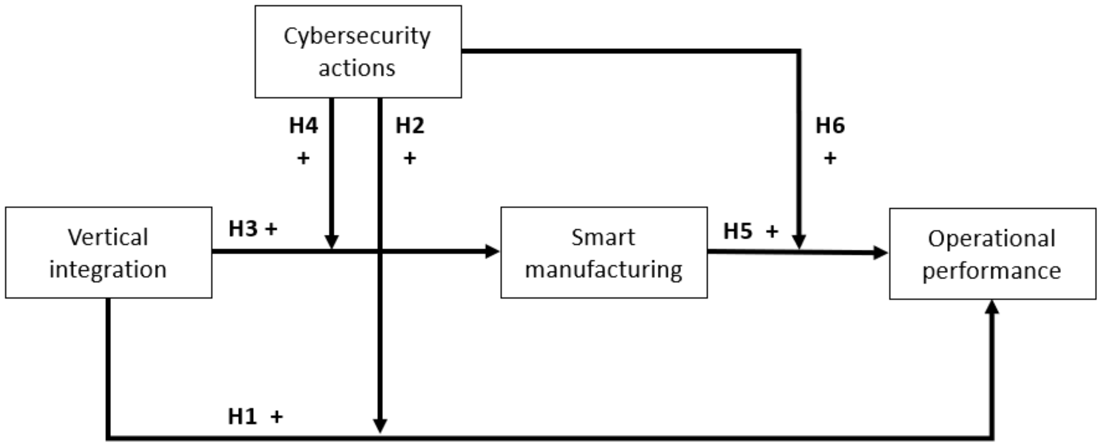

Figure 1. Conceptual research model.

3.1 Vertical integration and its effect on Smart Manufacturing

Vertical integration is defined as the integration of information systems from different hierarchical levels of the company - from the factory floor to middle and senior management levels - to provide real-time data flow and support decision-making (Meindl et al., 2021). Tabim et al. (2020) showed that vertical integration allows intelligent machines to form a self-organized system that can be dynamically reconfigured to adapt to different products. Morgan et al. (2021) states that companies increase their operational performance by collecting and processing large amounts of information, making the production process transparent, increasing production reliability, and factory flexibility. We argue that companies that implement vertical integration can increase operational performance.

The literature recognizes that vertical integration is the first step to achieving Smart Manufacturing, capable of providing real-time data visibility (Schuh et al., 2020). In this sense, we argue that only with successful implementation of vertical integration can Smart Manufacturing provide the expected operational performance. For example, a manufacturing company that has a range of smart manufacturing point technologies, such as collaborative robots, AGVs, and smart glasses, will only be able to achieve the expected performance in relation to these technologies when it obtains vertical integration. Vertical integration provides visibility and context to real-time data that will flow through the systems and, consequently, through all the technologies that the company uses. Without vertical integration, the technologies work in information silos, with completely closed systems. Thus, we argue that vertical integration should be a precursor to Smart Manufacturing.

At the core of the Industry 4.0 concept, Smart Manufacturing technologies function as the central pillar of internal operations activities (Ahuett-Garza and Kurfess, 2018), considering all the technologies involved in the production system. Meindl et al. (2021) show that among the five possible dimensions within Industry 4.0 - Smart Manufacturing, Smart Products, Smart Working, Smart Consumption, and Smart Product-service - the Smart Manufacturing dimension is the first objective of Industry 4.0. Therefore, we assume that Intelligent Manufacturing is the beginning of Industry 4.0. This vision follows the recent chronological evolution of the Industry 4.0 concept, which has its roots primarily in advanced manufacturing systems and their connections to other company processes (Yin et al., 2018, Dalenogare et al., 2018). We argue that the implementation of Smart Manufacturing generates higher operational performance for companies.

Thus, based on the aforementioned discussion, we propose the following three hypotheses:

H1: Vertical integration will enhance the level of operational performance

H3: Vertical integration is the gateway to Industry 4.0, therefore, it must be an antecedent of Smart Manufacturing

H5: Smart Manufacturing generates greater operational performance

3.2 The moderating role of cybersecurity actions

A good cybersecurity system in an organization can facilitate its core competence and enhance its organizational performance (Ravichandran et al., 2005; Smith et al., 2010). According to the findings of the study conducted by Hasan et al. (2021), cybersecurity readiness significantly influences organizational security performance. This result suggests that an organization that increases its cybersecurity readiness will achieve superior security performance by reducing data breaches over time, establishing a legitimate security reputation, enhancing internal process security, and developing a reliable system with appropriate capabilities for information processing. Furthermore, studies by Savas et al. (2017) and Rindasu et al. (2017) reveal that low or absent cybersecurity readiness can pose significant challenges for an organization in acquiring the necessary resources to establish an appropriate level of cybersecurity to protect its digital assets. As a result, the overall performance of the organization may be negatively affected. Smith et al. (2010) and Tsou and Hsu (2015) argue that ensuring cybersecurity can result in better financial returns and a stronger reputation. In addition, adherence to cybersecurity policies and standards in organizations strengthens security controls, system controls, backup recovery, and emergency planning, which in turn have a powerful impact on achieving core competence and superior organizational performance. In general, the literature suggests that companies that invest in cybersecurity actions improve their operational performance.

It is already established in the literature that the implementation of vertical integration increases operational performance in companies. Therefore, when a good cybersecurity system is combined with vertical integration, operational performance is enhanced. Cybersecurity has been observed in the literature as a factor that limits companies' willingness to advance in vertical integration of systems due to concerns about being hacked and suffering impacts on their production activities (Qian et al., 2012; Tabim et al., 2021). It is important to keep in mind that vertical integration represents a large integration of different layers of systems, including SCADA, MES, ERP, and sometimes also APS, PLM, and other applications that are used in various departments of the company (Antonio et al., 2017; Longo et al., 2017). In this sense, any cybersecurity-related problem can become a systemic information problem for the company. Therefore, we argue that vertical integration is enhanced for smart manufacturing when the company implements a good cybersecurity system.

One of the key principles of Industry 4.0 in the domain of Smart Manufacturing is the implementation of vertical integration. Although smart manufacturing comprises several other technologies such as sensors, collaborative robots, artificial intelligence (AI), and simulation, the central goal of smart manufacturing is to obtain transparent, predictive, and adaptive manufacturing systems. That is, it is not enough to adopt technologies in isolation to achieve this goal, it is necessary that the principle of vertical integration integrates data across all hierarchical layers of the factory. Thus, we argue that vertical integration is enhanced for smart manufacturing when the company implements a good cybersecurity system.

Therefore, we propose the following hypotheses:

H2: Vertical integration is enhanced for operational performance when the company implements a good cybersecurity system

H4: Vertical integration is enhanced for smart manufacturing when the company implements a good cybersecurity system

H6: Smart manufacturing is enhanced for operational performance when the company implements a good cybersecurity system

4 RESEARCH METHOD

4.1 Data collection and sample

We conducted a cross-sectional survey in the manufacturing sector, specifically targeting companies associated with the Brazilian Machinery and Equipment Builders' Association (ABIMAQ). We chose ABIMAQ as our sample source due to its active involvement in industrial policies and strategies promoting the Industry 4.0 concept, which indicates a growing interest among its member companies. Additionally, ABIMAQ represents one of the strongest manufacturing sectors in the country. Our sample comprised 240 companies affiliated with ABIMAQ. The survey questionnaire was directed towards either the Chief Executive Officers or Operations Directors of these companies. We followed up twice, with each follow-up sent two weeks after the previous one. In total, we obtained 132 completed questionnaires for the variables examined in this study, resulting in a response rate of 55%. The high response rate can be attributed to the effective administration of the questionnaire. ABIMAQ's office played a vital role by proactively contacting all member companies to inform them about the survey. Furthermore, we presented our research in ABIMAQ's industrial seminars and distributed the questionnaires via institutional email, ensuring a systematic and organized data collection process. Table 1 displays the composition of our sample, including information on company size, respondent profiles, and the primary markets served by the participating companies.

Table 1. Sample characteristics

Company's sector	%	Nationality	%
Manufacture of machinery	23,85%	Brazilian	70,45%
Manufacture of industrial machines	13,08%	International	29,55%
Manufacture of automation machines	9,23%	**Main market**	
Manufacture of machinery, equipment and accessories for agriculture	9,24%	Regional	5,30%
Manufacture of vehicles	2,31%	National	76,52%
Manufacture of electrical and electronic devices	2,31%	International	18,18%
Others	40,00%	**Source of financial resources**	
Size		Bank	12,12%
Micro (<10 employees)	6,06%	Own resources	69,70%
Small (<100 employees)	34,85%	Subsidies	3,79%
Medium (<500 employees)	31,06%		
Large (>500 employees)	28,03%		

4.2 Measures and survey instrument

The questionnaire was developed based on previous constructions in the literature. The items used to measure each construct are shown in Appendix A. The construct 'vertical integration' [VERTICAL INTEGRATION] uses a five-item scale that composes vertical integration in ascending order of implementation, where the company can: (i) have only a PLC for machine operation, (ii) have a PLC with a SCADA system supervising these machines, (iii) have, in addition to the CLP and SCADA, an MES system for running the plant, (iv) have, in addition to the CLP, SCADA and MES working in isolation, an integration of everything with the ERP system, and (v) in addition to all the technologies mentioned above, a virtualization of processes moving towards what would be the evolution of vertical integration, which would be the digital Twin of the plant.

Five items defined the Smart Manufacturing [SMART MANUFACTURING] dimension of Industry 4.0, two of them focused on the virtualization of company processes, the first on equipment operation simulation and the second on digital twins of the plant (digital twins). The other items are focused on the virtualization of the company's tasks: augmented reality for activity checklists, virtual reality for prototype simulations (assembly, product development, etc.) and virtual reality for interaction with production operations. The construct of cybersecurity actions [CYBERSECURITY] is made up of five items that relate to measures that the company implements in relation to avoiding any risk of cybersecurity attacks. For example, clear strategy, employee training, rules and processes for employees, enforcement of software updates, backup, encryption of communication and rules for network access, and certification according to standards.

Regarding the dependent variable, we consider operating performance [PERFORMANCE] as a result of the company. The company's operational performance relates to different perspectives on how Industry 4.0 is helping the company in terms of productivity, flexibility, process safety and innovation in products and services.

Our statistical models also included three control variables. Company size was measured by the number of employees [Company size], and the level of technological acceleration existing in the company [Technological acceleration] was measured if it has a very low, low, moderate, high or very high level of technological acceleration. We also consider the level of change that companies in your industry are currently facing in terms of business model and product transformations [BM change], i.e. whether it has a very low, low, moderate, high or very high level of change in terms of your business model.

Following our conceptual framework represented in Fig. 1, we developed a questionnaire to evaluate Industry 4.0 technologies. The questionnaire assessed the existence or not of a type of technology and the level of implementation of such technology in the manufacturing companies. We used a five-point Likert scale varying from 1 – Very low implemented to 5 - Advanced implemented. Thus, the highest degree shows an advanced maturity of this technology.

4.3 Reliability and validity of measures

To examine unidimensionality, we used confirmatory factor analysis (CFA) with STATA 13.0. Our model showed good fit, since the reference values – i.e., Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA), Average Variance Extracted (AVE), Composite Reliability (CR), and Cronbach's alpha – were all above the threshold values (Hair et al., 2018). These values are shown in Table 2. All the constructs' items showed high factor loading (Appendix A). Also, the final, complete model reported good of fitness (CFI: 0.881; RMSEA: 0.082; $\Delta\chi 2$: 1040.96).

Table 2. Results of confirmatory factor analysis.

Construct	CFI	RMSEA	AVE	CR	Cronbach's α
[VERTICAL INTEGRATION]	0.987	0.066	0.480	0.870	0.780
[SMART MANUFACTURING]	0.983	0.073	0.490	0.890	0.800
[CYBERSECURITY]	0.999	0.024	0.480	0.81	0.904
[PERFORMANCE]	0.996	0.063	0.640	0.930	0.570

To check for discriminant validity, two-factor models were estimated using the Confirmatory Factor Analysis (CFA) technique, as proposed by Bagozzi et al. (1991). Two models were compared for each construct, where the correlation between constructs was restricted to one unit on the first model while this restriction was lifted on the second model. All results pointed to discriminant validity ($\Delta\chi 2>3,84$, $p < 0,01$). To check for data normality, we used the Anderson-Darling test and skewness and kurtosis values. The results indicated that the data were normally distributed. All results are summarized in Appendix B.

4.4 Validity and reliability tests

In order to ensure the accuracy and reliability of our data, we implemented both procedural and statistical methods to address any potential response bias in our study (Podsakoff et al., 2012). First, we conducted a pre-test with a group of 10 scholars and 7 practitioners to confirm the clarity and accuracy of our questionnaire. Scholars are affiliates to technological institutes of Brazil dedicated to the develop of innovative solutions based on Industry 4.0 technologies. Industry representatives are companies' CEOs that compose the directory board from ABIMAQ. They helped to align the questionnaire to the technical language of the companies.

To further address any potential response bias, we employed Harman's single-factor test, which indicated that our dataset exhibited low levels of common method bias, with only 36.389% of the total variance being extracted by one factor - well below the threshold of concern at 50% (Podsakoff et al., 2012). Secondly, we implemented the marker variable technique by adding an unrelated variable to our questionnaire to gauge if our results remained consistent. We chose a question assessing a support team to follow digital transformation, as it had no theoretical correlation to our study's constructs. The model's results remained consistent with the addition of the marker variable, leading us to conclude that response bias was not a significant issue within our dataset.

4.5 Data analysis

In our study, we aimed to test six hypotheses (H1 to H6) through hierarchical regression analysis. We first used ordinary least squares (OLS) hierarchical regression to investigate the impact of VERTICAL INTEGRATION on SMART MANUFACTURING, with the moderating effect of CYBERSECURITY ACTIONS added to the model. In the second stage, we examined the direct effect of VERTICAL INTEGRATION on OPERATIONAL PERFORMANCE, also with the moderating effect of CYBERSECURITY ACTIONS added to the model. Finally, we regressed OPERATIONAL PERFORMANCE on VERTICAL INTEGRATION, CYBERSECURITY ACTIONS, and SMART MANUFACTURING, with the moderating effect of CYBERSECURITY ACTIONS added to the model. We tested for moderation effects by standardizing the independent and moderator variables using mean centering (Z-score) and creating a multiplicative score for the interaction effect.

To ensure the validity of our results, we conducted several tests. First, we tested for normality using skewness and kurtosis, as described in section 3.3 (Appendix C), and we confirmed the necessary assumptions for OLS regression models, including linearity and homoscedasticity. We tested for linearity using partial regression plots and examined homoscedasticity by plotting standardized residuals against predicted values. Additionally, we checked the statistical power of the models and partial coefficients.

Following the results reported in Section 5, we conducted complementary tests to check the robustness of our models. We first tested the models by excluding the control variables, and we found that the predictor variables were not artifacts of the control variables. Next, for the model with a significant moderating effect, we checked the inclusion of each interaction term individually and assessed whether they altered the results of the interactions. We found that the results remained stable. Finally, we tested a competitive model considering Smart Supply Chain in place of Smart Manufacturing and found no statistical support for this model. Overall, the competitive model did not show statistical significance at $p = 0.05$.

5 RESULTS

5.1 Analysis of the moderating effects

The results of the OLS regression models are summarized in Table 2. For the first main stage, each of the hierarchical regression models was set in two steps. In the first step, we included only the control variables (Company size, Technological acceleration and Business model change). In the second step, we included VERTICAL INTEGRATION and CYBERSECURITY ACTIONS in the SMART MANUFACTURING. In the second stage, we tested the direct effect of VERTICAL INTEGRATION on performance metric (firstly including only the controls and then including the VERTICAL INTEGRATION independent variable). In the third main stage, we added SMART MANUFACTURING to assess their effects on the performance measurements.

In the third stage (Table X), we also included a step with the moderation effect of CYBERSECURITY ACTIONS on VERTICAL INTEGRATION for the SMART MANUFACTURING, and the moderation effect of CYBERSECURITY ACTIONS on SMART MANUFACTURING for the performance metrics. In this step, each of the hierarchical regression models was set in three steps (for simplification purposes, we did not include the results from the first step with controls only). In the second step, the constructs VERTICAL INTEGRATION, CYBERSECURITY ACTIONS and SMART MANUFACTURING were included. Finally, we included the moderation effect of CYBERSECURITY ACTIONS. As shown in Table 2, the final model with CYBERSECURITY ACTIONS as a moderator was statistically significant for OPERATIONAL PERFORMANCE ($F = 6270$; $p < 0.01$), explaining 22% of the variance.

Table 2. Results of the regression analysis.

	SMART MANUFACTURING		OPERATIONAL PERFORMANCE			
Company size	-0.061	-0.095	-0.141	-0.138	-0.132	-0.131
Technological acceleration	0.016	0.010	0.199**	0.199**	0.196**	0.203**
Business model change	0.058	0.081	0.135	0.133	0.126	0.114
VERTICAL INTEGRATION	0.414***	0.381***	0.143	0.146	0.083	0.090
CYBERSECURITY ACTIONS	0.218**	0.237**	0.292***	0.291***	0.260**	0.249**
SMART MANUFACTURING					0.146	0.186*
VERTICAL INTEGRATION x CYBERSECURITY ACTIONS		0.237***		-0.017		

SMART MANUFACTURING x CYBERSECURITY ACTIONS						-0.075
F-value	11.317***	12.116***	8.071***	6.683***	7.216***	6.270***
R^2	0.310	0.368	0.243	0.243	0.257	0.261
Adjusted R^2	0.283	0.337	0.213	0.207	0.222	0.22
Change in R^2	0.232	0.058	0.107	0.000	0.122***	0.004
n=132	*** p <0.01; ** p<0.05; *p<0,1					

For the first main stage, concerning VERTICAL INTEGRATION, our findings showed a statistical association with SMART MANUFACTURING (B = 0.381, $p < 0.01$). Regarding CYBERSECURITY ACTIONS, our findings showed statistical associations with SMART MANUFACTURING (B = 0.237, $p < 0.05$) and OPERATIONAL PERFORMANCE (B = 0.291, $p < 0.01$). For the second stage, SMART MANUFACTURING showed a statistical association with OPERATIONAL PERFORMANCE (B = 0.186, $p < 0.1$).

To evaluate mediation effects, it is necessary to calculate indirect effects (Preacher & Hayes, 2008). To examine the hypotheses related to mediation effects in our study, we utilized the PROCESS procedure developed by Hayes (2013). This methodology employs bootstrapping, which provides increased statistical power compared to the Sobel z test (Zhao et al., 2010) when assessing conditional indirect effects. Consistent with the recommendation of Preacher and Hayes (2008), we conducted 5,000 bootstrap samples. We found partial mediation, as the direct effect remained significant in Smart Manufacturing models as mediators between vertical integration and operational performance. This means that higher levels of operational performance are achieved with the support of vertical integration. The estimates, standard errors, significance levels, as well as the corresponding lower (LLCI) and upper (ULCI) confidence intervals, are presented in Table 3.

Table 3. Indirect effects (bootstrapping outcome).

Interactions	Bootstrap outcome			95% confidence interval		Total and direct effects	Sig.	Conclusion
	Mean	SD	Sig.	LLCI	ULCI			
VERTICAL INTEGRATION -> SMART	0.0947	0.0436	<0,01**	0.0102	0.1841	TOTAL EFFECT	0.0001	PARTIAL

Interactions	Bootstrap outcome			95% confidence interval		Total and direct effects	Sig.	Conclusion
	Mean	SD	Sig.	LLCI	ULCI			
MANUFACTURING -> OPERATIONAL PERFORMANCE						DIRECT EFFECT	0.0201	
VERTICAL INTEGRATION*CYBERSECUTIRY ACTIONS -> SMART MANUFACTURING -> OPERATIONAL PERFORMANCE	0.00861	0.0394	-	0.0224	0.1745	-	-	-
CYBERSECUTIRY ACTIONS -> SMART MANUFACTURING -> OPERATIONAL PERFORMANCE	0.0786	0.0313	<0,01**	0.0224	0.1452	TOTAL EFFECT DIRECT EFFECT	0.0000 0.0035	PARTIAL

For the last stage, regarding the hypothesis that CYBERSECURITY ACTIONS have a moderating effect on VERTICAL INTEGRATION and SMART MANUFACTURING, the results in Table 2 show a moderating effect of CYBERSECURITY ACTIONS on the relationship between VERTICAL INTEGRATION and SMART MANUFACTURING, supporting H4 in OPERATIONAL PERFORMANCE.

6 DISCUSSIONS AND CONCLUSION

The existing literature on cybersecurity has focused on technical aspects, looking only at technology and not at operational performance (Lezzi et al., 2018; Haleem et al., 2022). Our study provides an advancement towards a business perspective, aiming at operational performance and providing a theoretical and empirical basis for decision-making regarding the implementation of cybersecurity measures. We demonstrate how vertical integration generally supports smart manufacturing and is strongly associated with higher levels of operational performance in digital transformation.

Our tests reveal that vertical integration does not have a direct effect on operational performance. rather, it has an indirect effect on performance through smart manufacturing. Vertical integration proved to be a precursor to smart manufacturing, satisfying hypothesis H3. Therefore, when considering vertical integration as an antecedent to smart manufacturing and incorporating cybersecurity actions into vertical integration, our results are positive, supporting hypothesis H4 that vertical integration is enhanced for smart manufacturing when a company implements cybersecurity measures. Thus, vertical integration is moderated by cybersecurity when associated with smart manufacturing, meaning that the presence of cybersecurity actions alters how vertical integration contributes to the development of smart manufacturing.

We confirmed that smart manufacturing has a direct impact on operational performance in our findings, supporting hypothesis H5. However, when adding cybersecurity actions to the interaction between smart manufacturing and operational performance, we did not observe a significant impact, rendering hypothesis H6 unsupported. Additionally, we confirmed that vertical integration and cybersecurity actions have indirect impacts on operational performance, albeit independently (not as moderation). This implies that each of them can contribute to performance through their support of smart manufacturing, but whether they are implemented together or not is not central to operational performance, although it is crucial for smart manufacturing.

Therefore, cybersecurity actions should be implemented considering this entire scenario. For cybersecurity actions to have an effect on operational performance, it is necessary to implement them in conjunction with vertical integration, prior to smart manufacturing rather than after.

6.1 Theoretical contribution

The literature on operations management in the context of Industry 4.0 has extensively discussed cybersecurity, focusing on providing cybersecurity guidelines for factories. However, this is the first attempt to provide an understanding of the role of cybersecurity actions in the implementation of vertical integration in smart manufacturing. The novelty of this perspective lies in our in-depth exploration of the topic, considering aspects of vertical integration that involve the integration of various technologies such as SCADA, MES, APS, PLM, and ERP within the context of Industry 4.0. Specifically, we examine the real-time data flow enabled by IoT systems. By adopting a performance-oriented perspective, we analyze the relationships that exist when implementing cybersecurity actions in a factory. Furthermore, this study demonstrates that vertical integration serves as a precursor to smart manufacturing, but needs it needs the support of cybersecurity actions to be more effective. While previous studies have examined the implementation of vertical integration from an isolated perspective (e.g., Sony and Naik, 2019; Hoyer et al., 2020; Nimawat and Gidwani, 2020; Lin et al., 2019), this is the first study to investigate the dynamic aspect of implementation that cybersecurity managers need to consider. Hence, our study sheds light on the role of cybersecurity action implementation for vertical integration and smart manufacturing in terms of performance. It also provides a broader conceptual contribution to the overall literature on Industry 4.0.

6.2 Managerial and practical implications

Managers and professionals can draw several conclusions from our study. Our research has clarified the importance of implementing cybersecurity actions within a company to achieve performance goals. It has shown, from a new perspective, that in order to attain the expected performance, cybersecurity actions should be implemented alongside vertical integration, preceding the implementation of other technologies that make up smart manufacturing, such as collaborative robots, additive manufacturing, and AGVs. Vertical integration requires cybersecurity actions due to its complex layer integration, spanning from operational technologies to information systems. Therefore, managers and professionals should pay closer attention to their Industry 4.0 management, aiming to plan a robust implementation of cybersecurity actions that support vertical integration, enabling operational performance. Our key point is that managers must recognize that vertical integration, combined with cybersecurity actions, should be implemented prior to smart manufacturing.

7 REFERENCES

AHUETT-GARZA, H., & KURFESS, T. (2018). A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart manufacturing. Manufacturing letters, 15, 60-63.

BAGOZZI, R. P., YI, Y., & PHILLIPS, L. W. (1991). Assessing construct validity in organizational research. Administrative science quarterly, 421-458.

BENITEZ, G. B., GHEZZI, A., & FRANK, A. G. (2023). When technologies become Industry 4.0 platforms: Defining the role of digital technologies through a boundary-spanning perspective. International Journal of Production Economics, 260, 108858.

COHEN, Y., FACCIO, M., PILATI, F., & YAO, X. (2019). Design and management of digital manufacturing and assembly systems in the Industry 4.0 era. The International Journal of Advanced Manufacturing Technology, 105, 3565-3577.

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, 204(December 2017), 383–394. https://doi.org/10.1016/j.ijpe.2018.08.019

DAWSON M., "Segurança cibernética na indústria 4.0: as armadilhas de ter sistemas hiperconectados", J. Strategic Manage. Viga. , vol. 10, não. 1, pp. 19-28, 2018.

DENG, J., & SAVAS, O. (2017). Data and Research Initiatives for Cybersecurity Analysis. In Big Data Analytics in Cybersecurity (pp. 309-328). Auerbach Publications.

FRANK, A. G., DALENOGARE, L. S., & AYALA, N. F. (2019). Industry 4.0 technologies: Implementation patterns in manufacturing companies. International Journal of Production Economics, 210(September 2018), 15–26.

HALEEM, A., JAVAID, M., SINGH, R. P., RAB, S., & SUMAN, R. (2022). Perspectives of cybersecurity for ameliorative Industry 4.0 era: a review-based framework. Industrial Robot: the international journal of robotics research and application.

HOYER, C., GUNAWAN, I., & REAICHE, C. H. (2020). The implementation of industry 4.0–a systematic literature review of the key factors. Systems Research and Behavioral Science, 37(4), 557–578.

ISMAIL, A., & KASTNER, W. (2016). Vertical integration in industrial enterprises and distributed middleware. International Journal of Internet Protocol Technology, 9(2–3), 79–89.

LEZZI, M., LAZOI, M., & CORALLO, A. (2018). Cybersecurity for Industry 4.0 in the current literature: A reference framework. Computers in Industry, 103, 97-110.

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.

LIN, B., WU, W., & SONG, M. (2019). Industry 4.0: Driving factors and impacts on firm's performance: An empirical study on China's manufacturing industry. Annals of Operations Research, 1–21.

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.

MORGAN, H. M., SUI, S., & MALHOTRA, S. (2021). No place like home: The effect of exporting to the country of origin on the financial performance of immigrant-owned SMEs. Journal of International Business Studies, 52, 504-524.

MULLET, V., SONDI, P., & RAMAT, E. (2021). A review of cybersecurity guidelines for manufacturing factories in industry 4.0. IEEE Access, 9, 23235-23263.

NIMAWAT, D., & GIDWANI, B. D. (2020). Prioritization of important factors towards the status of industry 4.0 implementation utilizing AHP and ANP techniques. Benchmarking: An International Journal.

PÉREZ-LARA, M., SAUCEDO-MARTÍNEZ, J. A., MARMOLEJO-SAUCEDO, J. A., SALAIS-FIERRO, T. E., & VASANT, P. (2018). Vertical and horizontal integration systems in Industry 4.0. Wireless Networks, 2.

PODSAKOFF, P. M., MACKENZIE, S. B., & PODSAKOFF, N. P. (2012). Sources of method bias in social science research and recommendations on how to control it. Annual review of psychology, 63, 539-569.

PREACHER, K. J., & HAYES, A. F. (2008). Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. Behavior research methods, 40(3), 879-891.

PRINSLOO J., S. SINHA E B. VON SOLMS, "Uma revisão dos riscos de segurança do processo de fabricação da indústria 4.0", Appl. ciência, vol. 9, não. 23, pp. 5105, novembro de 2019.

RÎNDAȘU, S. M. (2017). Emerging information technologies in accounting and related security risks–what is the impact on the Romanian accounting profession. Journal of Accounting and Management Information Systems, 16(4), 581-609.

SONY, M., & NAIK, S. S. (2019). Ten lessons for managers while implementing Industry 4.0. IEEE Engineering Management Review, 47(2), 45–52.

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?. Information Systems Frontiers, 1-18.

TAMAS, L., MURAR, M., & TAMAS, L. (2019). Smart CPS: vertical integration overview and user story with a cobot Smart CPS: vertical integration overview and user story with a cobot. International Journal of Computer Integrated Manufacturing, 32(4–5), 504–521.

TANGE K., M. DE DONNO, X. FAFOUTIS E N. DRAGONI, "Uma pesquisa sistemática de segurança industrial da Internet das Coisas: requisitos e oportunidades de computação em névoa", IEEE Commun. Pesquisas Tuts. , vol. 22, não. 4, pp. 2489-2520, 4º quart. 2020.

ZHOU, P., ANG, B. W., & HAN, J. Y. (2010). Total factor carbon emission performance: a Malmquist index analysis. Energy Economics, 32(1), 194-201.

Appendix A. Questionnaire

Questionnaire items to assess Vertical integration (VERTICAL INTEGRATION)

Concordance Likert scale: 1. Not interested in implementing to 5. We have advanced implementation. *Cronbach = 0.78; CR = 0.87; AVE = 0.48. Factor loadings are shown in parentheses.*

a) Os equipamentos da nossa empresa são operados mediante computador local (ex. através de CLP) (0,66)
b) Os dados dos equipamentos da nossa empresa são capturados através de um sistema SCADA (0,78)
c) Os equipamentos da nossa empresa estão conectados para integração de dados utilizando um sistema MES (0,88)
d) Os nossos dados da produção estão integrados com outros níveis da empresa (integração MES-ERP) (0,57)
e) Nossa empresa realiza simulação de processos produtivos (0,45)

Questionnaire items to assess Smart Manufacturing (SMART MANUFACTURING)

Concordance Likert scale: 1. Not interested in implementing to 5. We have advanced implementation. *Cronbach = 0.80; CR = 0.89; AVE = 0.49. Factor loadings are shown in parentheses.*

f) Nossa empresa realiza simulação de operação de equipamentos (0.74)
g) Nossa empresa utiliza gêmeos digitais da planta (digital twins) (0.61)
h) Nossa empresa utiliza realidade aumentada para checklists de atividade (0.61)
i) Nossa empresa utiliza realidade virtual para simulações de protótipos (montagem, desenvolvimento de produtos, etc.) (0.67)
j) Nossa empresa utiliza realidade virtual para interação com as operações produtivas (0.83)

Questionnaire items to assess Cybersecurity actions (CYBERSECURITY)

Concordance Likert scale: 1. Not interested in implementing to 5. We have advanced implementation. *Cronbach = 0.90; CR = 0.81; AVE = 0.48. Factor loadings are shown in parentheses.*

a) Nossa empresa possui estratégia de segurança cibernética (0.61)
b) Os colaboradores de nossa empresa foram treinados em segurança cibernética (0.59)
c) Em nossa empresa existem regras e processos para os colaboradores (e.g., geração de senha, uso de armazenamento privado, backups, acesso à rede, etc.) (0.83)
d) Em nossa empresa existem soluções técnicas que impõem, por exemplo, atualizações de software, backup, criptografia de comunicação e regras para acesso à rede (0.92)
e) Nossa empresa possui certificados de acordo com normas de segurança da Informação (e.g., ISO-27000) (0.32)

Questionnaire items to assess Operational performance (PERFORMANCE)

Concordance Likert scale: 1. strongly disagree to 5. I fully agree. *Cronbach = 0.57; CR = 0.93; AVE = 0.64. Factor loadings are shown in parentheses.*

a) A transformação digital está ajudando está ajudando a melhorar nossa produtividade (0.80)
b) A transformação digital está ajudando a melhorar nossa flexibilidade para atender mudanças do mercado mais rapidamente (0.83)
c) A transformação digital está ajudando a melhorar nossa segurança nos processos de trabalho (0.89)
d) A transformação digital está ajudando a sermos mais inovadores nos produtos e serviços oferecidos (0.64)

Appendix B Bivariate correlation matrix

	Variáveis	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Company size	-						
2	Technological acceleration	0.03959	-					
3	Business model change	0.176**	0.359***	-				
4	VERTICAL INTEGRATION	0.329***	0.328***	0.155	-			
5	SMART MANUFACTURING	0.192**	0.201**	0.154*	0.513***	-		
6	CYBERSECURITY ACTIONS	0.489***	0.173**	0.168*	0.535***	0.423***	-	
7	OPERATIONAL PERFORMANCE	0.08	0.337***	0.252***	0.342***	0.333***	0.357***	-
	Mean	3.075758	3.371212	3.598485	3.340909	2.037879	3.272727	4.045455
	S.D.	0.737452	0.859658	0.881185	1.117724	0.841711	1.105786	0.836784
	Skewness	-0.70057	0.00532	-0.61092	-0.07554	1.019627	-0.11313	-0.32438
	Kurtosis	0.7271	-0.67309	0.19805	-0.74717	1.647665	-0.70049	-0.92952

*** p <0.01; ** p<0.05; *p<0,1

5. FINAL CONSIDERATIONS OF THE THESIS

This thesis proposes a methodology to support companies in implementing vertical integration that allows companies to advance in Industry 4.0. Throughout the three stages of research carried out, it was possible to create knowledge that brings great contributions to the academic-theoretical environment and the practical-managerial environment.

This work presented three articles, each corresponding to a specific objective of this thesis. Figure 1 presents the relationship between the three articles of the thesis. While Article 1 addresses what factors companies should consider when adopting information systems for vertical integration, Article 2 addresses the asymmetry of information between buyers and suppliers for implementing MES, and Article 3 addresses implementing cybersecurity actions in vertical integration.

The three articles were developed sequentially to form a complete perspective of selection, implementation, and use of information systems in the context of Industry 4.0. The first article focused on selecting information systems for Industry 4.0 using the TOE framework and the decision process. Then, article 2 focused on implementing information systems for Industry 4.0, managing the information asymmetry between buyers and suppliers. Furthermore, finally, the third paper focused on the use of information systems for Industry 4.0 with the implementation of cybersecurity actions to support vertical integration in operations. The results of each of these articles that make up this thesis form a set of descriptive models that bring clarity to implementing vertical integration in the context of Industry 4.0 and help managers make decisions.

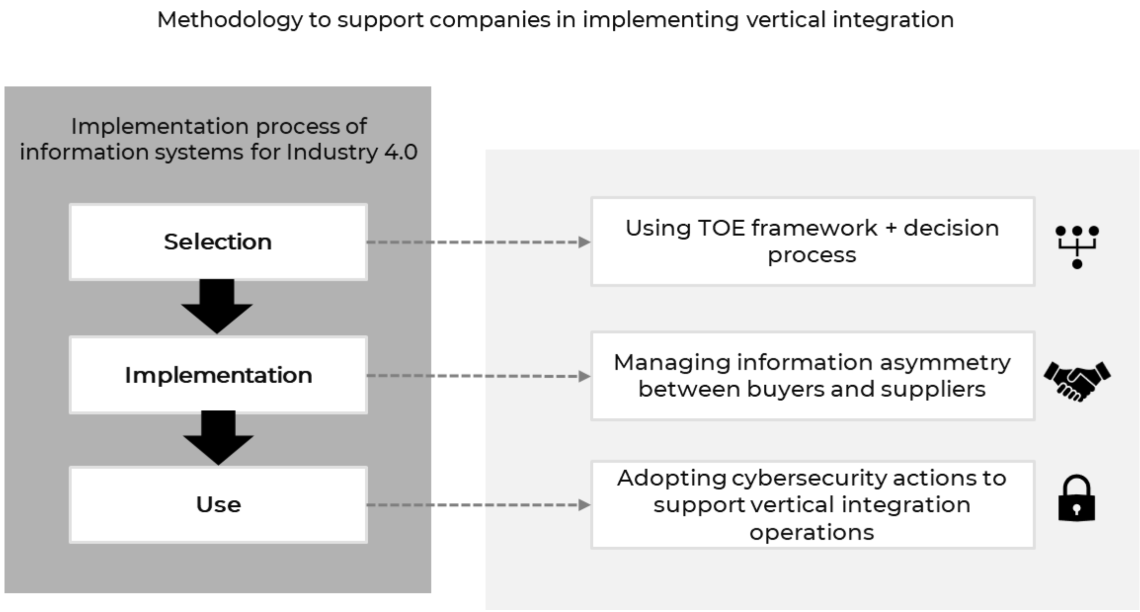

Figure 1. Articles relationship

5.1 THEORETICAL CONTRIBUTIONS

This thesis covers a complex and interrelated system of different information technologies, which requires a wide range of requirements compared to studies that address adopting a single technology. This includes technological, organizational, and environmental perspectives. It emphasizes the importance of considering various factors when adopting information systems to implement vertical integration in Industry 4.0. It identifies tensions that arise during the adoption process due to the complexity of integrating different information technologies. Tensions are discussed, as well as sociotechnical factors of different dimensions that can come into conflict. These tensions and conflicts pave the way for future research, exploring their origins, and approaches to managing them and developing additional theories about the sociotechnical aspects of adopting vertical integration in information management.

Furthermore, this study has significant theoretical implications by offering a comprehensive and qualitative understanding of MES implementation in the context of Industry 4.0. It highlighted how technological complexity could lead MES buyers and sellers to interpret the system's characteristics differently. Using the information asymmetry lens, we demonstrate that the successful purchase and implementation of MES in Industry 4.0 starts in the pre-engagement phase, a step often needs to be considered by academics and practitioners. Furthermore, we explore perspectives on knowledge-sharing and buyer-supplier configuration, revealing that different levels of MES complexity require distinct knowledge-sharing dynamics to overcome barriers between actors and establish successful buyer-supplier collaborations. This combination of theories resulted in a conceptual framework that scholars can adapt to analyze the adoption of complex information systems in other contexts.

This study has important theoretical implications when examining the role of cybersecurity actions in implementing vertical integration in smart manufacturing. Addressing the performance perspective, we analyze the relationships that arise when implementing cybersecurity measures in a factory. The study shows that vertical integration is an essential precursor of smart manufacturing but requires the support of cybersecurity actions to achieve greater effectiveness. In this way, we clarify the role of cybersecurity measures in vertical integration and smart manufacturing, focusing on performance. These findings contribute to the theoretical understanding of the interplay between cybersecurity and vertical integration, providing valuable insights for researchers and academics in the field of Industry 4.0.

5.2 PRACTICAL CONTRIBUTIONS

This study has significant practical implications for managers and provides specific guidelines for these professionals. First, the importance of balancing legacy systems with reengineering the company's infrastructure during the adoption of an information system for vertical integration is highlighted. This is especially relevant considering that vertical integration combines different technologies acquired at different times. Managers must assess the feasibility of this integration and the resulting flexibility to meet the demands of Industry 4.0, which requires greater flexibility. In addition, the importance of balancing technological requirements with organizational readiness and employee knowledge is highlighted. Social aspects must be addressed, and managers must promote digital culture, develop training programs and recruit qualified human resources when implementing vertical integration. A tension was identified between carrying out small tests and prioritizing investments versus seeking solidity through large technology providers. One option is to take an ecosystem approach, involving a group of companies working together to create an enabling environment for small tests. This approach allows for dealing with the complexity of demands and avoiding dependence on a single vendor for implementation.

The results of this thesis have significant practical implications for buyers and suppliers in implementing MES as a gateway to Industry 4.0. Many manufacturing companies need more preparation regarding internal capabilities and ill-defined expectations in their MES implementation projects. MES vendors also need help meeting buyers' expectations due to an asymmetry of information. For small businesses with limited resources, off-the-shelf solutions with basic MES functionality and plug-and-play hardware can be an affordable option to improve productivity. More mature companies seeking vertical integration must internally develop the necessary knowledge and rely on a specialized IT team to outsource MES development. A deepening in the implementation of MES and vertical integration is necessary for advanced companies in Industry 4.0 that seek advanced levels, such as 'digital twins' in real-time and autonomous processes. In this case, customizing the MES to integrate the company's systems fully is essential.

The present study highlighted the importance of implementing cybersecurity actions in a company to achieve performance goals. From a new perspective, it was demonstrated that these actions should be implemented in parallel with vertical integration before adopting other smart manufacturing technologies, such as collaborative robots, additive manufacturing, and AGVs, to achieve the desired performance. Vertical integration requires cybersecurity measures due to the complex integration of different layers, from operational technologies to information systems. Therefore, managers and professionals must be aware of Industry 4.0 management, planning a robust implementation of cybersecurity actions that support vertical integration and guarantee operational performance. Our key point is that managers must recognize the importance of implementing, before smart manufacturing, vertical integration in conjunction with cybersecurity measures.

This research emphasized the importance of implementing cybersecurity measures in a company to achieve performance targets. These measures should be implemented concurrently with vertical integration before adopting other smart manufacturing technologies. Vertical integration requires cybersecurity measures due to the complexity of integration between different technological layers. Therefore, managers and professionals must be aware of Industry 4.0 management, planning a solid implementation of cybersecurity measures that support vertical integration and guarantee operational performance. The main takeaway is that managers must recognize the importance of implementing vertical integration with cybersecurity measures before moving toward smart manufacturing.