

INDUSTRY 4.0 IN WAREHOUSE ERGONOMICS: POSSIBLE APPLICATIONS OF EMERGING TECHNOLOGY

PhD. thesis – Summary

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1. Summary of the PhD Thesis

The PhD research starting point was related to the recent development of the Industry 4.0 concept and the potential applications in the logistic system context. Both theoretical and practical perspectives have been considered for increasing warehousing speed and accuracy to cope with ever changing industry and customer requirements. During the literature review of different aspects considered relevant for the PhD research there have been discovered that ergonomic solutions for logistic operations were not considered to be the first area of interest in improving logistic systems, specifically the warehouses' workplaces and their general working conditions. Most researchers were invested in how the Industry 4.0 paradigm would apply to processes automation and robotization and not how it could be applied to the human worker's activity optimization. Thus, the topic importance and relevance cannot be ignored in research anymore.

Some arguments of introducing the Industry 4.0 paradigm in the logistics activities are provided by facts that have been provided by important international organizations:

- A Price Waterhouse Cooper (PWC) survey (2016) on Industry 4.0 implementation has shown that industrial leaders are digitizing essential functions of the enterprises, both “within their internal, vertical operations processes, as well as with their horizontal partners along the value chain. They are additionally enhancing their product portfolio with digital functionalities and introducing innovative data-based services”. The study results showed an expectation of digitization expenses to increase from just 33% in 2017 to over 70% in 2020 (PWC, 2016).
- According to the World Economic Forum White Paper Digital Transformation of Industries in 2016, within SCM “key technologies will be included autonomous transport and drones, sensors for monitoring supply chains and 3D printing technology. Digitally enabled companies will incur procurement costs of 0.22% of net revenue, less than half of those of their peers (0.5%)”. The value of digitization within the next decade will exceed €1333 billion (World Economic Forum, 2016).
- The supply chain will evolve and become smarter, more transparent, and more efficient because of this digital transformation and the subsequent use of intelligent cooperative systems. “There will be a particular focus in new models which will be more closely to individual customer needs, promoting a significantly increase of the decision-making

quality and become more and more flexible and efficient in the near future” (Barreto et al., 2017).

- Concerning distributions centres (DC) Industry 4.0 technologies can help enable automated systems to adapt to their environment to execute tasks more efficiently in collaboration with humans. Both from the technological and organizational point of view equipment, such as low-cost sensors, computer vision, augmented reality (AR), wearables, Internet of Things (IoT), analytics and high-performance computing can be used to enhance existing automation and remove the existing historical situation of low automation in DCs without highly standardized products. The last years trend has shown that the ways in which DC facilities are being used is changing and there is a need for smarter, more adaptable systems services (Deloitte, 2016). Companies are aware of this change and are proceeding to adapt their investments accordingly. Based on a recent international study of DCs, half of the surveyed IT and operations decision makers planned to move to a more modern, full-featured warehouse management system in 2015. By 2020 this number increases to 75%. 51% of those surveyed expected increased investment in real-time location systems that track inventory and assets throughout the warehouse as well as, equipping staff with technology (73%), bar code scanning (68%), tablets (66%) and Internet of Things (62%). IoT alone is predicted to connect 20 billion devices or ‘things’ to the existing internet infrastructure by 2020 (Zebra, 2016).

In order to reduce the productivity dips caused by poor ergonomic design of processes, that appears when ergonomics is seen as an afterthought rather than the first analysis that needs to be done, a solid ergonomic application framework is necessary to be developed. Besides the technological modifications that need to be ergonomically designed and integrated, Industry 4.0 also offers technological opportunities to support work-based learning, to reduce operators’ physical loads and better monitor their health. Although robotics and human-machine interaction are disciplines with an extend literature, but the actual complexity of professional human behavior opens new ways for research that allow creating new paradigms (Munoz, 2017). The relative lack of understanding from the business world regarding emerging ergonomics developments in the research world also proves to be a fertile ground not only for improvements based on knowledge transfer, but for setting new and innovative developments.

Within the present PhD. research framework, the possibility of applying Industry 4.0 technology in the warehouse of a manufacturing facility will be analyzed. The existing market technology will be categorized, examined, and rated based on its capacity to improve the ergonomic efficiency within the warehouse, as part of the logistics system. Based on this rating and existing ergonomic framework, a model will be developed that can be used in a business environment, to track the current level of ergonomic applications, implementation practiced within the company and a development and to show the investment pathway needed to reach Industry 4.0 benchmarks.

The motivation of the research topic is determinate because ergonomics is becoming increasingly important in warehousing and logistics. Currently, due to European Union (EU) and national legislation, companies in Western Europe must reconsider their policies and focus more on individual rights, on implementing solutions of human-friendly logistics via excellent logistics ergonomics. The focus on reducing warehouse personnel turnover in to reduce the unsafe environment that workers might experience. The companies with the most stable and productive warehouse working teams are the ones with the most developed programs for safety training, ergonomics, and housekeeping.

The increased interest in ergonomics, to reduce worker turnover, is coming at a time when companies are also introducing Industry 4.0 techniques and technologies. “Scientific research will always be impeded if clear definitions are lacking and it has been shown so far that companies face difficulties when trying to develop ideas or act without understanding what to aim towards” (Hermann et al., 2015). In addition, “most companies in Germany do not have a clear understanding of what Industry 4.0 is and what it will look like” (Pascual et al., 2019; Eco – Verband der deutschen Internetwirtschaft, 2014). This creates a situation where industry experts in Germany confirm that after the implementation of Industry 4.0 in their companies, the productivity gains are up to 50%, depending on the complexity of production use cases (Bauernhansl et al., 2014), but at the same time they are not entirely sure what they are applying, and do so in a non-structured way.

This proves that the current situation requires a structured analysis to define if ergonomic applications of Industry 4.0 technologies are suited for a specific company, turning the currently practiced empiric approaches into scientific ones. Companies need to understand what Industry 4.0 benefits they can reap and how to leverage those benefits into creating a safety, more issue-free work environment for their human operators. Due to the interconnectivity of Industry 4.0 technologies, companies also need to understand the legal limit of their application and how to approach their presentation to the operators that would be in direct contact with them.

The scope of the PhD program is to develop a set of researches focus on designing a systematic and integrated approach of warehouse ergonomics condition improvement, based on the Industry 4.0 framework. Currently existing approaches of the ergonomics science has been in deep analyzed and they are the basis of the theoretical developments and experimental studies. *The general objective of the PhD research is to evaluate and characterize the relevant business research directions of warehouse ergonomics and develop an Ergonomics Maturity Model for a large-scale industry environment by using various interdisciplinary research of different management areas.* For this purpose, a methodological, procedural, and organizational approach will be developed to complete existing research gaps and facilitate practical improvements and optimizations in companies, too. The proposed *Ergonomics Maturity Model* will be applied (tested and validated) in a use case of a low volume high complexity project in which ergonomic needs are underserved. **The operational objectives of the research approach are:**

OP1. Analysis and synthesis of bibliographic references necessary to create an overview of ergonomics applications in logistics. This will provide the scientific basis for the research on ergonomics applications in a warehouse environment to present not only as a basis for the present research work, but also for further researches in this area - Chapter 2;

OP2. Experimental research on the ergonomics intervention and implication in a current supply chain organization of a multinational production company (implementations of the experiments on current ergonomic issues within the manufacturing warehouse facility of the company’s Belgian branch) - Chapter 3;

OP3. Experimental research on a warehouse processes improvement capability (implementation of the experiments at a Belgian manufacturing warehouse facility to identify ergonomic improvement capabilities both in the classical ergonomic approach as well as with the application of Industry 4.0 technology) - Chapter 4;

OP4. Theoretical developments and experimental research for the Ergonomics Maturity Model design and a related ergonomics maturity assessment tool (theoretical research has been accompanying by testing and validation phases within a use case of a low volume high complexity project developed in a Belgium companies and based on current legal and ethical factors) - Chapter 5.

The overall goal and operational research targets are systematically developed and documented in the different chapters of the PhD thesis as shown in Figure 1.

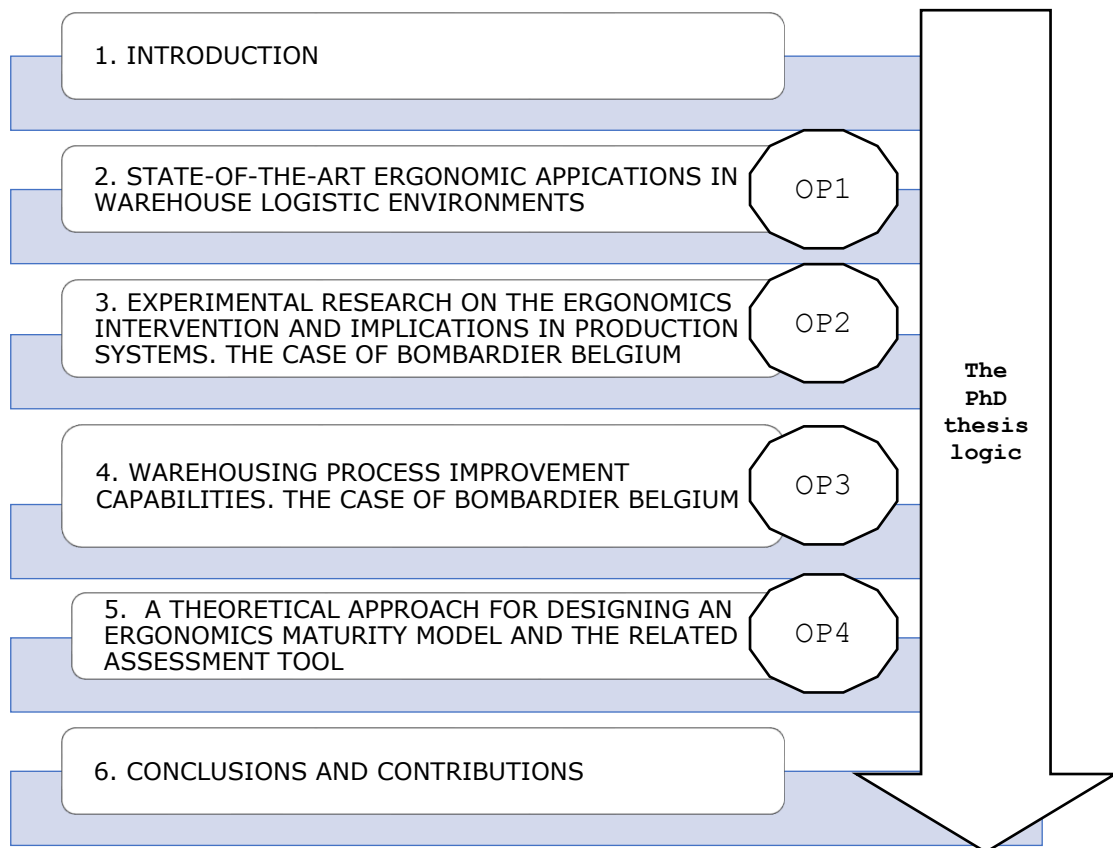


Figure Error! No text of specified style in document.. The general overview of the PhD thesis associated with the research approach (own flowchart)

The PhD thesis consists of 6 chapters with a total length of 183 pages (including the references list of articles, books and web pages that were used and adequately cited in the PhD. thesis text, but not the Annexes). In addition, 7 Annexes were defined to support the scientific debates and explanations with supplementary details. In totally, the PhD thesis is developed o 216 pages and consists of 20 tables, 68 figures, and 1 mathematical formula.

The way on how each operational objective has been targeted is proved by the content of each PhD thesis chapter that described the developed research activities, the results achieved together with relevant conclusions. Briefly, each chapter content is described in the following.

Chapter 1, the “INTRODUCTION”, describes the problem of the research topic, the motivation, and the scientific and practical importance. Using selected examples from the literature, the challenge and the current state of research is underlined. Furthermore, the objectives of the PhD approach are briefly outlined.

Chapter 2, entitled “STATE-OF-THE-ART ON ERGONOMICS IN WAREHOUSE LOGISTICS”, provides an overview of the current state of research, with bibliographic reference and focus on relevant research results. The purpose of the chapter is to give the reader an understanding of what the theoretical context is regarding supply chain management, logistics, warehousing, and ergonomics, to ease the technical understanding of the topic being discussed. Further, the chapter presents the current research into warehouse ergonomics, presenting the physical and mental strains that workers must overcome to be able to accomplish

their tasks. The chapter ends with a presentation of Industry 4.0 solutions currently already being applied by the industry to monitor or improve ergonomics and how this topic can be further developed and improved upon.

Chapter 3, with the title “EXPERIMENTAL RESEARCH ON THE ERGONOMICS INTERVENTION AND IMPLICATIONS IN PRODUCTION SYSTEMS. THE CASE OF BOMBARDIER BELGIUM” examines the current ergonomic reality of a low volume high complexity manufacturing plant in Belgium. The company chosen for the experimental research (preliminary diagnosis in the real economic environment) is Bombardier Transportation Belgium NV which designs and manufactures a large variety of solutions in the field of rail transportation. The company’s portfolio consists of rail vehicles, propulsion sub-systems, as well as controls units, bogies, signaling systems, and associated services for the rail transportation products such as vehicle refurbishment, modernization, and fleet maintenance. It is a representative company in the field being on the third place in the worldwide in the 2017 top 10 ranking of global Original Equipment Manufacturers (OEMs) as shown in Figure 2. Bombardier Transportation (BT) follows the CRRC Corporation Limited of China and Alstom company from France, according to the SCI Verkehr¹ consulting company’s study.

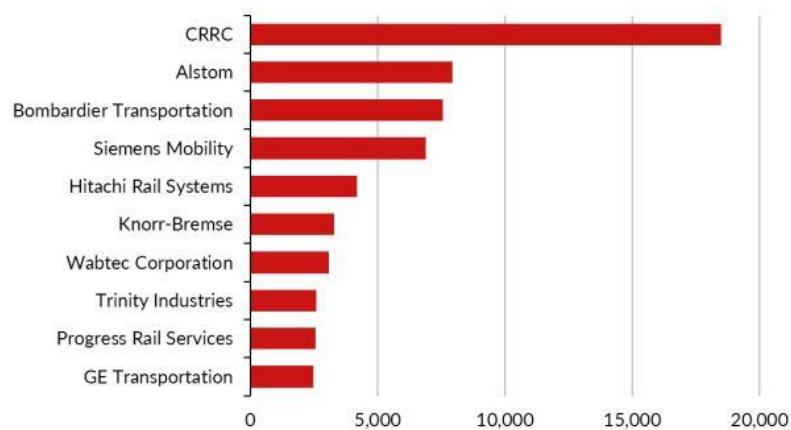


Figure 2. The top 10 hierarchy of the largest railway OEMs by turnover in 2017 (€m)²

The described research context has offered a relevant experience and results on the state of the ergonomics interventions, as well as its implications for warehouse work processes improvement. Furthermore, through the four experiments, the inbound and internal supply chain of the company is analyzed, the ergonomic aspects of the warehousing facilities are looked at and the possibility to use wearable computers in the environment is tested. The experiments fields of interest are related to the most vulnerable areas of the internal logistics system operation which were identified based on the reference review and observations in the company. Following experimental researches are described:

1. A study on the company’s internal supply chain ergonomics;
2. A study on the rack’s metrics;
3. The study of the cycle time Kanban bin fill-up;
4. The ergonomic assessment of the Kanban human operators.

The experiments results offer a better understanding of the challenge’s manufacturing companies face when dealing with warehouse ergonomics. In addition, the studies have

¹ SCI Verkehr is the most prestigious consultancy company focused on the international railway and logistics industry, <https://www.sci.de/?L=1>

² Leenen M. and Wolf A. (sept.14, 2018). SCI study forecasts upturn in global rail market, International Railway Journal. Retrieved from: https://www.railjournal.com/in_depth/sci-study-forecasts-upturn-in-global-rail-market

provided valuable knowledge about the AS-IS situation of the warehouse ergonomics and open the perspectives for improvements.

Chapter 4, entitled “WAREHOUSING PROCESS IMPROVEMENT CAPABILITIES. THE CASE OF BOMBARDIER BELGIUM”, valorized the knowledge pool of research results build through the studies presented in the previous chapter, by analyzing the ways in which the ergonomic reality in Bombardier’s warehouse can be improved. The chapter presents both traditional improvement methods based on Lean Six Sigma methodology and tools, as well as improvements that could be attributed to the implementation of automation and Industry 4.0 technologies.

First, a deep study on re-defining the workspace the analysis of the Kanban bin filling process is presented based on the Ishikawa method and 5Whys tool. These have been conducted to a detail analysis of 14 point of improvements, which are discussed following with the defined improvement impact effort matrix. The improvements are related to the following aspects:

- BT company culture;
- Project based versus process-based culture;
- Logistical MPR flow definition;
- Employee morale;
- Logistics policy;
- BT HSE strategy (0 accidents, not 0 long term problems);
- Managerial capabilities;
- Weight to lift/ergonomics policy creation;
- Workspace reorganization Kanban area;
- Workspace reorganization rack area;
- Visual management Kanban area;
- Visual management rack area;
- Time schedule for warehouse workers;
- Rethinking Kanban bin on rack logic.

Furthermore, in the chapter there are analyzed the Industry 4.0 solutions for improvement with the help of an ergonomics efficiency formula and provides advice related to the implementation of these tools in the environment case analyzed. The research conclusions focus on a comparative analysis of the improvements implementation considering the overall efficiency of automation and Industry 4.0 technology.

In Chapter 5, with the title “A THEORETICAL APPROACH FOR DESIGNING AN ERGONOMICS MATURITY MODEL AND THE RELATED ASSESSMENT TOOL”, is presented a proposed theoretical model for ergonomics improvement.

In subchapter 5.1 the theoretical concept is presented following the research design approach. Ergonomic axiomatic design is discussed with regards to its utility in the current endeavor. The goal of the designed Ergonomics Maturity Model is explained as being aimed at bridging the understanding between academic and industrial experience.

In sub-chapter 5.2 the associated assessment tool is presented. The working of the tool as well as the purpose it has in guiding management professionals in their search for better ergonomic environments are discussed. The tool is filled in with the data from Bombardier’s ergonomic assessment and a sample improvement process step is shown to test and validate the Ergonomics Maturity Model and the way it should be practically exploited.

In Chapter 6, CONCLUSIONS AND ORIGINAL CONTRIBUTIONS, the overall results of

the research are summarized, and the core messages of the findings are presented. Reference to the previously identified gaps in the research is made together with their complete description. Finally, the thesis ends with a list of REFERENCES which contains 404 cited titles (articles, books, and web pages) and a list of 7 Annexes including details of the different research phases and my CV with the publications list.

The research results we disseminated in 18 articles published in international conferences' proceedings and journals, from which 1 in ISI journal, 6 in ISI proceedings and 7 BDI index papers. All the articles were published during the PhD programme (2017 – 2020) the complete list of them being included in the Annex 7.

2. The Original Contributions of the Research

The original contributions are reflected by the *research results achieved* in different stages of the PhD programme and that were included in the PhD thesis as following:

- The analysis and synthesis of the main and relevant references in the field of supply chain management and the ways in which the business is developing with the advent of the Industry 4.0 paradigm to better meet customer needs and expectations (similar with a state-of-the art in the field) - Chapter 2;
- Application of ergonomics approach and principles within the field of warehouse logistics. The split was made between physical and mental workloads and it concluded that the current level of ergonomic knowledge and application in warehouses is minimal, that worker health and safety are not seen as anything more than legal compliance topics - Chapter 2;
- Providing Industry 4.0 ergonomic solutions; they were presented and categorized in solutions that monitor the worker and solutions that improve the worker's job by making it more ergonomic - Chapter 2;
- Diagnosis and analysis of the supply chain environment related to the case study company (the research context definition with details on the process flow). The warehouse environment was audited and presented in detail, noting the particularities of the related industry - Chapter 3;
- Design and implementation of four preliminary studies within the company's premises (research results being published in important articles):
 - Engineering responsibility in ergonomics design;
 - Kanban rack weight distribution and its ergonomic implications;
 - Cycle time of Kanban bin filling;
 - Fitbit usability and data gathering capabilities.

These preliminary researches enabled a better understanding of the ergonomic gaps within the company's processes and assessed the possibility of applying Industry 4.0 solutions in the company's warehousing reality - Chapter 3;

- Development of an *ergonomic approach based on an efficiency formula* used to analyse the ergonomic benefits of the automation and Industry 4.0 improvements (together with the identification of company improvement possibilities based on the initial diagnosis, audit) - Chapter 4;

- Designing of the *Ergonomics Maturity Model* and an associated software tool to support the practical exploitation of the created model. The tool offers the user a guiding line through the process of understanding their current ergonomic standing, the points they should strive to improve and the time and effort it would take them to complete such an improvement. This is the main theoretical contribution to the mass of research – Chapter 5;
- Analysis of the legal environment in the EU and Belgium and how this may contribute and impact the industrial level application of worker monitoring wearable computers– Chapter 5.

Different research approaches with the related results have been the subject of several *dissemination activities* (followed by a peer review process). Thus, 18 articles were published in international conferences' proceedings and journals, from which 1 in ISI journal, 6 in ISI proceedings and 7 BDI index papers. All the articles were published in the period 2017 – 2020 and the complete list of them can be seen in the Annex 7 of the present PhD thesis.

Finally, there have been considered the original *contribution and exploitation of these research results for didactical purposes*, mainly for the *Occupational Health and Safety* subject of study in the context of the master program, Engineering and Management for Competitiveness and Quality (developed at Politehnica University of Timisoara, Faculty of Management in Production and Transportation, since the academic year 2019-2020).

3. The research limits

The current PhD thesis was based on the practical research done in a low volume, high complexity assembly plant in Belgium. The project chosen specifically for analysis was in the start-up phase, meaning that the parameters measured during the analysis may not be fully representative of a serial production environment, which is the more common state of a project. Future research should repeat the measurements in a serial production environment. Furthermore, additional studies with more participants would improve the validity of the results.

Due to the high amount of improvements that needed to be done to the company's ergonomic state, and the limited amount of time available for the PhD research, it was not possible to repeat the initial measurement in an improved environment to see how and if this environment improves for the workers and allows for more efficient utilization of Industry 4.0 investments to be made. This type of measurement should be repeated so that the efficiency of the improvement ideas can be assessed, and the course of the company's improvement journey could be corrected should they prove to not be efficient.

Each improvement possibility was analysed independently. That means that the interaction between applying various combinations of improvements is not clear. It should be researched to understand if the combinations increase each other's potency or if they are detrimental to one another.

The theoretical model and tool have only been applied to the case study factory. The validity of the concepts explained should be tested in multiple environments to assess their weaknesses and suggest possible improvements/modifications. On top of this the audit tool can be easily improved by moving the coding environment from VBA to a more visually capable language, thus offering a better user interface and experience to the utilizer. The current tool does not take into consideration the time, effort, and money necessary to improve a specific process. The tool would provide a lot more support to the user if this information were readily available, either benchmarked from the industry or calculated for each company based on the input the user

gives.

Finally, the legal framework analysis done for the possibility of applying data gathering technology at a European level would benefit from a cross country comparison, in order to understand the ways in which the EU legislation is being interpreted at a national level. This should be done in hopes of creating a cross European view on the points which every country agrees with and where national understanding of European legislation differs.

4. Ethical implications of the research

As the research dealt with the gathering of personal and medical data for scientific purposes it is necessary to state the ethical clearances that were done for the protection of the gathering and the processing of workers' data.

Firstly, the research was developed independently and impartially. The author was present in the factory premises on a consultant contract, with the specified goal of analyzing the AS-IS situation in the company's incoming logistics setup, from the procurement of the parts to the moment the pieces are delivered to the production line with the purpose of installation. The consultancy services ended with the delivery of the consultancy report, part of which was used with consent within this thesis.

The confidentiality of the participants was ensured by anonymizing data directly at the gathering site. The observation sheets and questionnaires used were not filled in with participants' names or any defining characteristics, opting instead for giving them ordinal numbering that cannot be traced back to the person who filled the information in.

The company's management was requested access to the company's workers in written format before any contact was taken with them. The participant to the survey and the questionnaire voluntarily answered the request for collaboration. All their responses were recorded under anonymity and only aggregate data is presented in the final thesis.

Informed consent was requested from the warehouse workers who wore the Fitbit™ tool and the data presented in the thesis and the consultancy report does not make mention of name or function.

The information gathered during the measuring campaigns was presented to the workers directly involved and insights were shared into how it was possible to utilize the same measurement equipment in their private lives as well, in order to change their lifestyle and health related behavior.

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