Proceedings of the Hamburg International Conference of Logistics (HICL) – 29

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Published in: Data science and innovation in supply chain management
Wolfgang Kersten, Thorsten Blecker and Christian M. Ringle (Eds.)
ISBN: 978-3-753123-46-2 , September 2020, epubli

A Procedural Model for Exoskeleton Implementation in Intralogistics

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Purpose: Exoskeletons are robotic devices worn on the human body which mechanically support the operator's muscle skeleton. This study answers the following research question: Given insights drawn from a comprehensive literature analysis and two case studies which concern success factors for deployment projects, how can a systematic procedural model be used to support exoskeleton implementations in intralogistics?
Methodology: This study follows the design-science research process developed by Peffers et al. (2006). The research gap was identified based on a systematic and comprehensive review of literature which reflects the current state of research. Insights gained via this process were compared with empirical data from pilot installations at two case companies: a Swedish market leader in the furniture industry and a leading German coatings manufacturer.
Findings: A procedural model was designed to systematically consider success factors for an implementation which involves (1) workplace context; (2) human context and exoskeleton selection; (3) economic context; (4) pilot testing, evaluation, and maintenance; (5) deployment and training; and (6) go-live and support. It addresses technical, commercial, and social domains. The latter is critical to success, as it ensures staff acceptance.
Originality: Exoskeletons can contribute to solving challenges such as demographic transitions and skills shortages in logistics. The procedural model closes a research gap from a scientific perspective and enables practitioners to exploit the potentials of successful exoskeleton introduction. Case studies in two different branches ensure practical relevance and significantly expand the state of research regarding the efficient achievement of implementation goals.

First received: 6. Mar 2020 Revised: 20. Jun 2020 Accepted: 26. Jun 2020

1 Introduction

Intralogistics refers to planning and controlling the flow of goods within a company site, such as a plant or distribution center (Arnold, 2007). Three prime factors pave the way for the dissemination of exoskeletons in this domain. First, demographic changes are leading to labour shortages (Garloff and Wapler, 2016; Sahashi et al., 2018). Second, monotonous, repetitive movements and postural stress result in musculoskeletal disorders among workers, thereby causing 22% of all sick days in Germany (Meyer et al., 2019). Third, the proportion of manual work in intralogistics is relatively high in many companies. On the one hand, there is a trend towards the automation of processes and workplaces (Mikušová et al., 2017). On the other hand, not all human work can be easily replaced with technology if the space is limited or the job requires complex gestures, precise gripping or dexterity (Dahmen et al., 2018a; Sylla et al., 2014). Moreover, the costs of automation solutions are often prohibitively high compared to the costs associated with human workers (Bogue, 2018).

As ergonomic-assistance systems, industrial exoskeletons provide a way to improve both ergonomics and work performance. Exoskeletons are mechanical structures which are worn on the human body to support the user’s muscle skeleton for certain movements and postures, thereby addressing ergonomic needs for the upper and lower extremities and/or the trunk (Bogue, 2018; De Looze et al., 2016; Fox et al., 2019) while performing tasks such as lifting and carrying goods. Exoskeletons are associated with potential ergonomic benefits for workers such as enhanced strength and endurance (Bogue, 2018), reduced physical strain and stress (Butler, 2016;

Fox et al., 2019; Hensel and Keil, 2018), decreased disorders of the musculoskeletal system and other occupational injuries. Thus, exoskeletons can result in a reduction of employee sick days (Schmidtler et al., 2015; Sylla et al., 2014). Exoskeletons can help employees who have physical limitations and are in the process of inclusion or occupational reintegration (Hensel and Keil, 2018).

From a business perspective, such improvements imply increased productivity (Butler, 2016; Schmidtler et al., 2015), lower costs (Bogue, 2018; Dahmen et al., 2018a; Todorovic et al., 2018), higher quality (Butler, 2016; Dahmen et al., 2018a; Spada et al., 2017; Todorovic et al., 2018) and greater flexibility (Constantinescu et al., 2015). However, the level of dissemination in companies is relatively low (ABI Research, 2019). To date, there is no tested procedural model which can help practitioners implement exoskeletons in intralogistical processes.

The research question of this study can be summarized as follows: Given insights drawn from a comprehensive literature analysis and two case studies which concern success factors for deployment projects, how can a systematic procedural model be used to support exoskeleton implementations in intralogistics?

The following section provides an overview regarding the state of the research from which the research gap can be derived. Next, Section 3 spells out the research methodology. Subsequently, sections 4 through 7 follow the phases of the design-science research process. In the concluding section, the findings of this study are summarized and implications for research and practice are discussed.

2 State of the field and the research gap

To sharpen the research agenda, the current state of research had to be determined by an extensive literature review following the framework by Vom Brocke et al. (2009). Relevance is enhanced by avoiding repeated analysis of what is already known (Baker, 2000), and rigor is derived from an effective use of the existing knowledge base (Hevner et al., 2004). A preliminary evaluation of article titles and abstracts reduced the number of publications from 3,248 from 10 databases to a sample of 54 articles based on the following criteria: currency, relevance, authority, accuracy, and purpose. To ensure the high quality of the sources, the focus was placed on publications in scholarly journals and proceedings of conferences.

Many papers examine the influence of exoskeletons on workplace ergonomics, often with a narrow scope of specific application scenarios: e.g., working overhead or supporting particular body parts with a specific exoskeleton type (Baltrusch et al., 2018; Bosch et al., 2016; Butler, 2016; Ebrahimi, 2017; Graham et al., 2009; Picchiotti et al., 2019; Poon et al., 2019; Rashedi et al., 2014; Rogge et al., 2017; Schmidtler et al., 2015; Steinhilber et al., 2018; Sylla et al., 2014). Studies in the industrial context mainly address assembly tasks in manufacturing (Fox et al., 2019; Staub and Anderson, 2019; Sylla et al., 2014)—in particular, in the automotive industry (Constantinescu et al., 2015; Dahmen et al., 2018a; Hyun et al., 2019; Spada et al., 2017). In contrast, exoskeletons in intralogistics is an applied research area that has received relatively little attention in the literature (Hensel and Keil, 2018; Schmidtler et al., 2015; Winter et al., 2019). Few studies focus on the economic implications of utilizing industrial exoskeletons (Dahmen et al., 2018a; Schmidtler et al., 2015; Todorovic et al., 2018).

The available studies are very heterogeneous in terms of research methods and the empirical database, so that the results are not strictly comparable. Research is often limited to general-level analysis (Todorovic et al., 2018) and case studies (Butler, 2016; Steinhilber et al., 2018; Sylla et al., 2014). Due to a low number of test persons and laboratory conditions, the findings of many empirical studies do not go beyond a proof of concept (Hensel and Keil, 2018). Some findings are documented in the form of single (experimental) case studies (Butler, 2016; Sylla et al., 2014), which cannot be used for a valid induction because of their limited sample scope. In addition, their constructs and indicators are often not sufficiently validated. However, such studies are essential to determining cause-effect relationships in a scientifically accurate manner. Dahmen et al. (2018a) present a holistic-planning method for exoskeleton implementation in manufacturing which is based on a set of assessments. Hensel and Keil (2018) provide hints for implementation in industrial practice. However, there is no comprehensive, generalizable procedural model in the literature which considers intralogistics requirements.

The issues can be summarized as follows: There is no holistic procedural model for implementing exoskeletons in intralogistics. Structured information about the success factors of exoskeleton deployment is weak. For practitioners, it is difficult to understand how investments in exoskeletons contribute to value creation. Accordingly, two research questions were addressed:

RQ1: Given the success factors identified in literature, how can a systematic procedural model be used to structure the implementation process for exoskeletons in intralogistics?

RQ2: Which goals should be pursued with which methods in each phase of the procedural model to increase the probability of success of an exoskeleton-implementation project?

3 Research methodology

Design science provides a suitable methodological framework for construction-oriented research projects (Zelewski, 2007). This study follows the design-science research process presented by Peffers et al. (2006), which is comprised of six steps: problem identification and motivation, objectives for a solution, design and development, evaluation, and communication (see Figure 1). The methodology is oriented towards Peffers et al. (2006) and the guidelines of Hevner et al. (2004). While the procedure of Peffers et al. (2006) describes the research logic of a design-science approach, the recommendations of Hevner et al. have become established in the publication practice for documentation of the scientific nature of such an approach (Zelewski, 2007).

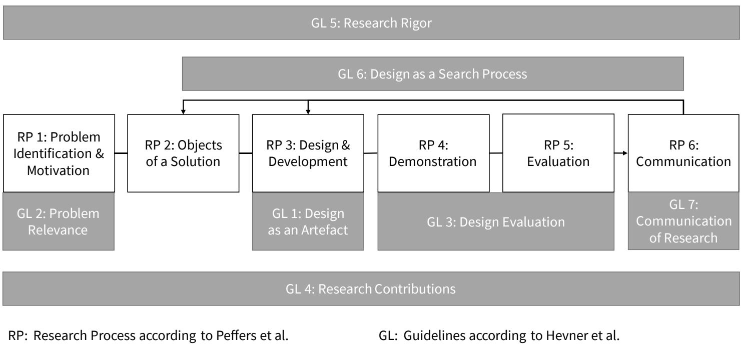

Figure 1: Design-science research process and guidelines, following Zellner (2015).

First, to capture and analyze the state-of-the-research completely, systematically, and comprehensibly, the research gap was identified based on a comprehensive literature review, following Vom Brocke et al. (2009). Second, the findings were compared with insights gained from two case companies. Two research objectives were pursued. On the one hand, a qualitative-explorative goal was achieved: the capture of subjective assessments and interpretation patterns with which to compare the situation-specific contextual conditions. Semi-structured interviews and questionnaires were used to identify the individual perspectives and patterns that are lost in the variances of quantitative group studies. On the other hand, the goal of empirically validating the theoretical findings was pursued: Case studies have a validating function when theory-based research hypotheses are compared with the results of the case evaluation. Because they are used to identify industry specifics, the case studies comprise pilot implementations at a German coatings manufacturer and a leading Swedish company in the furniture industry. The artifactual solution developed in this study is a procedural model for the implementation of exoskeletons in intralogistics. A procedural model is a representation of the activities to be carried out within the framework of an overall task (Schütte, 1998).

4 Problem identification and motivation

There is no holistic procedural model available in the literature for guiding practitioners in implementing exoskeletons in intralogistics processes (see Section 2). This lack may lead to a higher risk of poor decisions, avoidable costs, and excessively long project duration. Moreover, it is difficult for practitioners to understand in detail how investments in exoskeletons contribute to improvements in productivity and quality and to decreasing disorders of the musculoskeletal system. A procedural model in the form of a standardized process would structure the fulfilment of the overall task so that progress can be tracked and documented during the implementation project. Moreover, such a procedural model could promote a common understanding of the process and cross-functional cooperation between the departments involved.

5 Objectives for a solution

The first objective is to concisely identify the main impacts of exoskeletons in intralogistics processes. The second aim is to help companies implement exoskeleton solutions. Therefore, this paper develops a procedural model for systematically structuring the deployment process. In the procedural model, the overall task is divided into modular activities and is structured systematically in a logical and chronological sequence (Schütte, 1998). In this respect, a procedural model represents the essential elements of a process (e.g., activities, tools) and the mapping of their interrelationships. It reduces the risk of wrong decisions which might otherwise result in unnecessarily high project costs and project duration and a suboptimal solution in operations. Motivation of project participants increases as they understand the benefits of exoskeletons. The bundling of success factors from the literature analysis and empirical data streamlines the implementation of the best possible solution.

6 Design and development

6.1 Overview

A model is a simplified representation of a complex system whereby the real world is represented in terms of elementary levels and laws (Adam, 1997). The object—the implementation process of an exoskeleton solution—is systematically described in a model to create important properties comparable to real counterparts (Börner et al., 2012). The artifact to be designed is a procedural model: a systematic framework for the temporal and logical structuring of the activities to be performed within an exoskeleton implementation. The following section describes the design principles applied. The succeeding sections outline the overall set-up of the procedural model and describe its individual phases in detail.

6.2 Design principles

Modeling is a design process in which designers build a model according to a user's needs (Vom Brocke, 2007). The model should be suitable as a guideline whereby practitioners can facilitate exoskeleton deployment in the application domain of intralogistics. The target group comprises project managers and team members of exoskeleton-deployment projects and logistics-process owners. The prerequisites for applicability by such users include comprehensibility, simple applicability, and practical relevance. The quality of a model shall be ensured by following the principles of proper modelling (Becker et al., 1995).

6.3 Procedural model

6.3.1 Overview

The procedural model comprises six phases: (1) workplace context; (2) human context and exoskeleton-type selection; (3) economic context; (4) pilot-testing, evaluation, and maintenance; (5) deployment and training; and (6) go-live and support (see Figure 2).

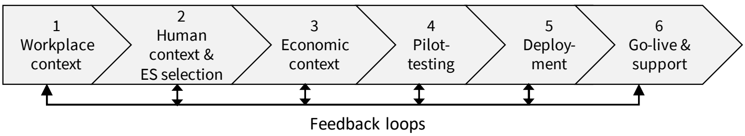

Figure 2: Procedural model for exoskeleton implementation in intralogistics

An exoskeleton implementation aims at increasing economic efficiency while reducing physical stress for workers. Its benefits, measured in terms of ergonomics and improved work performance, are jointly determined by a number of factors. Some of these factors are interdependent, so they should be determined simultaneously. To make the model manageable for practitioners, these interdependencies are partly fragmented. Thus, iterative solutions or recursions are required at some points in the procedural model. For example, a workplace limits the selection of a potential exoskeleton. However, there may be also restrictions with regards to exoskeleton selection due to the physical characteristics of individual workers. Figure 3 presents an overview of the contextual factors and key interdependencies addressed in the following sections. Outcomes per phase will be looped back to preceding phases to optimize the configuration of the human-machine interface (HMI).

Ergonomists, company physicians, occupational safety persons, work councilors and above all affected workers and supervisors should be involved in the selection, piloting and roll-out of the exoskeletons at an early stage (Hensel and Keil, 2018; Rogge et al., 2017).

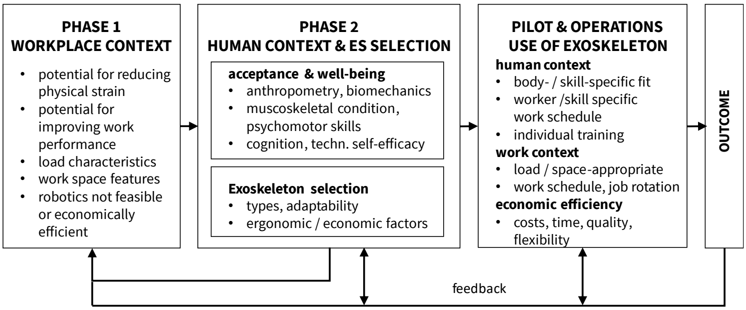

Figure 3: Overview of selected contextual factors and their interdependencies

6.3.2 Phase 1: workplace context

The context for exoskeleton use is determined both by the activities of a workplace and by the individual characteristics of its workers. The objective of the first phase is to pre-select suitable workplaces. The human context—i.e., the individual requirements a worker has for an exoskeleton—are addressed in Phase 2.

There are a large number of "paper and pencil" methods for the ergonomic assessment and categorization of workplaces. These include EAWS (European Assembly Worksheet) and OCRA (Occupational Repetitive Actions), which are used to analyze loads, postures, and/or repetitions in a process (Daub, 2017). Against the background of their inaccuracy, biomechanical measurements based on kinematics and kinetics data are preferable. Electromyography measurements provide information about which muscle areas are particularly stressed (Sahashi et al., 2018).

The following criteria point to the potential suitability of a workplace for the use of an exoskeleton and can be utilized as a pragmatic quick check:

1. There are (monotonous, repetitive) movements or postures which cause physical strain of workers, e. g., while lifting or lowering heavy loads (Dahmen et al., 2018b; Daub, 2017; Winter et al., 2019), and there is a potential for improving ergonomics. Sufficient space for working with the exoskeletons is available.
2. Load characteristics—such as the shape, weight, and kind of goods to be handled—are suitable (Fox et al., 2019).
3. Safety-related legal and occupational requirements can be met (Dahmen et al., 2018b).
4. The potential exists for improving work performance with respect to time, costs, flexibility, or quality (Dahmen et al., 2018a; Todorovic et al., 2018). There are few occasions for walking long distances, thus compensating the positive impact on economic efficiency (Fox et al., 2019). The cost of alternative robotics solutions is too high (Sylla et al., 2014).
5. Operation is not suitable for robotics in terms of feasibility, speed or flexibility. For example, activities require complex gestures, precise gripping, dexterity or sensory inputs, or the available space is limited (Dahmen et al., 2018a; Fox et al., 2019; Sylla et al., 2014). Wide and frequent variations of activities and goods to be handled are caused by uncertain demand and dynamic customer requirements.

6.3.3 Phase 2: human context and exoskeleton type selection

On one hand, the ergonomic parameters of exoskeleton use are to be set so that the physical strain on workers is reduced. Exoskeletons should help staff work safely and ergonomically, reducing fatigue and stress. On the other hand, work performance should be improved with respect to economic efficiency (see Phase 3). Both improvements result from a variety of partly interdependent factors. Besides the workplace requirements (Phase 1), the task-specific selection of an adequate exoskeleton type and the individual characteristics of a worker determine the success of exoskeleton operations. In what follows, the selection criteria for exoskeleton types are outlined first; then the worker-specific criteria are presented.

A variety of exoskeleton types exist. Fox et al. (2019) have identified eight different types, which are categorized in terms of the body part assisted, sources of support, and sources of power. Daub (2017) provides common classifications (following Bai and Christensen, 2017; Bosch et al., 2016; Bueno et al., 2016; Lee et al., 2012; Rogge et al., 2016):

a) Application: rehabilitation, assistive robots, human amplifier, combined use.

b) Human body part being supported: limbs, trunk, or the whole body.

c) Effect mechanism (deviating from Daub, 2017): (1) passive, (2) active, and (3) hybrid exoskeletons. (1) Passive exoskeletons support the wearer by means of mechanical aids, such as a spring or cable, which absorb any loads which occur like a counterweight and thus convert them into energy to support a posture or a motion (Fox et al., 2019). (2) Active exoskeletons (wearable robotics) also provide external-force support via sensors and ac-

tuators such as electric motors or pneumatic systems. (3) Hybrid exoskeletons are active exoskeletons that are controlled by nerve signals and bioelectric sensors (Stewart et al., 2017).
d) Power-transmission methods: gear drive, cable drive, linkage mechanism or other.
e) Alignment of the degree of freedom between human and robotic joints: anthropomorphic vs. quasi-anthropomorphic and non-anthropomorphic.
f) Control methods and sensor infrastructure: cognitive human-robot interaction, wherein the interaction occurs via human cognitive processes versus (physical human-robot interaction, which involves physical interaction.
The critical movements or postures identified in Phase 1 should be assisted by the exoskeletons. Exoskeletons usually support specific regions of the body, such that the concrete-load situation and the affected physical-constriction areas ultimately determine the selection of the system. The factors mentioned in Phase 1, the "workplace context", should be assessed in conjunction with a specific exoskeleton (e.g., whether escape routes can be used when wearing the exoskeletons). The ease with which an exoskeleton can be put on and taken off should also be checked (change-over time, see Phase 3). Dahmen and Constantinescu (2020) present a scoring-based model for preselecting a suitable exoskeleton for a specific workplace.
When selecting an exoskeleton, the risks of its use must also be considered. Rigid systems that support specific body parts restrict and weaken other parts (Daub, 2017). The worker who operates in an exoskeleton has a limited degree of freedom and movability (Schmidtler et al., 2015). Heavy and motion-limiting exoskeletons in particular reduce the ability to cover long distances (Fox et al., 2019). Accordingly, the weight and dimensions of the exoskeleton are another selection criterion. The physical strain on workers

might be high, as workers suffer from load shifts to different parts of the body. So far, there are hardly any reliable findings from longitudinal studies in occupational science regarding the possibly negative long-term consequences of exoskeleton use (Hensel and Keil, 2018; Steinhilber et al., 2018). This research gap results in ergonomic and legal risks that are difficult to assess.

Besides the activities at a specific workplace (Phase 1) and the selection of an adequate exoskeleton type to support a particular task, the fit to the characteristics of an individual worker also determines the success of applying an exoskeleton. On the one hand, *success* refers to human acceptance and well-being achieved by reducing physical strain. On the other hand, success is determined by improving work performance with respect to time, costs, or quality. The factors of the human context are comprised of a workers' individual anthropometry, biomechanics, musculoskeletal condition, psychomotor skills, plus the cognition and self-confidence needed to cope with the new technology (Fox et al., 2019; Schmidtler et al., 2015; Sylla et al., 2014). These person-specific factors need to be considered when selecting (and if necessary, adapting) an exoskeleton type to ensure a sufficient fit between the individual characteristics of a worker, his or her workplace, and the task to be performed (Daub, 2017; Hensel and Keil, 2018). Since these factors—the workplace (and its tasks), the selection of an exoskeleton type (or its adaptation), and the characteristics of a worker—are strongly interdependent, the fit between them is ideally determined by IT-based simulations (Sylla et al., 2014; Constantinescu et al., 2016). If the technical means or skills are not available for this, the fit should be sought in iterative feedback cycles in real-life set-ups.

In the literature, human-exoskeleton interactions are generally evaluated by defining indices of performance for a specific application scenario (such as joint velocity) or by measuring interaction forces (Schmidtler et al. 2015; Sylla et al., 2014). Moreover, sensor data such as electromyographic measurements (EMG) and time-synchronized video recordings are also used (Winter et al., 2019). However, "soft" factors, such as subjective perceptions of discomfort, must be considered when evaluating exoskeleton scenarios, as these are key to increasing the workers' acceptance (Daub, 2017; Rogge et al., 2017; Winter et al., 2019) and thus constitute a critical success factor. In one case study, worker acceptance was severely affected by workplace bullying through condescending remarks regarding the presumed low performance and visual appearance of an exoskeleton system. Involving employees voluntarily from the beginning of the project and actively engaging them in shaping their work context (for example, by allowing them to review trial runs) promotes acceptance of the exoskeleton solution. The same applies to intuitive adjustment of the device to the individual body measurements.

6.3.4 Phase 3: economic context

Phase 3 addresses the evaluation of an investment in exoskeleton capabilities with regards to economic efficiency. Table 1 provides an overview of the potential factors to be considered for the analysis (Bogue, 2018; Butler, 2016; Dahmen et al., 2018a; Schmidtler et al., 2015; Todorovic et al., 2018). To ensure the value orientation of an exoskeleton investment, assessment of the economic impact should be based on the economic-value-added (EVA) concept, which is widely accepted as a financial metric for measuring value (Young and O'Byrne, 2001). The EVA shows how much value is added to the capital employed in each year of the forecast, thereby supporting a dynamic perspective. To ensure relevance for logistics operations, the EVA model should be based on the approach of Feldmann and Pumpe (2017).

6.3.5 Phase 4: pilot testing, evaluation and maintenance

Testing is a process of executing a system with the intent of finding errors or potentials for improvement. For an example, consider any activity which

Table 1: Potential factors for analyzing impacts on the economic efficiency

Impact area	Factors and assumed direction of effect
Time	(-) Decrease of cycle time for a task (higher throughput due to improved ergonomics, stable quality, higher motivation) (+) Increase of set-up time, e. g. for putting on and taking off the ES or battery charging of active ES (+) Increase of time needed for covering distances on foot
Costs one-time	(+) Acquisition costs or development costs for in-house development (+) Training (-) Integration of impaired workers
Costs ongoing	(+) Rental or license fees (+) Depreciation (+) Maintenance, repair (+) Storage (+) Energy (+) Space required (-) Sick days (-) Financial consequences associated with occupational injuries (-) Overtime
Flexibility	(+) Employability of worker and workplace (+) Capabilities with regards to variant diversity / work assignment
Quality	1. Process quality (+) Precision (+) Error prevention, embedded Poka Yoke (+) Stable workflow 2. Product quality (+) Degree of accuracy (+) Scratch protection

is aimed at evaluating an attribute or capability of a system to determine whether it performs as required (Mathur and Malik, 2010). A pilot setting should be used for initially testing, with regards to ergonomic and economic requirements, interactions between the workplace, the task to be performed, and the worker using the exoskeleton. First, the technical requirements of the solution with regards to the workplace context (Phase 1) and the exoskeleton ergonomics must be validated. At present, there are no standardized testing methods available (Rogge et al., 2017). A holistic assessment should combine subjective, biomechanical, and mechanical testing methods, thereby building on available orthopedic examination tools. Dahmen and Hefferle (2018) have identified 36 scientific-assessment methods. Hensel and Steinhilber (2018) see added value in the combined observations of laboratory and field studies. The authors propose a test cycle analogous to that used in software development, which is based on the advanced V-model by Mathur and Malik (2010), featuring unit, integration, system, user acceptance, and performance testing.

Second, the acceptance and well-being of the workers (Phase 2) must be ensured. For a successful implementation, practical aspects such as comfort, usability, security, and user acceptance should be considered (Hensel and Steinhilber, 2018). Due to inherent hazards to the health and safety of workers, a risk assessment based on the relevant guidelines and a declaration of conformity by the manufacturer is essential (Hensel and Keil, 2018). To assess the subjective perception of workers, Hensel and Keil (2018) recommend measuring strain relief, discomfort, usability, and user acceptance. Third, economic efficiency (Phase 3) must be evaluated by a profitability analysis.

On the one hand, an exoskeleton potentially reduces physical strain on workers. On the other hand, negative effects may also occur, which may restrict its applicability and acceptance. These may include (following cited in Fox et al., 2019) balance problems (Kim et al., 2018), friction and pressure at fixation and support points (Bosch et al., 2016; Huysamen et al., 2018; Rogge et al., 2017; Winter et al., 2019), or unpredictable loading (Picchiotti et al., 2019; Weston et al., 2018). Special attention should be given to usability and economic efficiency in workplaces which require that long distances be covered on foot (Winter et al., 2019).

The usability of the exoskeletons plays an important role in practical use, both in the execution of the supported activity and in secondary activities such as driving a forklift truck and donning and removing the exoskeleton. With decreasing usability and increasing discomfort, user acceptance decreases; thus, the probability of sustainable use also decreases. Some exoskeletons reach their limits when moving in confined spaces and overcoming distances on foot. Upper-body-supporting exoskeletons are often designed for only one activity such as lifting such that workers may feel uncomfortable and lack maneuverability when walking and sitting. In intralogistics, however, many workplaces are characterized by alternating activities.

Initial pilot testing and ongoing maintenance work together to achieve a high quality, reliable, and efficient solution. In addition to tasks like cleaning, maintenance involves modifying an existent exoskeleton system—which is comprised of the workplace, tasks, human workers, and exoskeletons—to correct faults and exploit potentials for improvement. For example, load carriers or routes may have to be adjusted or an exoskeleton tailored to fit the body of a specific worker, work plans are aligned with the skills of different workers, and confidence may be improved through task-specific job training (Fox et al., 2019). Iterative feedback loops must continuously convert the insights gained both from initial pilots and ongoing operations into improvements in ergonomic- and economic-target dimensions (see Figure 3).

6.3.6 Phase 5: deployment and training

Phase 5 encompasses deployment testing and training as the final activities of the implementation project before transition to the daily operation of the line organization. Deployment testing verifies that the correct system elements, functionalities, and procedures are defined and implemented in the operational environment (Mathur and Malik, 2010). Moreover, it assures that the responsible persons in the line organization are enabled to run, maintain, and support the system. Training is the process of learning the physical and cognitive skills needed to perform specific tasks in an exoskeleton work context, which include knowing safety instructions.

6.3.7 Phase 6: go-live and support

Phase 6 comprises the "go-live" and support. At go-live, the exoskeleton solution is formally available to workers in regular operations. A support plan outlines a detailed on-site support strategy for a solution’s "go-live" and post-"go-live" periods. It identifies the tasks and roles required to facilitate the exoskeleton solution, outlines the escalation process and issue resolution, and assigns staff to the support roles. Ongoing care and occupational health monitoring of exoskeleton users is essential (Daub, 2017). The risk of atrophic muscle diseases caused by using an orthosis over a long period of time and psychological effects due to stigmatization must be identified in a timely manner so that countermeasures can be taken (Hensel and Keil, 2018).

7 Demonstration and evaluation

To demonstrate and evaluate the efficacy of the artifact used to solve the problem, case studies were conducted at two companies: a Scandinavian market leader in the furniture industry and a leading German coatings manufacturer. The findings were integrated into the development of the procedural model such that the following description provides only a rough outline.

7.1 Use case 1: furniture industry

7.1.1 Situation

The first case company is a furniture-store chain with worldwide distribution networks. Pilot runs were conducted at a German distribution site. A broad spectrum of loads (in terms of dimensions, weights, and packaging variants) had to be handled. Loads packed in cartons or films weighed between 0.2 to 30 kg. The units' dimensions ranged from 20 mm (L) x 20 mm (B) x 10 mm (H) to a length of up to 2,500 mm and breadth/height of up to 1,000 mm.

The two application scenarios were manual-order picking processes for store replenishment and picking of customer orders, particularly focusing on the differences between a goods-to-person versus a person-to-goods set-up. The first case employed a goods-to-person picking scenario: An electric overhead rail conveyor (EORC) transports articles on loading units from a high-bay warehouse to stationary picking stations and—after the articles have been picked directly from the hangers of the EORC, as the source pallet—takes away the emptied loading units for downstream handling. To

reduce the grasp depth, the provisioning is arranged parallel to the long side of the loading units, thereby realizing a maximum grasp depth of 800 mm. The grasp height ranges from +500 mm to +1,650 mm. The entire process uses DIN EN 13698-1 flat pallets as loading units. At the end of the picking process, the target pallets are taken away to stationary staging points.
The second application scenario tested person-to-goods picking. The articles to be picked are available on stationary source pallets located at floor level and on the first tier of a racking system. In stand-on operations which use a horizontal order picker, the worker moves from one rack bay to the next to gather the items. The items are removed from the racks, either by first alighting from the horizontal order picker or by reaching over for them directly without dismounting. The target pallets are carried on the forks of the horizontal order picker. With the loading units stored in the racking systems with their narrow sides facing the aisles, the grasp depth can be as much as 1,500 mm and the grasp height between 0 mm (floor level) and +2,550 mm. The DIN EN 13698-1 flat pallets and overlong pallets orientated towards DIN EN 13698-1 are used as loading units.

7.1.2 Methodology

Active and passive exoskeletons were assessed regarding work performance and ergonomics—especially wearing comfort. Two field trials validated work processes in two-shift operations over a one-week period using seven experienced workers with an average age of 46. Following a participatory approach, the exoskeleton users provided subjective evaluations. To assess the subjective perception of workers, ratings of strain relief, discomfort, usability and user acceptance were taken following Hensel and

Keil (2018). The assessments were done via questionnaire-based surveys in cooperation with the workers' council.

7.1.3 Evaluation

The metric “order lines picked per time unit” served to evaluate the work performance of the picking process. No performance improvements were observed. On the contrary, in the second scenario, a slight reduction of performance was measured which resulted from the restricted freedom of movement on the horizontal order picker. After a short familiarization phase, the times required for putting on and taking off the exoskeletons could be reduced to just a few seconds without assistance. Increased flexibility was not observed. For the overhead grasping required in the second scenario with a grasp height of >1,800 mm, some workers reported that the exoskeleton was a hindrance.

The wearing comfort of the exoskeletons was generally described as not bothersome. However, sweating at the exoskeleton contact points with the body was frequently mentioned as a cause for discomfort. Ergonomic and healthcare parameters could not be analyzed due to the short observation period and the data-collection approach. Nevertheless, the majority of workers reported that their back muscles at the end of the shift did not feel strained. The influence of exoskeletons on motivation and workplace esteem was assessed positively.

7.2 Use case 2: coatings manufacturer

7.2.1 Situation

The second case company develops and produces coatings for the automotive industry and decorative paints. The pilot run took place in the finished-goods warehouse at the German headquarters. Its operations include pallet movements, picking of goods, packing of goods, and loading of trucks. The main handling unit is the industry pallet (1,200 mm x 1,000 mm, CP1). Intermediate bulk containers placed on pallets are also common. The loads analyzed were distinguished by the size and weight of the packaging units. The category "big packagings" was used for loads ranging from 10 to 35 kg. Typical load units include containers, barrels, hobbocks, drums, and cans. The process follows the principle of person-to-goods. Handling aids such as vacuum lifters help the workers with material handling. The category "small packagings" encompassed loads below 10 kg, while carton boxes comprising two units can have a total weight of up to 20 kg. For this load category, the goods-to-person principle is applied.

Three application scenarios were analyzed. The first scenario is a workplace for picking goods in which loads are lifted and carried from stored pallets at a picking platform following the goods-to-person principle. The units handled are cartons, cans, and boxes weighing from one to 10 kg. The main movements and postures were bending over, cutting straps, lifting the load, turning and placing the load on a conveyor belt. The second scenario is a workplace for packing goods from chutes to mixed pallets for outbound shipments. It deals with the same loads as above and follows the goods-to-person principle. The activities covered include taking the goods from the chute from a sideward position, turning towards the pallet, placing the goods on the pallet, wrapping the pallet in foil, and utilizing a forklift to move the pallet. The third workplace deals with packing goods according to airfreight requirements based on the person-to-goods-principle. Handling units include cartons, cans and hobbocks ranging from one to 20 kg. The workers have to walk from a packing table to a storage location, lift the goods to a pallet, pull the pallet close to the packing station with a lift truck, take the goods from the pallet, pick up a folded carton and unfold it, place the goods inside the carton and fill it with padding chips, and finally close and strap the carton before placing it in a staging area.

7.2.2 Methodology

An active exoskeleton was tested intensively for one day by four test persons. Six probands tested a passive exoskeleton over a period of two months. The test persons were experienced workers with an average age of 36. The subjective feedback of the test persons was obtained via semi-structured interviews.

7.2.3 Evaluation

All interviewees confirmed that exoskeletons support the physical handling of goods and increase the ergonomics in intralogistics operations, especially when bent forward during picking and packing. Participants suggest that back strain and associated pain are mitigated by the passive exoskeletons. In contrast, the active exoskeletons caused back pain in one test person due to its weight. The active exoskeletons limited the workers' mobility more than the passive exoskeletons due to the size and weight of the former. For the same reason, both exoskeletons were considered more suitable for use in workplaces which employ the goods-to-person principle. Particularly in the case of the person-to-goods set-up, the bulkier active exoskeleton was a hindrance in overcoming walking distances. The most frequently highlighted disadvantage of both exoskeleton types was its limited usability on the forklift truck. Moreover, the active exoskeletons could not be worn on an industrial truck due to the dimensions of the lateral mounted engines. Its applicability in workplaces with limited space was constrained for the same reason. Most test persons perceived the passive exoskeletons as easy to put on and comfortable to wear in terms of pressure points and friction. However, the heat development was widely perceived as disadvantageous. Two workers reported problems in adjusting the exoskeletons to their individual needs.

Operational staff plays a significant role in successfully deploying new technologies. Accordingly, the workers must be involved at an early stage. By bringing in ideas, defining requirements, and evaluating the performance, they are committed to sustainably using the solution. At both case companies, the workers appreciated the early integration and ongoing support. 75% of the test persons would like to integrate exoskeletons permanently into their processes. The majority of test persons expressed a desire for smaller, lighter, and tighter-fitting exoskeletons that are easier to put on and take off and do not restrict their movability—especially with regard to changing activities with fork-lift trucks, among others. However, most employees did not show any interest, as only 5% and 10% (for active exoskeletons and passive exoskeletons, respectively) of the regular staff in the finished-goods warehouse took part voluntarily. Potential reasons for this include anxiety regarding testing procedures, lack of pre-injuries, lack of knowledge about the exoskeleton's benefits, and fear of derogatory comments from fellow employees.

8 Communication

8.1 Conclusions

8.1.1 Principal conclusions

This paper aimed at supporting practitioners in deploying exoskeletons. It makes two contributions which address two gaps in the current literature. The first contribution is to provide a systematic procedural model with which to help intralogistics practitioners implement exoskeletons, given the insights provided by a comprehensive literature review and two case studies. This is relevant, as extant studies typically focus on specific exoskeleton types and application scenarios—mainly in manufacturing. The second contribution is to provide frameworks, methods, and success factors for each phase of the procedural model, thereby to increase the probability of success of an exoskeleton deployment. This is essential, as practitioners need simple and comprehensible guidelines if they are to succeed.

8.1.2 Implications for research

Due to their skills and flexibility, human workers will continue to be a success factor in the future of intralogistics. Exoskeleton solutions can contribute to solving current challenges in intralogistics such as demographic transitions and competitive pressures to increase productivity. This explorative study has pursued the goal of generating inductively derived findings and developing a new theoretical concept from them. This was accomplished based on a comprehensive literature review and two case studies. The result is the procedural model, which expands the state-of-research. However, some limitations of the presented model should be mentioned. The framework is to be interpreted in view of the specific context of a particular company and the particular goods analyzed. The cause-and-effect relationships between exoskeleton utilization and the business targets could not be quantified in monetary values. Detailed case studies which focus on a specific exoskeletons and industry are desirable, using the presented framework for systematic analysis.

There are various starting points for further developing the presented framework. On the one hand, gaps in the applied methods and concepts can be closed. On the other hand, new methods and concepts can be added. Potential extensions comprise a differentiation with regards to specific exoskeleton types and industry requirements. It is desirable to quantify the economic impacts for a specific intralogistics process. In addition, other target areas can be integrated into the model, such as motivational aspects or potential impacts on health costs for society. Potentially negative effects of exoskeleton use—e.g., with regard to psychological effects and the risk of atrophic muscle diseases when using an orthosis over a long period of time—should be identified through field studies and occupational physiology studies (Hensel and Keil, 2018).

Understanding how sensor data from exoskeletons can be aggregated on Internet-of-things platforms for drawing insights regarding the optimizing of ergonomics and work performance could promote the integration of exoskeletons into overall Industry 4.0 solutions (ABI Research, 2019). Moreover, we should consider whether the increased availability of robotics-as-a-service operating models (i.e., leasing robotic devices rather than purchasing the equipment) would lead to an increased dissemination of exoskeletons.

8.1.3 Implications for practioniers

Exoskeletons offer opportunities with which to address the challenges of mass customization, an ageing workforce, and cost pressures without investing in automation technology that is not yet fully capable of replacing the flexibility of human workers. The procedural model supports efficient exoskeleton implementation. It closes a relevant research gap, helping structured decision-making implement the most appropriate solution. Relevant guidelines and success factors are systematically explained to advise the practitioner on how to proceed. Pilot applications in two different branches ensure practical relevance. Expectations from a commercial perspective, such as increased efficiency, have not been confirmed in the case studies. In particular, the covering of long distances by employees may compensate for potential productivity advantages in picking processes.

Qualitative feedback from users and supervisors gave clear indications of the barriers to implementing technological innovations in practice. Implementing the technology alone is not enough; the social domain forms a critical basis for a successful exoskeleton implementation by ensuring acceptance by the staff. A structured change-management process with early employee involvement has proven to be a crucial step in ensuring sustainable success. When they are allowed to bring in ideas, define requirements, evaluate the performance and decide if the technology is beneficial or not, employees become committed to the future solution. A successful implementation of exoskeletons has the potential to prevent occupational injuries associated with physical stress and increase economic efficiency in intralogistics processes.

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