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A CAD-Based Tool to Support the Configuration of Parts Storage Shelving in Assembly Workstations †

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Abstract: The supply of parts to the workstations of assembly lines is a critical design and operational issue. Even if automation and collaborative robots are increasingly used in industry, human operators are frequently employed in manual parts picking and assembly. These are time-consuming activities asking to be efficiently performed at a high rate and for prolonged periods. Therefore, ergonomic analysis is necessary to reduce the risk of work-related musculoskeletal injuries due to biomechanical loads. Proper layout of shelves storing part containers along the production line, and the location of containers on the shelves, may improve picking efficiency and reduce biomechanical risk. Several manufacturing companies use computer-aided ergonomic tools to improve the study of manual production lines, racking, shelving, and workstations. The paper describes the development of a support tool to configure industrial light shelves for feeding the assembly lines. The approach includes the development of a knowledge base to support the geometrical configuration of the shelving and the ergonomic analysis based on the RULA method, considering the shelf's positions and the operator's postures. As a test case, the model has been used to evaluate the ergonomic score of the configured shelving based on a prescribed picking sequence. Results show that the proposed approach can help in comparing the goodness of candidate shelving layouts to improve the design of parts storage systems to reduce operators' workload and ergonomic risk.

Keywords: configuration; CAD-based tool; ergonomics; RULA; industrial shelving

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1. Introduction

The industry is going to be more and more automated and mechanized; however physical human work is still needed in many small-medium enterprises. Physical effort can produce disorders in the musculoskeletal system of the workers. Manual activities increase the risk of injury in case the workstations are not well-designed [1]. The relative risk assessment is an obligation from the point of view of laws and international standards [2]. Therefore, ergonomic analysis is an essential practice in every workplace to avoid Work-related Musculoskeletal Disorders (WMSD) and Work-related Musculoskeletal Injuries (WMSI), which refer to painful conditions affecting the muscles, tendons, and nerves. These injuries commonly arise within the workplace because of physical tasks performed during regular and repetitive work activities [3].

The feeding of assembly lines is a typical industrial activity that can employ human operators. This activity is an essential phase in the production of products. The feeding phase concerns the material handling from the warehouse and shelving to workstations [4]. Time and paths in the material handling should be improved to increase production efficiency and optimize the overall system. In the manufacturing industry, the material is often stored at the border of line in practical containers such as boxes placed on light shelves. The operator goes to the shelves to pick the required material according to the picking orders related to the production planning [5]. Proper box distribution may improve picking efficiency and reduce biomechanical risk for the operators.

Workstations and assembly lines require a detailed evaluation of the postures assumed by the operators to avoid biomechanical risks, job hazards, and possible injuries [6]. Therefore, several standardized methods for ergonomic assessment are proposed and discussed in the literature [7]. Commercial software tools can calculate ergonomic scores related to different postures [8]. The analysis can also include 3D virtual manikins with the definition of loads and postures [9]. The interaction between operators and the manufacturing environment can be virtually evaluated using a digital mock-up of the human body and simulating the manual tasks [10]. This approach can integrate with Virtual Reality-based tools to evaluate real-time postures and enhance the user-centered design of the ergonomic workstations [11].

Advanced CAD tools with manikin modeling can be used for evaluating the ergonomic risk of workstations and shelves [12]. However, this analysis is based on manikin modeling. The designer must evaluate each scenario by combining the load conditions with the geometrical layout of the workstations. Focusing on the ergonomic design of light shelving, there is a lack of optimization tools in the literature for supporting the shelf configurations and the positions of boxes.

This paper aims to develop a 3D CAD configuration tool specific for industrial light shelving by implementing a Knowledge Base (KB) to analyze the ergonomic impacts of the shelf layout considering box position and picking frequencies. For each box type and position, the postures of the operators are estimated by tables with data acquired from the observation. The Rapid Upper Limb Assessment (RULA) method is used for assessing the ergonomic risk related to each picking move from the configured shelf. A final ergonomic index is computed to evaluate the overall configured shelving with the adopted box positions.

The remainder of the paper consists of four sections. Section 2 introduces the state-of-the-art on work and ergonomic measurement. Section 3 describes and analyzes the methodological approach proposed. Section 4 reports a test case. Finally, conclusions are reported in Section 5.

2. Background Research

The design of assembly lines, workstations, and shelves is defined by factors such as work measurement and ergonomic analysis. In general, the workplace must guarantee the psychophysical well-being of man, safety, and performance [10]. These aspects must be evaluated before the assembly line is operative [13].

2.1. Work Measurement

Knowing the time required for manufacturing and assembling various parts or components, many parameters can be evaluated to optimize the manufacturing system such as the total labor cost associated with the product or service, the necessary number of workers or staff members, the appropriate type and capacity of equipment needed, and others. Accurately determining task durations offers valuable insights for effective planning, performance evaluation, and cost management in various organizational contexts [14].

Methods-Time Measurement (MTM) is a well-established approach utilized for planning and designing production systems. Originally based on time management, it proves to be highly beneficial in assessing workloads and optimizing production systems, both in advance and during ongoing production operations. This method uses predetermined times for designing work processes and involves analyzing, describing, structuring, and planning manual tasks through defined process modules. MTM serves various purposes, with its primary application in time management, where time values for manual processes are recorded and utilized for cost calculations, production control, and enumeration [15].

Adopting work measurement tools allows to design effective work cycles from the operator's efficiency and productivity perspective. However, the design of workstations must also consider the ergonomic impact on the operators. Therefore, the following sections deal with ergonomic methods and tools in the literature.

2.2. Ergonomic Methods

Several methods and approaches have been developed over the past few decades to investigate workplace risks as far as manual material handling is concerned. Some of the most used methods are RULA, Rapid Entire Body Assessment (REBA), Ovako Working posture Assessment System (OWAS), and National Institute of Occupational Safety and Health (NIOSH) lifting equation [16]. These methods are classified as observation-oriented because the ergonomic risk is evaluated by examining the operative postures, using direct observation, video, or photos. Some of them are reported in international standard such as ISO 11228 [17] and EN 1005 [18].

The RULA method, developed by Mc Atamney and Corlett of the University of Nottingham, is one of the most used in the literature. This method studies the analysis of the positions adopted by the upper limbs to generate a procedure by which an individual, with a relatively short training course, can evaluate a workstation [19]. As output, RULA generates a comprehensive score reflecting the overall importance of the body regions such as arms, shoulders, wrists, neck, trunk, and legs [20].

The RULA procedure identifies high-risk situations and provides actions to mitigate those risks. This method serves as a tool for checking postures requiring modifications and indicating the steps to be taken to minimize potential dangers. In brief, the RULA method has the following objectives:

- To establish a rapid screening system for workers prone to upper limb ailments.
- To identify muscle strain caused by working posture and exertion of force during work, including static or repetitive efforts.
- To provide immediate results that can be incorporated into a more comprehensive ergonomic assessment including epidemiological, physical, and mental aspects.

The application of the RULA method includes the record of the work postures during tasks, the score calculation, and the development of a scale of action levels that offers guidance on the level of risk involved. The score calculation is performed through precise tables and cards that attribute an overall score to a specific posture. If the final score is 1 or 2, the analyzed posture is acceptable. If the final score is 3 or 4, the analyzed posture must be placed under investigation because it could, over time, lead to injuries for the worker. Values greater than 5 are not acceptable.

Kee and Karwowski compared RULA, REBA, and OWAS methods by analyzing different working postures from various manufacturing industries such as iron and steel, electronics, automotive, etc. [27]. The RULA method tends to overestimate the postural loads, if compared with REBA and OWAS. This trend is confirmed for balanced postures, where the body weight is distributed on two legs and feet.

RULA and REBA are the most applied ergonomics methods because they consider each physical body part. Boulila used RULA and REBA to evaluate the ergonomic analysis in mechanical processing such as drilling, milling, and turning [32]. The differences between RULA and REBA were also analyzed by Hita-Gutiérrez et al. [28]. While REBA considers the position of the lower extremities of the worker, RULA simplifies the legs evaluation. The better or worse method to apply depends on the situation and resources. For example, OWAS is more adapted for evaluating postures adopted in a given task, considering frequencies and time [29]. Man-to-goods order-picking activities can be also evaluated using the OWAS method [30].

Another ergonomic index is the NIOSH lifting equation, specific for load handling [31]. This method assesses the risk of WMSD in repeated lifting tasks, considering seven factors such as load, horizontal lifting distance, vertical lifting height, vertical travel distance, asymmetry, duration of lifting period, and gripping [33]. However, the NIOSH lifting equation method is suitable where most of the time is spent on manual material handling.

In this paper, RULA is the method applied for the ergonomic analysis because it is a quick tool, used to evaluate repetitive movements. This method shows two limitations. The first one is a poor analysis of the leg's position. The second one is the limited evaluation related to the lifting load. However, these two limitations can be acceptable in the proposed test case, focused on the ergonomic design of single shelving, because picking levels do not require considerable leg effort; moreover, low loads are considered.

2.3. Ergonomics and Design

Different design approaches integrate ergonomic analysis to define and optimize space occupation in industrial environments. A lack of ergonomic evaluations of products, workplaces, or public facilities may cause discomfort or challenges for workers and users [21]. Digital human modeling (DHM) is an emerging approach that simulates human interaction with products or work environments in a virtual setting [22]. This virtual evaluation process is highly beneficial for developing user-centered products, as it allows the insertion of human factors principles during the early stages of design. DHM helps to reduce design time and enhances overall quality. It has found widespread application in various industries such as manufacturing, agriculture, healthcare, transportation, and aviation. On the other hand, ergonomic design can be also pursued using customized applications and knowledge-based tools that integrate know-how, formulas, and engineering tools.

The development of Knowledge-Based tools is widely used in engineering design to solve advanced modeling problems by customized rules and formulas. Generally, these tools are often plug-ins of commercial CAD software and enlarge the functionalities of the host system. The KB guides the definition of the geometrical dimensions by solving design rules, constraints, and functions. In ergonomic analysis, Knowledge-based tools can implement functionalities to support the designer when defining new products or manufacturing systems. Such tools can be implemented in C++ or Visual Basic. In [23], Otto et al. used Visual Basic to develop a tool for investigating the workplace design for order pickers that manually collect items from the shelves of a warehouse. Sanchez-Lite et al. [24] presented a postural assessment method, called the Novel Ergonomic Postural Assessment Method (NERPA), for supporting the design of product-process by integrating DHM and a 3D CAD software. Another tool was proposed by Di Angelo et al. [25] that presented a method for posture prediction of the upper trunk of video terminal (VDT) operators based on the integration of knowledge base, artificial neural network, and 3D scanner. In [26] Pavlovic-Veselinovic et al. studied the development of a computer-based expert system to identify ergonomic risks in different jobs. Their tool provides prevention advice through the formalization of expert knowledge. This system uses a knowledge base that considers symptoms, engaged body parts, work environment, work chair, work tools, and organization factors.

While work measurement and line balancing are issues related to production requirements, the ergonomic analysis mainly evaluates the postures. This analysis is essential in small and medium-sized enterprises where manual labor is predominant. Several methods are available for work measurement and ergonomic study. However, specific applications still require the development of customized tools, such as knowledge-based systems, for including ergonomic analysis in design.

The paper provides a CAD-based tool customized for the ergonomic design of shelving. The proposed tool compares different box positions providing an overall ergonomic index. Moreover, this approach can be integrated with a multi-objective optimization tool for searching the lower-risk configuration (future development). This approach can be reused with different CAD software; thus, it is not related to specific commercial tools.

3. Method

This section describes the methodological approach to support the ergonomic design of shelves for manually feeding the assembly lines (Figure 1). The input data consists of two different levels. The first level concerns the shelf parameters such as height, width, number of modules, and vertical levels. The second one concerns the data about the box list, such as the type and size of the boxes, box quantity, material picking frequencies, and content weight. As an assumption, the assignment between boxes and contents has been previously defined in the proposed research.

The Configuration tool for shelving is a CAD-based plug-in that interacts with Autodesk Inventor®. The application has been developed by Visual Basic programming language and includes rules and functions related to the RULA method for performing ergonomic evaluation (Ergonomic tool).

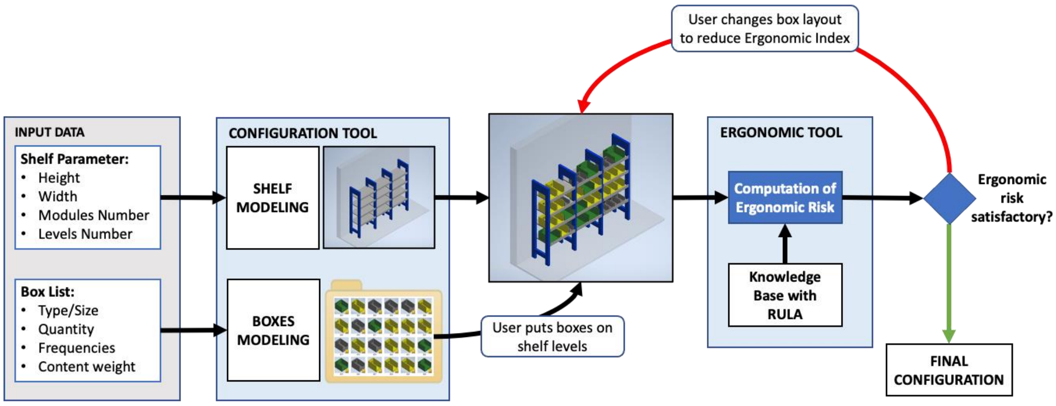

Figure 1. The methodological approach used for the ergonomic design of shelving, considering the impact of the box distribution.

The Configuration tool automatically generates the virtual CAD models of shelving and boxes using the user-defined geometrical parameters. The box CAD model contains data about type, quantity, picking frequencies, content weight, etc. Three box sizes have been analyzed in this research. The box classification is Small, Medium, and Large. Box classification and dimensions are reported in Table 1.

Table 1. Box classification and dimensions.

Type	Color	Width (mm)	Height (mm)	Depth (mm)
Small	Dark gray	150	125	230
Medium	Yellow	210	200	350
Large	Green	315	200	350

The first task of the Configuration tool is to support the geometrical modeling of the shelving and define the models of the boxes with data. The user interacts with the application to set the geometrical data related to the 3D CAD model of the shelving. At this level, the user must also define and place the boxes on the shelf levels to produce the virtual assembly of the complete shelving. The second task of the tool is to analyze the ergonomic impact related to the shelf (Computation of Ergonomic Risk), considering the box distribution and the related picking frequency (Ergonomic tool).

The ergonomic score of the shelving is calculated using a KB that implements postural information and RULA scores related to the height of the shelf levels and the size of the boxes. The posture position and angles related to arms, wrist, neck, trunk, and legs were previously acquired from the direct observation of some operators. This information is stored inside the Ergonomic tool through tables.

$$Shelving\ Ergonomic\ Score\ (SES) = \frac{\sum_{i=1}^{N} RULA_{Score(box,position)}{}_{box\_i} \times Frequency_{box\_i}}{Total\ Frequency} \quad (1)$$

The ergonomic score of the final shelving (SES) is calculated as an average RULA score weighted by the picking frequencies (min^{-1}), as reported in Equation (1). This score is evaluated using the traditional RULA table. If the final ergonomic is not acceptable, the user can manually redefine the boxes' position in the virtual assembly and recalculate the resultant score through the developed tool. This loop is "trial and error" because the user changes the positions of the boxes on the base of the computed ergonomic risk without using optimization algorithms.

4. Test Case

As a test case, the ergonomic study of a three-column shelving with four levels is proposed here. The geometrical dimensions of the shelving are 2450 mm (width), 2000 mm (height), and 500 mm (depth). The objective is to define the position of 35 boxes on this light shelving. The boxes contain materials for feeding an assembly line. The operator manually picks the material from the boxes. Each material is associated with a box; thus, a picking frequency (evaluated as min^{-1}) is assigned to each box. There are 8 Large boxes, 17 Medium, and 10 Small. The sum of the picking frequency of all boxes is 1.5 min^{-1} (total picking frequency), which means that there are 90 picks per hour in the analyzed shelving. The weight related to each picking is always under 1.5 kg.

Figure 2 describes two different box distributions related to the analyzed shelving. The user begins with the geometrical configuration of the shelf using the developed Configuration tool. Then, the user puts the box models into the virtual assembly of the shelf and uses the Ergonomic Tool for calculating the ergonomic index (SES). Figure 2a reports the first box configuration with an ergonomic index of 3.81 (SES). On the other hand, Figure 2b reports an improved distribution with a reduced ergonomic index, 3.23 SES. Even if the changes in the box distribution are manual, the Ergonomic tool automatically calculates the impact index and indicates the most impacting boxes, allowing different box distributions to be evaluated inside the CAD environment. However, shelving dimensions and picking frequencies can limit the improvement of the ergonomic optimization process.

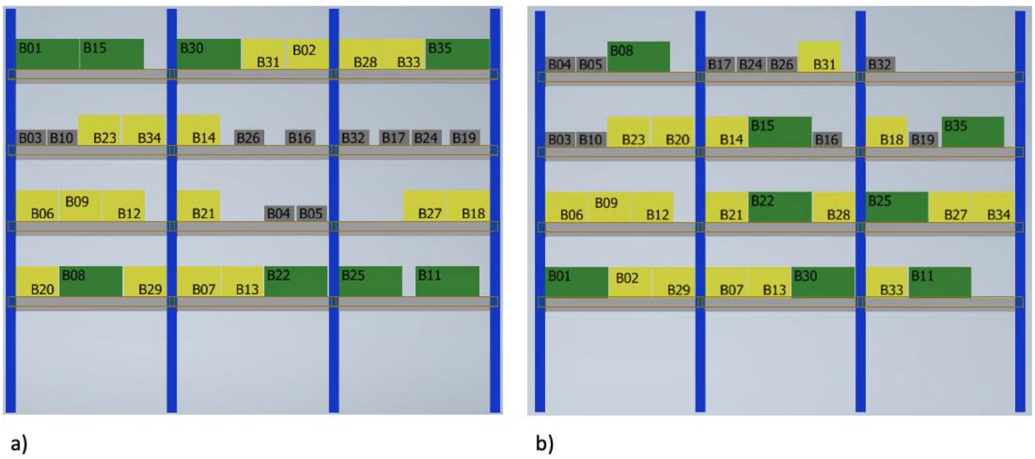

Figure 2. Different box distribution for the test case shelving: (**a**) the first box distribution with ergonomic index 3.81 (SES); (**b**) the improved box distribution with ergonomic index 3.23 (SES).

5. Conclusions

The proposed tool improves the ergonomic design of shelving and aims at reducing the risks of musculoskeletal disorders and injuries. The general scope of the proposed research is to implement a method to optimize the shelves' geometrical configuration and the box distribution considering the ergonomic analysis. Even if the test case is only based on the definition of the box distribution, the tool can also optimize the height of the vertical levels. Moreover, the shelving dimensions can be changed to enlarge the space to optimize the box distribution. Therefore, the paper only reports a part of the complete research, which is related to the 3D CAD configuration of the shelf and the relative ergonomic evaluation focused on the activity related to the material picking. The ergonomic analysis is performed using a KB tool which implements data for the evaluation of the RULA score.

As a future development, generative algorithms will be included in this approach to optimize the box distribution for reducing the ergonomic index. The improved version of the tool will optimize the number of levels per column and the height of each shelf level. A CAD generation tool could automatically model the shelving assembly with boxes. Moreover, the REBA, OWAS, and NIOSH lifting methods could be evaluated and compared with RULA.

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