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Enabling Concurrent Multi-Objective Optimization of Worker Well-Being and Productivity in DHM Tools

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Abstract. Work-related musculoskeletal disorders (WMSDs) are often associated with high costs for manufacturing companies and society, as well as negative effects on sustainable working life of workers. To both ensure workers' well-being and reduce the costs of WMSDs, it is important to consider worker well-being in the design and operations of production processes. To facilitate the simulation of humans in production and improve worker well-being, there are numerous digital human modelling (DHM) tools available on the market. Besides simulation of humans in production, there are numerous production simulation software to simulate production flows of factories, robots and workstations that offer the possibility of improving the productivity of the stations, optimizing the layout and the configuration of the production lines. Despite of the capabilities of DHM and production flow simulation software, there is a lack of tools that can handle an overall optimization perspective, where it is possible to concurrently treat aspects related to both worker well-being and productivity within one tool. This study presents a prescribed tool that enables concurrent multi-objective optimization of worker well-being and productivity in DHM tools by analyzing the impact of different design alternatives. The tool was assessed in a workstation layout optimization use case. In the use case, risk scores of an ergonomics evaluation method was used as a measure of well-being, and total walking distance and workstation area were used as measures of productivity. The results show that the optimized solutions improve both total walking distance, workstation area and ergonomic risk scores compared to the initial solution. This study suggests that the concurrent multi-objective optimization of worker well-being and productivity could generate more optimal solutions for industry and increase the likelihood for a sustainable working life of workers. Therefore, further studies in this field are claimed to be beneficial to industry, society and workers.

Keywords. Ergonomics, production, optimization, layout

1. Introduction

There is a constant strive in industry to reduce costs while keeping or increasing productivity and quality. In manual work, such as in manual assembly, work-related musculoskeletal disorders (WMSDs) are often associated with high costs for production companies [1]. European Agency for Safety and Health at Work estimates these costs to

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EU €476 billion a year [2]. Hence, in order to both ensure workers' well-being and reduce the costs of work-related musculoskeletal disorders (WMSDs), it is important to consider worker well-being in the design and operations of production processes. In production, workers typically perform tasks that can be strenuous, with the consequent risk of WMSDs. However, sometimes it is impossible or hard to replace or adapt specific tasks, either due to lack of means or the complexity of the task itself. This means that, despite aspiring to consider worker well-being, most of the time, there still will be some non-ergonomic tasks that are hard and/or expensive to resolve.

In the ongoing Industry 4.0 and Industry 5.0 trend, digitalization and automation are key factors. Automation can be used in factory plants and also in office areas for improving efficiency. Following the industrial trend, there is a need for increasing the automation level in simulation tools to reduce manual work. One of the technologies available to enhance planning and design of factories is simulation. To facilitate the simulation of humans in production and improve worker well-being, there are numerous digital human modelling (DHM) tools available on the market, such as Siemens Jack [3] and IPS IMMA [4]. Besides simulation of humans in production, there are numerous production simulation software to simulate production flows of factories, robots and workstations, such as FACTS Analyzer [5] and Siemens Tecnomatix Plant Simulation [6]. Production simulation software such as FACTS Analyzer usually offer the possibility of improving the productivity of the stations, optimizing the layout and the configuration of the production lines [7–9]. Previous studies have identified central elements of DHM tools and suggested structured processes for how to apply DHM tools in design and development processes [10–12] and considered these aspects at the design level of a workstation [13]. However, there is a lack of tools that can handle an overall optimization perspective, where it is possible to treat aspects related to both worker well-being and productivity within one tool. In order to handle the overall optimization perspective, a framework and a prototype has been developed, which is reported in [14,15]. However, the early prototype required a lot of manual work to set up and run optimizations, requiring also programming skills from the engineers using the tool.

In order to reduce the manual work required in DHM tool optimizations, this study presents a tool that enables concurrent optimization of worker well-being and productivity in DHM tools with the support of a wizard. The prescribed tool aims to help users to perform optimizations of worker well-being and productivity by reducing the quantity of manual work to set up the definition of optimizations in DHM tools and simplifying the task for engineers requiring no programming skills.

2. Method

A software-based tool is prescribed that enables concurrent optimization of worker well-being and productivity in DHM tools by helping the user with the support of a wizard. Following, the tool is tested in a use case of workstation layout optimization.

2.1. Optimization workflow

The tool follows the workflow of a multi-objective optimization framework of worker well-being and productivity reported in [15] (Figure 1). The optimization framework consist of these major sections: *Optimization definition, Model creation in DHM tool,* *Optimization process, Presentation of results in decision support tool*, and *Selection of solution.*

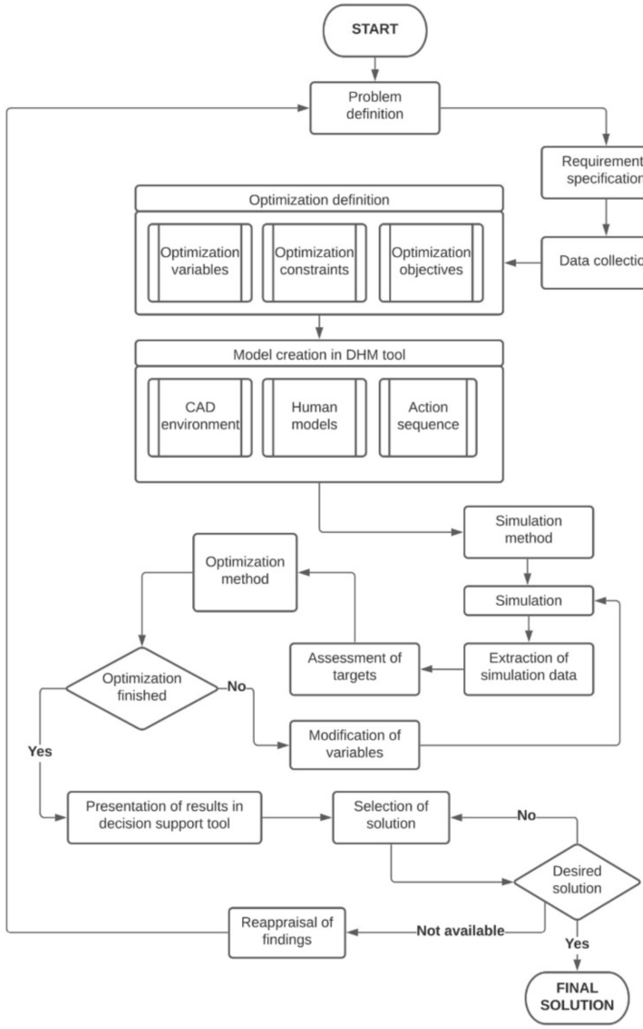

Figure 1. Framework of optimization in DHM tools [15]

2.2. Design and creation of the tool and communication with the DHM tool

The tool is standalone to enable communication with different DHM tools. The tool can communicate with DHM tools by using communication methods such as file transference and User Datagram (UDP) and Transmission Control (TCP) protocols. The aim of the tool is to gather information from the DHM tool and iteratively modify the model in the DHM tool to find more optimal solutions (i.e. non-dominated solutions) regarding both worker well-being and productivity. The tool can analyze the scene by measuring different objectives, such as the time to perform the tasks, the distances between the objects and manikin postures. In addition to that, the tool can analyze the collision between objects in the scene to validate the design solutions of the workstation.

The import of the data requires processing the posture data of the manikins in the DHM tool and recalculating the postures. This recalculation is necessary due to the difference in human skeleton model configurations between different DHM tools. To enable user interaction, the tool also includes a graphical interface developed with the C++ programming language based QT framework [16]. The graphical interface allows the user to communicate with the DHM tool to import the data of the scene.

The tool includes the measurement of both worker well-being and productivity metrics. To measure the worker well-being, the tool includes the ergonomics evaluation methods RULA (Rapid Upper Limb Assessment) [17] and REBA (Rapid Entire Body Assessment) [18] to evaluate worker well-being, in addition to a scripting interface that allows scripting additional ergonomics evaluation methods by the user. To measure productivity metrics, the tool allows using the time of the tasks and cycle time of the workstation, in addition to a scripting interface to add additional production metrics.

The tool was tested in a use case of a workstation layout optimization to check its usability and efficiency. The use case represented a pedal car assembly workstation at Scania Smart Factory Lab. The assembly involved a worker picking up parts and tools from several racks and assembling the parts in the pedal car by using the tools. The aim of the optimization was to locate the racks in order to reduce the cycle time of the workstation, total area occupation and the RULA risk score. For the use case, the tool was connected to the DHM tool IPS IMMA by using the LUA scripting interface available in IPS IMMA. An engineer from the industry set up the optimization, ran it and decided the solutions with the tool and support of the wizard.

3. Results

This section covers the results of following the optimization framework steps where the tool was used for the workstation layout optimization. The process was divided into two parts, the model creation and optimization definition, and the results of the optimization.

3.1. Model creation and optimization definition

To start with the optimization process, the first steps were the *Problem definition*, *Requirements specification* and *Data collection* (Figure 1). In this use case, the workstation consisted of the assembly of a pedal car performed by a worker. The tasks related to the workstation involved picking up parts of the pedal car from four racks and using tools to assemble them into the pedal car. The location of the racks and positioning of parts and tools in them affected both the time to perform the tasks and the walking distance of the worker. To analyze and optimize the location of the racks, a *DHM model was created* (Figure 1) in IPS IMMA. The scene included the geometries of the environment, pedal car, racks, tools and parts and the manikin and the assembly operations (Figure 2).

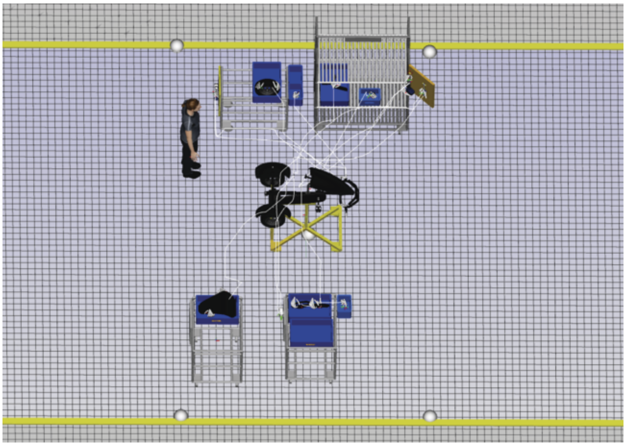

Figure 2. Workstation model in IPS IMMA

Before performing an optimization the workstation was analyzed in the tool. The tool allowed analyzing the initial configuration of the layout regarding the cycle time, area occupation and RULA risk scores for the assembly tasks (Figure 3).

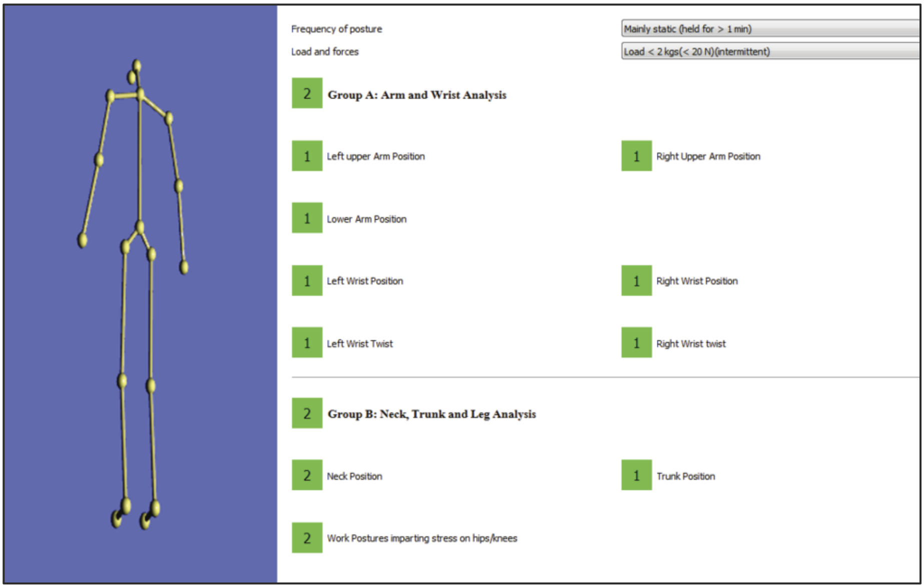

Figure 3. Manikin level analysis interface showing RULA results

After analyzing the scene, the next step was the *Optimization definition* (Figure 1). The use case was a layout optimization of the racks, therefore, the optimization variables in this use case corresponded to the *X* and *Y* coordinates of the racks that store the tools and parts to assemble in the pedal car. The coordinates of the four racks, $X_1 \ldots X_4$ and $Y_1 \ldots Y_4$, were the eight variables used for this optimization (Figure 4).

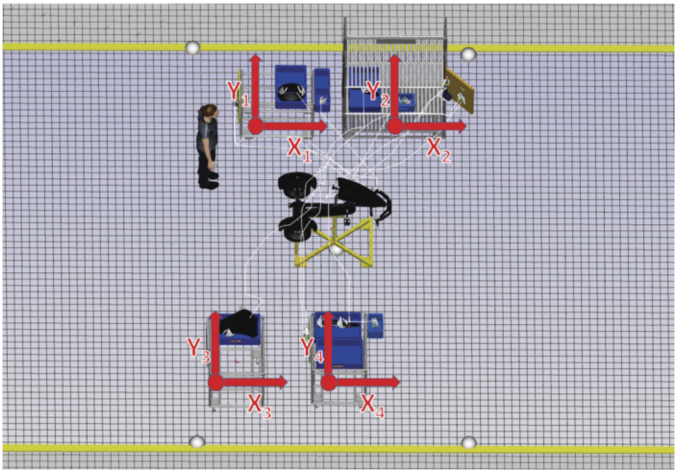

Figure 4. The coordinates of the four racks used as optimization variables

Once the variables were defined, the next step was to define the optimization objectives. In this use case, the total walking distance was used to both assess the worker well-being and productivity of the workstation. The ergonomics evaluation method RULA [17] was used as an optimization objective to assess the position of the manikin grasping parts and resources from the racks. In addition to that, the total area occupation of the workstation was used as an optimization objective. The optimization objectives could be created in the tool by selecting different levels of the scene and selecting to be minimized or maximized, being either integer or real numbers. For more complex objectives, i.e. walking distance and total area occupation, the objectives were scripted with JavaScript in the tool.

Optimization constraints were used to invalidate solutions that did not fulfil certain conditions. In order to avoid the collision between racks, a collision detection measure was used as a constraint. By using the collision detection measure as a constraint, when a solution given by the algorithm collided in the IPS IMMA scene, the solution was registered as an invalid solution. Invalid solutions were then avoided by the algorithm for the next iterations, reducing the number of iterations that created a collision in the scene.

The use of geometrical relations allowed to relate two or several objects in the scene to fulfil design conditions. In this case, geometrical relations were used to move together the racks with the resources located in them when the position of the racks changed.

The final step to define the optimization for the layout optimization use case was to set up the algorithm. In this case, the evolutionary algorithm NSGA-II [19] was used due to the possibility of setting up a multi-objective optimization. The iterations, crossover and mutation rates were choosing by testing the optimization with different values (Table 1).

Table 1. NSGA-II configuration

Setting	Value
Algorithm	NSGA-II
Iterations	6500
Crossover probability	0.9
Mutation rate	0.4
Child population size	150
Population size	150
Tournament size	2

Once the optimization was set up, the *Optimization process* (Figure 1) started. The communication with IPS IMMA started and the tool iteratively changed the scene by applying the values that the optimization algorithm provided for each optimization variable defined. The tool signalled IPS IMMA to rerun the simulations of the scene and export all the data from the scene to the tool to analyze it. The tool then calculated the optimization objectives defined (both normal and scripted objectives) and returned the values to the optimization algorithm. The optimization algorithm generated a solution space with the objective results and continued providing new values for optimization variables until the *optimization was finished* (Figure 1).

3.2. Results of the optimization

Once the optimization finished, the results were *presented in a decision support tool* (Figure 1), that allowed creating different plots and data visualization methods (Figure 5).

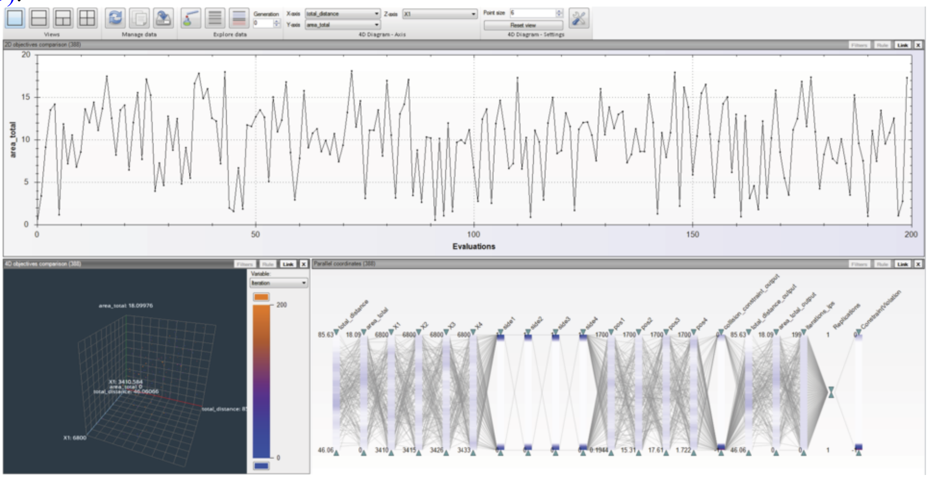

Figure 5. Decision support tool

The optimization was performed for 6500 iterations, however, 3062 iterations were invalid due to the collision between the racks. Once the iterations with collisions were filtered out, there were 3438 valid iterations without collision (Figure 6).

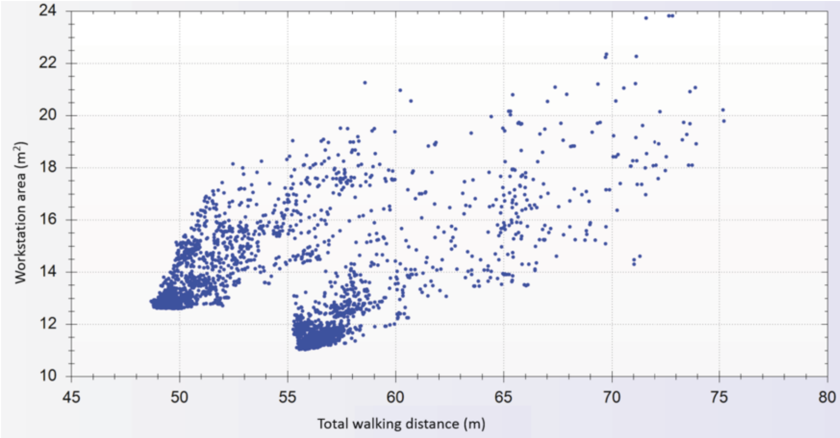

Figure 6. The 3438 valid iterations after filtering out iterations with collisions

After filtering the invalid solutions, the solutions could be sorted out by using non-dominated sorting, creating a Pareto front of optimal solutions. The valid solutions were then visualized in a 2D plot for the objectives of workstation area and total walking distance, while the objectives related to the RULA scores were represented by colouring the RULA scores of higher than 4 in red in order to avoid choosing solutions with a high risk of WMSDs (Figure 7).

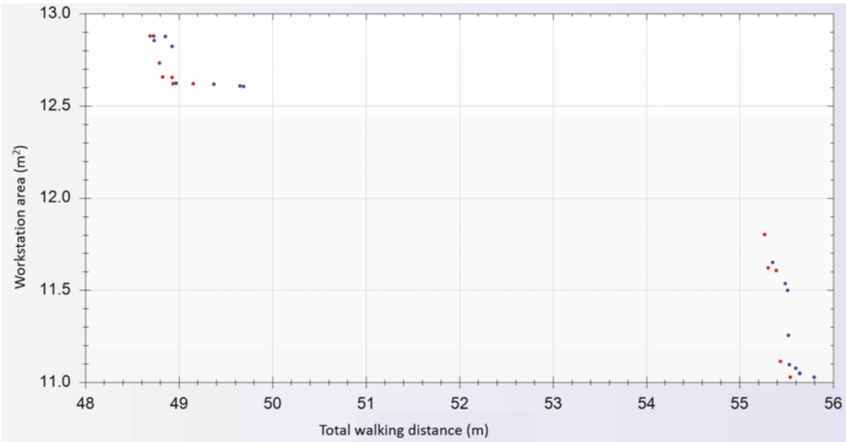

Figure 7. Pareto front solutions for workstation area and total walking distance with red-coloured high-risk WMSDs solutions

The Pareto front solutions represent the optimal solutions obtained in the optimization. If the initial workstation layout solution was compared with the minimum workstation area and minimum total walking distance solutions, the optimized solutions improved both objectives at the same time (Table 2).

Table 2. Initial solution comparison against Pareto front optimal solutions

Type of solution	Total walking distance (m)	Workstation area (m^2)	RULA score
Initial solution	59.9	17.4033	4
Minimum workstation area	55.8 (-6.9%)	11.03 (-36.6%)	3
Minimum walking distance	48.7 (-18.7%)	12.88 (-26%)	5

The minimum walking distance solution (Table 2) had a RULA score higher than 4, which RULA defines as a high risk of injuries, therefore, the solution was not chosen to avoid a high risk of WMSDs. In the next step, *Selection of the solution* (Figure 1), the chosen solution, in this case, was the one corresponding to a minimum workstation area. Once the solution was selected, the solution was loaded in IPS IMMA to compare it to the initial solution and to validate the layout of the workstation. The final solution shows that exchanging positions of the top racks and bottom rack, in addition to centering them, provided lower workstation are and walking distance results (Figure 8).

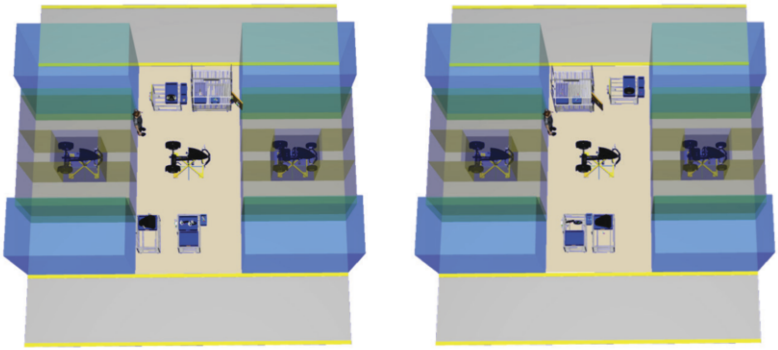

Figure 8. Initial solution (left) vs optimized solution (right) [14]

4. Discussion

The presented tool allows multi-objective optimizations of worker well-being and productivity and is capable to connect with various DHM tools. Using optimization algorithms to find optimized workstation designs allows the solution space to be explored by a strategic search through feasible solutions without manually processing each of all possible configurations. It is also possible to define constraints that will mark solutions as invalid. In this use case using collision detection between the racks eliminated 3062 solutions of 6500 where the racks collided, reducing the effort of the user on manually selecting valid solutions.

The results from applying the tool in the layout optimization case show that the tool can be used to enable concurrent optimization of well-being and productivity. The consideration of the total walking distance and workstation area together with the RULA scores allowed analysis of the impact of different designs of the layout. The results show that the optimized solutions improve both total walking distance, workstation area and RULA scores compared to the initial solution.

It is important to remember that observation-based methods such as RULA can result in overstated risk ratings in DHM tools, resulting in dramatic changes in risk ratings based on slight changes in joint angles when they are near the angle thresholds [20]. It is also crucial that the ergonomics evaluation method used is applicable to the type of work being carried out. RULA is an acceptable evaluation method in this study since it is commonly used to assess upper limb postures, and it provides integer values that can be used as optimization objectives by optimization algorithms. In future studies, the results could be improved by the use of time-based ergonomics evaluation methods and direct measurement methods with action levels [21], which would allow to assess the motion of the worker's more effectively.

The decision support tool helps users by providing graphical tools to find the most suitable solutions, such as 2D plots and parallel coordinate diagrams. In addition to that, the decision support tool allows adding filters to avoid extreme results, which in this case eliminated some of the Pareto front solutions due to the RULA scores being higher than 4.

The concurrent optimization of worker well-being and productivity could generate more optimal solutions for the industry and the life quality of the workers, therefore, further studies in this field could be very beneficial. Including more ergonomics evaluation methods, anthropometric diversity of workers and production metrics in workstation design, layout and line balancing optimizations could provide the industry with solutions that have not been explored yet. In addition to that, the development of tools that allow concurrent optimizations of worker well-being and productivity could enable the collaboration of production engineers and ergonomists in the search for more productive workstations that also improve the well-being of workers.

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