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Development and initial usability evaluation of a digital tool for simulation-based multi-objective optimization of productivity and worker well-being

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ABSTRACT

Engineers use modelling and simulation techniques to efficiently create, evaluate, and optimize design solutions. In an industrial production context, engineers often need to consider requirements related to both productivity and worker well-being in order to find successful design solutions. However, simulations related to productivity and worker well-being respectively, are typically carried out by different engineering roles, using different digital tools. This lack of integrated work procedure could lead to inefficient development processes and suboptimal design solutions. Additionally, since performing multi-objective optimizations is likely to be seen as a complicated task by engineers in areas such as design engineering, production engineering, and ergonomics, requiring specific knowledge and skills, such tasks are typically performed by engineers specialized on optimization. This paper presents the development and usability evaluation of a digital tool that supports engineers not specialized in optimization to define and perform simulation-based multi-objective optimizations of requirements related to both productivity and worker well-being in an automated and simultaneous manner. The digital tool is the result of research carried out over a period of four years, following an iterative development and assessment process by the means of use cases, done in close collaboration with potential users of the digital tool, i.e. engineers at several companies. The usability evaluation of the digital tool shows that potential users in the industry view the tool as a promising support for performing their engineering tasks in a more efficient and integrated manner.

1. Introduction

Modelling and simulation are used widely in industries such as the automotive industry because it enables efficient creation, testing, and optimization of the design of products and production systems in virtual worlds, rather than having to create, test, and optimize prototypes in the physical world [1,2,3,4]. Software that simulate humans working in production, commonly called digital human modelling (DHM) tools, enables assessment and optimization of worker well-being in regard to different workstation design alternatives, making it an essential tool to proactively ensure worker well-being when designing new production systems [5]. To optimize both productivity and worker well-being in the production development processes, e.g. when a workstation is not available in the real world, simulations of both human activities and production performance are required. However, simulations to optimize productivity and simulations to assess worker well-being are typically carried out by engineers with different roles. Production engineers typically address mainly productivity aspects, while ergonomists typically consider mainly worker well-being aspects. Hence, production engineers and ergonomists typically have different focuses and objectives, and use different tools [6]. Also, even though engineers of different professions are commonly experienced in the modelling and simulation tools they use every day, they cannot be assumed to be experts in the use of optimization for solving design tasks that cover aspects beyond their own field of specialisation. Therefore, performing simulation-based multi-objective optimizations of requirements related to both productivity and worker well-being is currently not common for engineers in areas such as design engineering, production engineering, and ergonomics. This lack of support tools for performing optimizations, in addition to using separate digital tools for simulation of productivity and worker well-being, could lead to inefficient development processes and suboptimal design solutions.

In recent studies, there are proposed methods for multi-objective optimization of productivity and worker well-being [7,8,9,10,11].

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There are examples of line balancing using energy expenditure models (i.e. models of human physical activity) that propose analytical and numerical approaches for line balancing [8]. There are also studies based on ergonomics risk indexes that aim to reduce the risk of work related injuries without decreasing production measures [12,13]. However, these studies consider a single approach simultaneously, either balancing or changing the design of a workstation, but they do not offer a solution that considers all the approaches at the same time. Also, these studies are punctual experiments, which do not offer a digital tool that implements these methodologies, integrating the solutions with DHM tools or production simulation tools.

Considering an overall production system optimization perspective, it is hypothesised that it should be possible to treat aspects related to both productivity and worker well-being within one method and, in turn, enable engineers to use one single digital tool. Due to this, a need and opportunity in this field of research is to explore and develop a method that concurrently considers requirements related to both productivity and worker well-being, and to implement the method in a digital tool so that both productivity and worker well-being can be optimized in an automated and simultaneous process. A previous study in this research project describes a framework to concurrently optimize productivity and worker well-being [14], applicable for both manual and automated simulation-based optimizations. In principle, all steps in that framework can be done manually, using appropriate software, e.g. DHM tools and/or production process simulation tools. Still, such a manual approach would be very time consuming and hence expensive. It is unlikely that engineers would perform hundreds or thousands of simulations in order to systematically identify the most successful solutions. In this paper, a digital tool to automate several steps of the framework is presented, with the aim to support engineers define and perform simulation-based multi-objective optimizations of productivity and worker well-being. In order to evaluate the usability of the digital tool, a usability study with potential users, i.e. engineers at several companies in the automotive industry, was carried out.

2. Method

The development of the digital tool was based on a framework of multi-objective optimization of productivity and worker well-being [14]. By analysing the framework, the first task was to identify the steps in the framework that were considered suitable for being automated in a digital tool. After identifying these steps, an iterative process of development of the digital tool was carried out in collaboration with potential users and stakeholders in industry. Finally, an industry-based usability evaluation of the current version of the digital tool was carried out.

2.1. Identification of steps of the framework to implement in a digital tool

A fieldwork study [15] was performed in order to understand which steps of the framework given in [14] could be implemented into a digital tool. The fieldwork included studies at more than ten partner companies in Sweden, involving professional engineers considered potential users of the digital tool. The fieldwork was done through a multitude of meetings, discussions, and presentations during a time span of four years. The main goal of the fieldwork study was to understand the way the engineers carry out their tasks today, the processes within where these tasks are performed, and the challenges they face in their day-to-day work. Also, wishes and demands of a potential digital tool were identified by the means of the fieldwork.

2.2. Digital tool development

The development of the digital tool was done in an iterative process of development and evaluation through several use cases. The use cases were mainly based on real industrial design problems. An initial study was done to find suitable ways to perform optimizations of objectives related to worker well-being [16]. The subsequent use cases included multi-objective optimization of the design of a welding workstation to improve productivity and worker well-being [14], simulation-based multi-objective optimization of welding tasks to improve worker well-being using time-based ergonomics evaluation methods [17], simulation-based multi-objective optimization of workstation layout to improve productivity and worker well-being [18], and knowledge discovery of multi-objective optimization results to find rules for future designs of workstations, reducing the need to perform new optimizations [19]. After each use and evaluation of prototype versions of the digital tool, by the means of the use cases, the results were presented to and discussed with the potential users at the industrial partners. Based on the experiences and feedback from each use case, the digital tool was further developed in an iterative manner in regard to functionality and usability.

2.3. Initial usability study of the current version of the digital tool

To evaluate the usability of the current version of the digital tool, study sessions based on semi-structured interviews [20] and the System Usability Scale (SUS) method [21] were arranged. Each session, taking approximately two hours, were divided into three stages: 1) demonstration of the digital tool where participants interacted with, and discussed, the digital tool through the person demonstrating it (approximately 30 min), 2) semi-structured interviews (approximately one hour and 20 min), and 3) the SUS questionnaire (approximately 10 min). The sessions were conducted with a total of 14 participants from five automotive companies in Sweden. Due to the limited availability of the participants, some sessions included individual interviews and some sessions included group interviews. In total, two group interviews with four participants each, one group interview with two participants, and four individual interviews were carried out. The 14 participants were engineers in the areas of design engineering, production engineering, and ergonomics. The participants were familiar with DHM tools, however, not all participants were direct users of DHM tools. Several of the participants represented more than one of these areas in their working role; therefore, the decision was made to make no specific classification of the participants in the study, and both the interviews and the SUS questionnaire study were conducted without any distinction of the participants. However, in this paper, the term “ergonomists” is used to refer to engineers who, to a large degree, are responsible for making worker well-being perspectives being considered, e.g. when workstation designs are evaluated.

The goal of the demonstrations and subsequent interviews was to present the digital tool and to obtain feedback on the digital tool’s functionality, user interface, and perceived overall effectiveness in optimizing productivity and worker well-being. During the demonstrations, participants were given a description of the digital tool and were encouraged to interrupt with questions or comments at any time, in addition to interacting with the digital tool through the person demonstrating it. This allowed for an interactive and collaborative approach to the evaluation process. After each demonstration, a semi-structured interview was held. The conversation was governed by prepared questions, and the interviewee engaged the participants to be involved in discussing each issue covered. In the group interviews, discussions between the participants were also engaged by the interviewee. When the discussion ended in a natural way or changed topic, the next question was presented to the participant or participants. The questions were shaped to encourage participants to provide constructive feedback and suggestions for improvement. The questions in the semi-structured interviews were divided into initial reflections on the digital tool, then assessing the actual situation in their companies, and finally, opinions about the digital tool.

Questions about the initial reflections of the digital tool:

- What are your initial thoughts on the digital tool?

- How user-friendly do you find the digital tool?
- How useful do you find the digital tool versus the manual approach?
- What features do you find more useful?
- Are there any additional features you would like to see added to the digital tool?

Questions to assess the actual situation in their companies:

- Do you perform manual optimizations?
- Do you consider several design variables?
- Do you consider worker well-being objectives and productivity objectives simultaneously?
- Do you use optimization algorithms?
- Do you save the different design alternatives you create to reuse them?
- Do you present to other people several design alternatives by using other tools (Excel, Matlab, several DHM tool files, etc.)?
- Do you visualize the solution before making a decision?

Questions about the participants' opinions about the digital tool:

- Do you think the digital tool could save you work time when you design production systems/products?
- Do you think the digital tool could provide better results than your actual approach?
- Do you think the digital tool could help the collaboration between engineers and ergonomists to obtain better designs that consider worker well-being and productivity?
- Do you think the digital tool needs more functionalities?
- Do you think the digital tool is difficult to use and needs to be more user-friendly?

In addition to the prepared interview questions, follow-up questions were stated by the interviewee at each area covered, formulated by the interviewee depending on the comments of the participants, hence following the semi-structured interview method [20]. Both group interviews and individual interviews were audio recorded, and notes were taken during the process. All participants gave consent to the study. At the end of the interview, the interviewee provided the SUS questionnaire to the participants and left the room. The SUS method provides ten questions to evaluate the usability of a system [21], in this case, the digital tool:

1. I think that I would like to use the digital tool frequently
2. I found the digital tool unnecessarily complex
3. I thought the digital tool was easy to use
4. I think that I would need the support of a technical person to be able to use the digital tool
5. I found the various functions in the digital tool were well integrated
6. I thought there was too much inconsistency in the digital tool
7. I would imagine that most people would learn to use the digital tool very quickly
8. I found the digital tool very cumbersome to use
9. I felt very confident using the digital tool
10. I needed to learn a lot of things before I could get going with the digital tool

All SUS questionnaire responses were registered anonymously. At the end of the questionnaire, an additional field for anonymous comments was available for participants to optionally leave additional comments.

3. Development of the digital tool

The following sections present the selected steps of the framework to include in the digital tool, as well as the developed digital tool itself.

3.1. Steps of the framework to include in a digital tool

Based on the understanding of potential users' current work methods and their expectations of functionality and usability of a digital tool, Fig. 1 shows how several steps of the complete optimization framework given in [14] were selected to be included in a digital tool, hence marked "Digital tool" in Fig. 1. The steps of the framework to be contained in the digital tool are: Optimization definition, Simulation method, Simulation, Extraction of simulation data, Assessment of targets, Optimization method, Modification of variables, and Presentation of results in decision support tool. Thus, the digital tool instantiates these steps of the framework and guides the user through the process to set up and run optimizations. The steps of the framework of Problem definition, Requirements specification, Data collection, Selection of solution, and Reappraisal of findings were considered not possible or suitable to be implemented into a digital tool (Fig. 1). The reasoning for that conclusion is that the fieldwork studies gave that these steps typically are handled differently at different companies, as well as the conviction that these steps are better suited for a manual approach since they are often based on knowledge from engineers, and since associated decisions typically are based on discussions within and between teams. The steps of the framework of Model creation in DHM tool (Fig. 1), i.e. CAD environment, Human models, and Action sequence were also not included in the digital tool since these steps are rather carried out in the DHM tool being used.

3.2. Developed digital tool – Ergonomics in Production Platform (EPP)

To ease communication with potential end users and other stakeholders along the research and development process, the digital tool was given the name Ergonomics in Production Platform (EPP), which is the term used for the developed digital tool from hereafter. The architecture of EPP, the analysis in EPP, and optimizations in EPP are explained in the following sections.

3.2.1. EPP architecture

In order to instantiate the selected steps of the framework in EPP, an analysis of the necessary tools to perform each step was done. The tools were then divided into different modules that communicate between them (Fig. 2):

- **Core**: controls all processes and memory management. Also, controls the multi-threading processes and creates new ones when necessary. The core is based on pure C++ (standard libraries) and QT graphical framework functionalities.
- **Interface**: interactive interfaces based on the QT graphical framework in C++ that allow user interaction. The interfaces run in separate threads to avoid freezing and unresponsive interfaces.
- **Ergonomics evaluation module:** allows to evaluate worker well-being by using different ergonomics evaluation methods such as RULA [22], REBA [23], OWAS [24], RAMP [25], and NIOSH lifting equation [26]. The evaluation of worker well-being is done by processing the postures of manikins in the DHM tool, using the exposure criteria in the selected ergonomics evaluation method. To facilitate the implementation of ergonomics evaluation methods, the ergonomics evaluation module includes automatic creation of criteria by predefined templates that support users to define their own ergonomics evaluation methods. If an ergonomics evaluation method has quantifiable postural conditionals, that is, evaluation by thresholds of joint angles or distance values, the ergonomics evaluation method can be implemented by using the criteria created by the ergonomics evaluation module. Subjective measurements can be added but they require additional user input data, which limit the automation of the optimizations.

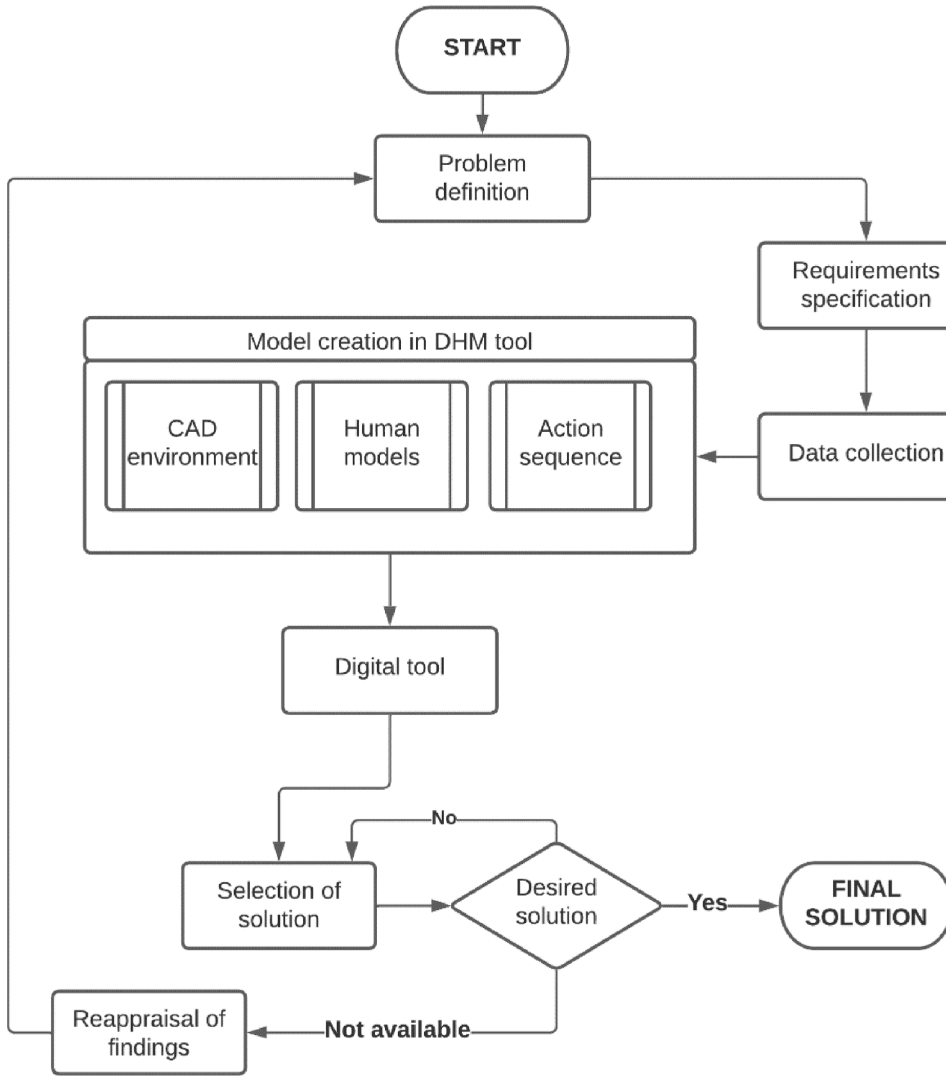

Fig. 1. Condensed version of the framework from [14], where the steps of the framework of Optimization definition, Simulation method, Simulation, Extraction of simulation data, Assessment of targets, Optimization method, Modification of variables, and Presentation of results in decision support tool all are being contained in a new step named Digital tool.

- **Optimization module:** converts the selected data into optimization data in a structure formed by variables, objectives, additional outputs and constraints. The module contains the NSGA-II [27], NSGA-III [28], and DEMO [29] optimization algorithms to perform optimizations. This module runs in a separate thread. The module is further explained in Section 3.2.3.
- **Input/output (IO) module**: converts the input and output data to the desired format.
- **Utils module:** includes mathematical libraries, functions of the operative system and import/export tools to enable file management.
- **Storage:** stores and manages all information for fast access for the core.
- **Export module:** allows exporting data in different formats depending on user needs.
- **Communication module**: includes several communication protocols such as named pipes (shared local memory), TCP and UDP. Makes direct communication with the external modelling, simulation and optimization software.
- **Report website:** automatic generation of JSON (JavaScript Object Notation) files that can easily be interpreted by websites. The developed HTML, CSS and JavaScript files serve as a template that automatically generates and opens a website in the default browser of the user.

The interaction between the user and EPP is done in the Interface and the Report website (both marked in green in Fig. 2). The rest of the modules process the information obtained from the user input, the DHM tool and the external optimization tools. However, the user does not need to interact with the rest of the modules. When performing an analysis or an optimization, the user only interacts with the interface and does not need to manually run any of the modules. The Core (marked in pink in Fig. 2) calls the modules that are necessary to process the operations requested by the user (marked in orange in Fig. 2). The Storage is both automatically controlled by the Core and can be accessed by the user through files. The external elements, the simulation tool (DHM tool) and other possible optimization and decision support tools (marked in grey in Fig. 2) are optional; that is, EPP can run without those elements.

In addition to communication with the modules, the Core can be accessed directly by using a scripting interface. All data available in EPP is kept in a JSON format that can be accessed by scripting in JavaScript while also allowing modification of the data and new calculations. The scripting interface, called Master script interface, can access all elements

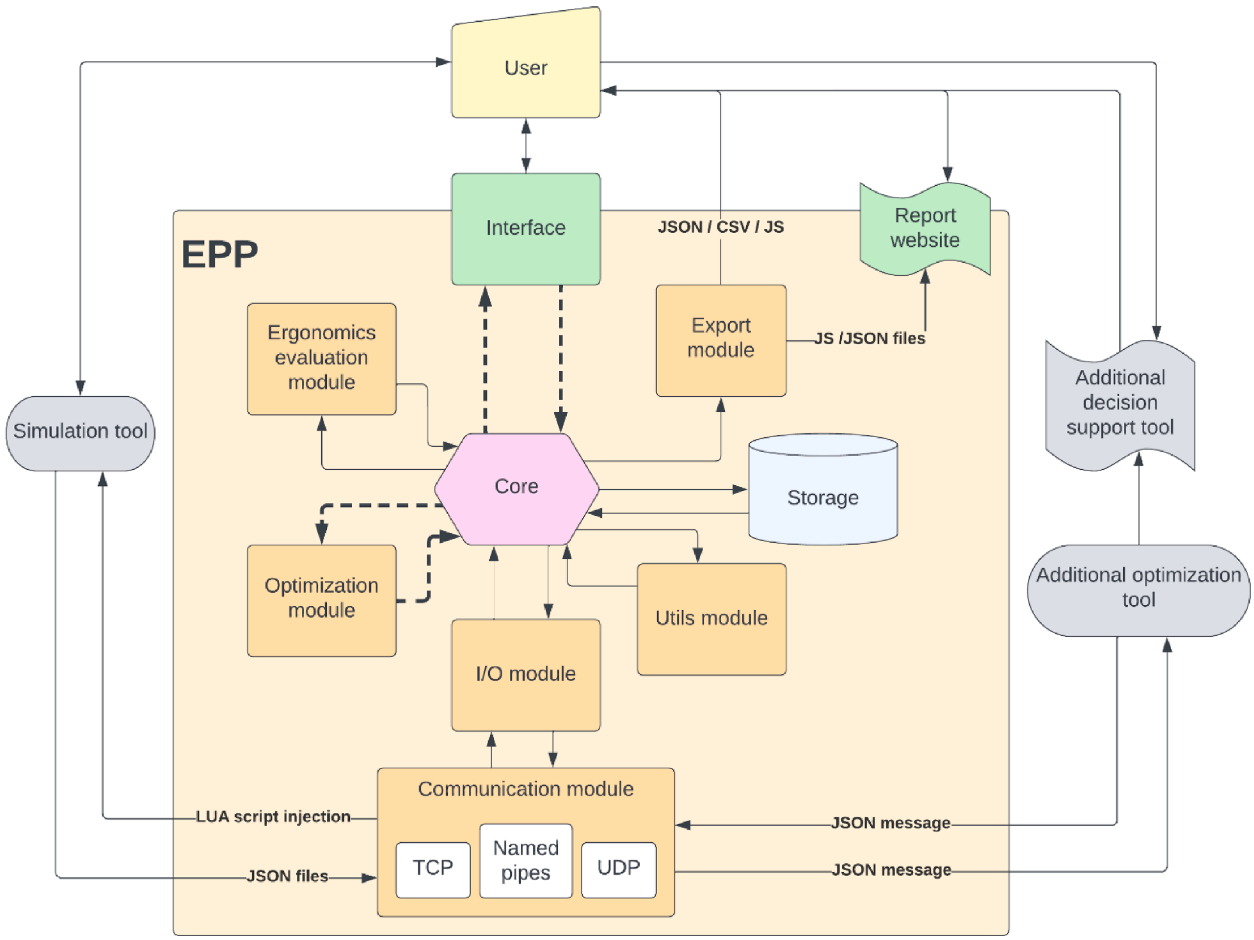

Fig. 2. EPP architecture.

and automatically generate scripts related to the elements by clicking on the element that the user wants to access (Fig. 3). All scripts created can be tested and debugged in the Master script interface by using the real-time JavaScript injection engine in EPP. The scripts can be stored in the user's computer and reloaded in EPP to allow reusability of the code.

3.2.2. *Analysis in EPP*

While EPP does not include the steps of the framework of Problem definition, Requirements specification, and Data collection (Fig. 1), an analysis tool has been built into EPP in order to facilitate analyses of productivity and worker well-being. When the user triggers EPP from the DHM tool or when the user requests EPP to import data from the DHM tool, the Core asks the I/O module to provide the data in a structured format. The I/O module asks the Communication module to communicate with the DHM tool and extract the data. Once the data processing is done, the Core loads an interface with all the elements available in the DHM tool (Fig. 4). The elements are structured from top to bottom as production line, workstation, task, manikin family and

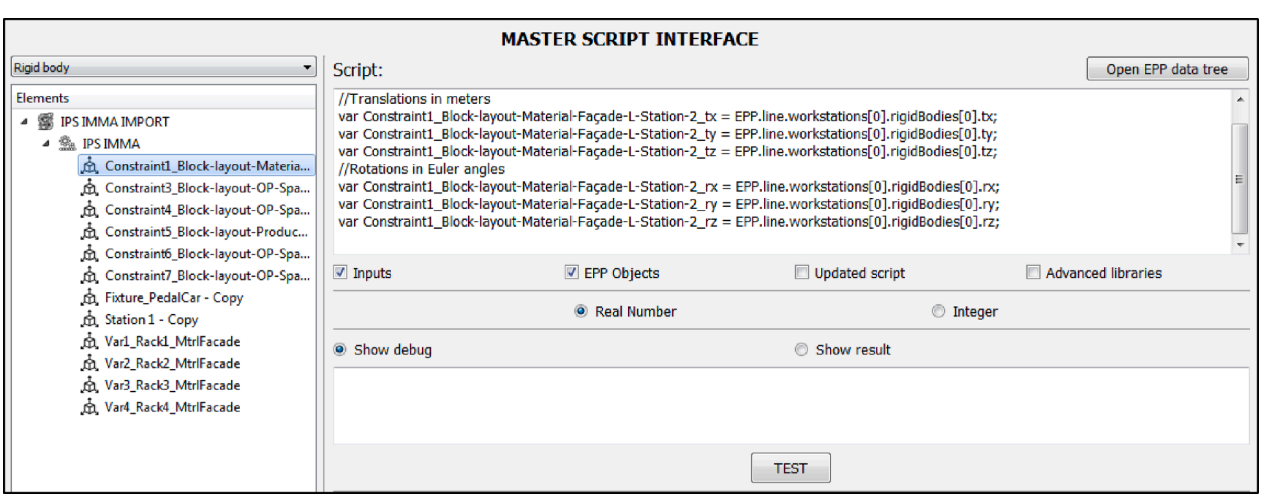

Fig. 3. Master script interface.

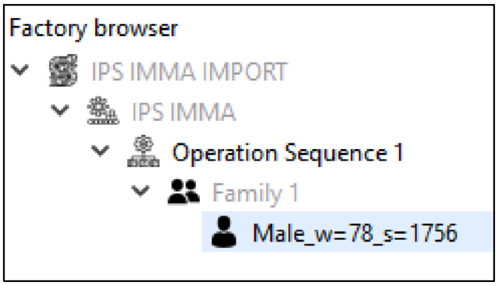

Fig. 4. Elements of the DHM tool loaded in EPP.

manikin (Fig. 4). If the DHM tool does not include one of the elements, an empty element is created to maintain the structure.

When the user clicks on any of the elements, EPP opens a tab with the possibility of analysing the element. For example, if the user clicks on a manikin, the information shown is related to the task the manikin is performing. The information shows direct measurements of the manikin, e.g. joint angles, as well as results from selected ergonomics evaluation methods, e.g. RULA [22] and REBA [23]. The information shown is synchronised with a time slider and a 3D view of a simplified manikin model for visual feedback (Fig. 5).

In addition to the available data, the user can use the Master script interface (Fig. 3) to further analyse the data available in EPP and create bespoke company-specific evaluations.

3.2.3. Optimizations in EPP

When the user requests to start an optimization, the Core loads the Optimization module (Fig. 2). First, the Optimization module asks if a new optimization should be defined or if an existing optimization should be loaded. In the case of loading an existing optimization, the user can jump directly to the results section or modify an existing optimization to run it again. This allows the user to create templates of optimizations or to fine-tune an existing optimization to find better results. Once the user starts defining an optimization, the Interface loads the visualization of the Optimization module (Fig. 6).

The Optimization module acts as a wizard that supports the user in the tasks to set up: (1) Optimization variables, (2) Optimization objectives, (3) Constraints, (4) Additional output, (5) Relations, (6) Optimization algorithm and (7) Settings. After that, it lets the user (8) Run the optimization and, once it is finished, view and load (9) Results (Fig. 6). The Optimization module indicates the actual status of the optimization set-up and the remaining tasks needed to run an optimization. These tasks are defined as done (green icon with check mark), ongoing (green arrow icon) and not done (red icon with cross) via the icons on the left side of the interface, as a guide for the user (Fig. 6).

Task (1) Optimization variables represent the design parameters that can be modified and that the user wants to find the best configuration for. These design parameters can include, but are not limited to, the height of objects, layout configurations, order of tasks and tool/part variations. Task (2) Optimization objectives represent the evaluation of the design, in this case, productivity and worker well-being measures. Ergonomics evaluation methods such as RULA [22], REBA [23], OWAS [24] and RAMP [25] and OWAS Lundqvist index [30] have been implemented in EPP to consider worker well-being objectives. Also, walking distances (spaghetti diagrams) and task times have been implemented to consider productivity objectives. Task (3) Constraints represent the conditions that must or must not occur. These conditions can be both in variable definitions (limits in the variables or forbidden

Fig. 5. Manikin and automatic well-being analysis in EPP – Example of RULA analysis made in EPP with postural data from the DHM tool.

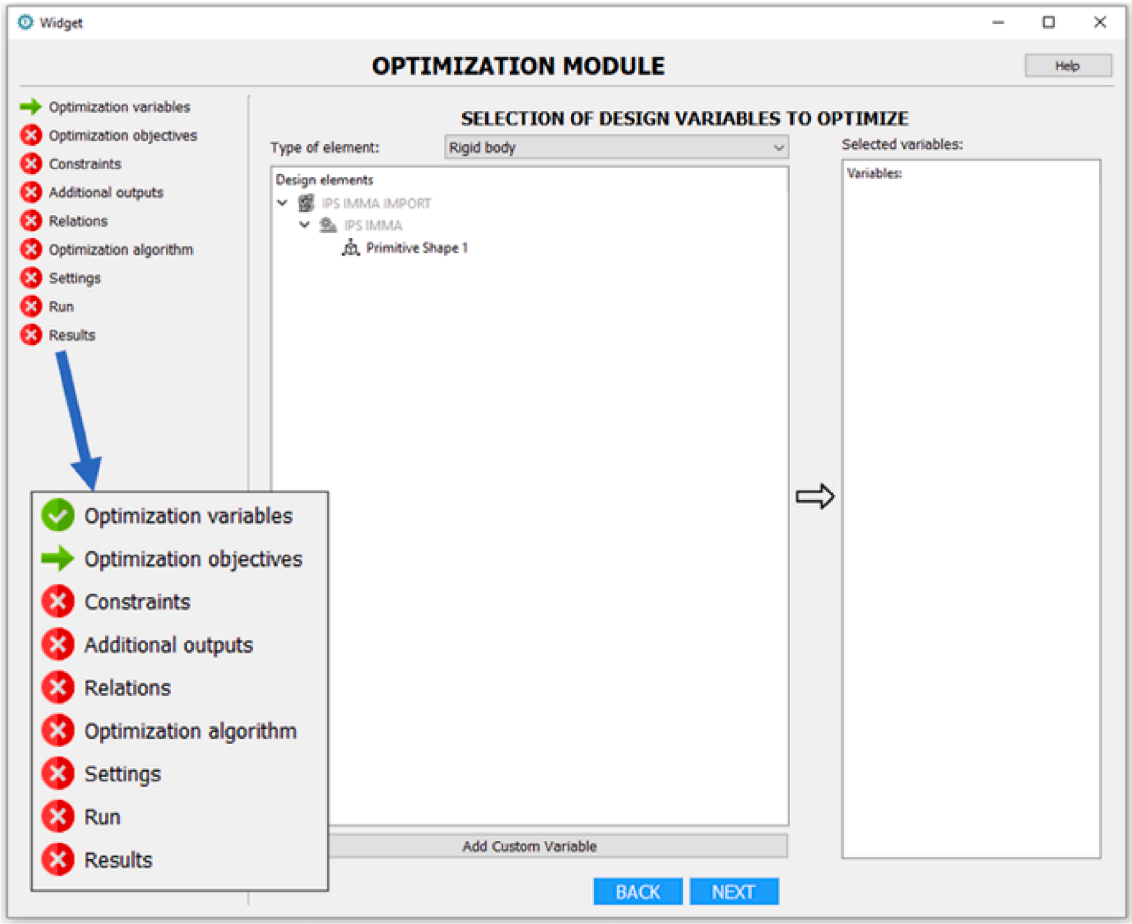

Fig. 6. EPP Optimization module.

values), objective values (unacceptable values of productivity and worker well-being), or other values not related to variables or objectives (e.g. collisions between objects or forbidden locations of parts). Task (4) Additional outputs are set up as measurements to track different parameters in each iteration; however, they are not considered by the optimization algorithm as an objective. Task (5) Relations allow scripting conditions between elements in the DHM tool, such as relative positions between objects (e.g. objects on top of shelves) or updating other elements relative to the design (e.g. updating actions of manikins depending on the position of an object). Task (6) Optimization algorithm allows selecting between different optimization algorithms and their configurations, offering an initial default configuration based on the number of variables and objectives. Tasks (7) Settings and (8) Run allow performing the optimization automatically by using optimization algorithms and saving the data of the optimization automatically. The final task (9) Results allow reloading any solution that has been run during the optimization, as well as using the report website as a decision support tool.

In each task, the Optimization module provides an interface to support the users set up the optimization. All tasks, from the exception of naming the elements and optional advanced functionalities (e.g. scripting), can be performed with just clicks and no keyboard input. Also, if the user does not define at least one variable and one objective, EPP alerts the user that those are required. In the first task (1) Optimization variables, the interface shows all the elements in the scene of the DHM tool that can be added as optimization variables (Fig. 6). Custom variables (variables not related to the DHM tool scene) can also be added to represent mathematical variables of the type integer, real and categorical numbers. Once an element has been selected, the Optimization module shows an interface that allows selecting translation and rotation coordinates, which, once defined, each coordinate becomes an optimization variable. Also, the functionalities "Get" and "Test" are available. "Get" allows retrieval of the actual position of the object in the DHM tool in real-time so that the user does not need to type numerical values of the position. The functionality "Test" is used to test the value that the user has defined in real-time in the DHM tool (Fig. 7).

The Optimization module follows the same process in the tasks of (2) Optimization objectives, (3) Constraints and (4) Additional outputs. The Interface with all available elements is shown, including all geometries, workstations, tasks, manikin families and manikins in the DHM tool and allows selecting elements and methods to create optimization objectives. In the case of worker well-being objectives, the manikins can be selected to use ergonomics evaluation methods as optimization objectives (Fig. 8). In the case of productivity, the time to perform the task and the walking distances of the manikins can be selected.

The Master script interface (Fig. 3) can also be used to define company-specific methods as objectives, constraints and additional outputs. For task (5) Relations, the Optimization module also allows scripting relations between objects. Scripting can be used to define distances between objects as well as rotations or orbital positionings. Also, the scripting can include logic to only trigger geometrical relations when certain conditions are fulfilled.

Task (6) Optimization algorithm is done in an interface that allows selecting and configuring optimization algorithms (Fig. 9) such as NSGA-II [27] and NSGA-III [28] evolutionary algorithms. Depending on the optimization algorithm selected, different options for configuration are offered to the user. EPP, based on the definition of the optimization in previous tasks, offers a balanced configuration as well as an

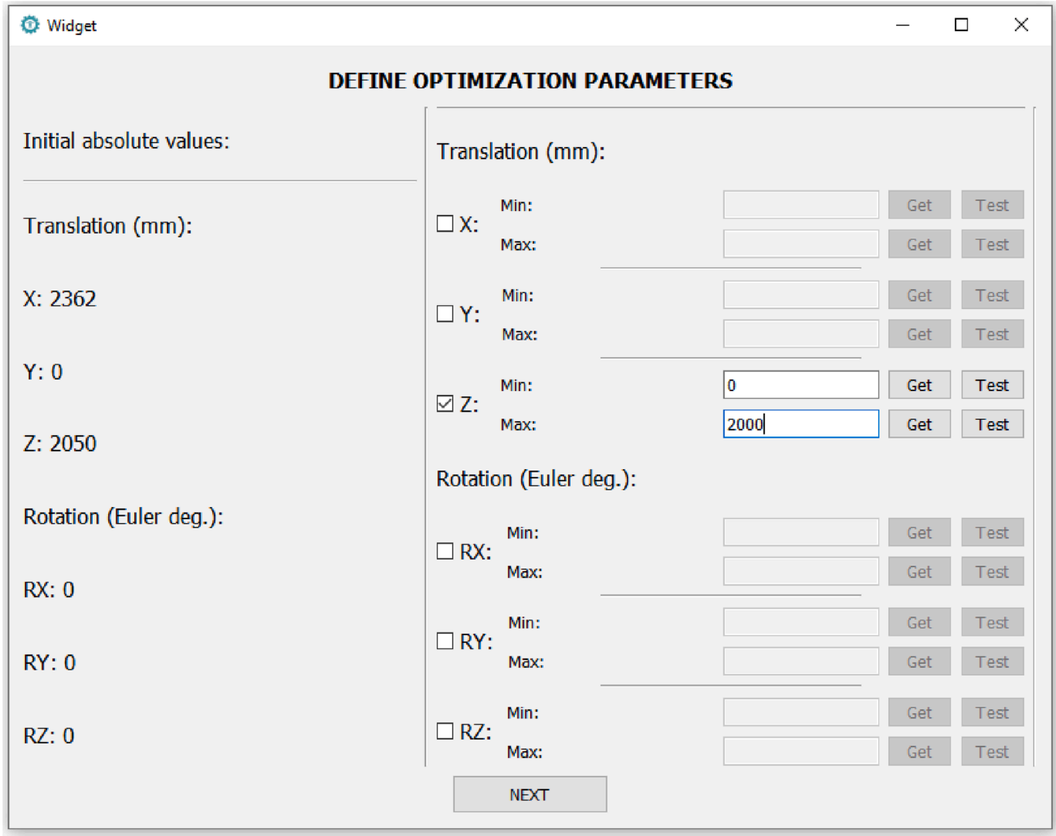

Fig. 7. Optimization variable definition – Example of setting up a variable for the height (translation in Z axis) of an object.

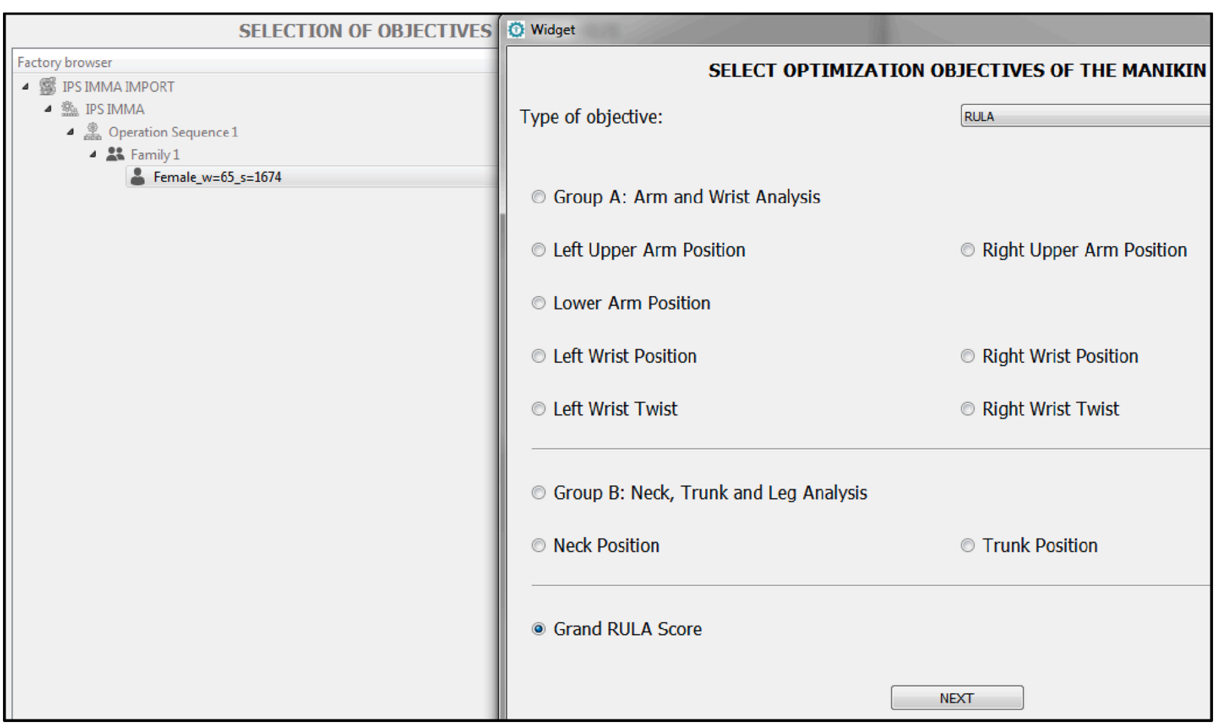

Fig. 8. Example of optimization objectives for a manikin.

appropriate optimization algorithm based on the number of objectives and variables in the optimization; therefore, the user can skip the configuration of the algorithm if he/she is not experienced in optimization algorithms. Also, the interface allows selecting the number of iterations to run and checking how long it would take to run that number of iterations. In addition to that, users can run the optimization

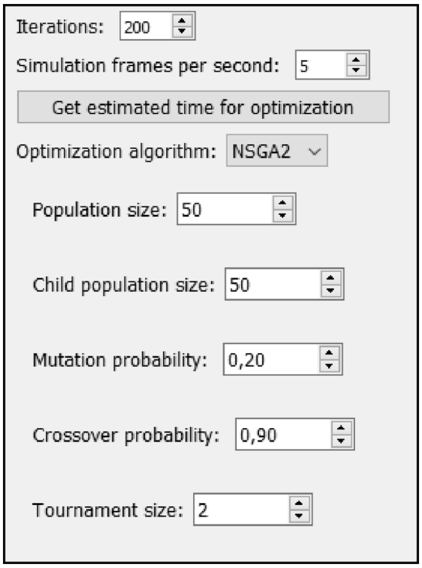

Fig. 9. Optimization algorithm interfaceFigure 10. Report website – General information of the optimization previously defined and performed.

for an infinite number of iterations and stop it when they consider that the results are appropriate.

The tasks of (7) Settings and (8) Run are automatic by default. The default settings of optimization save all configuration and results of the optimization while the optimization is running; therefore, if the optimization gets stopped, all results are saved in a JSON format file and can be retrieved. Also, during the optimization, the results can be analysed in real-time to assess if the optimization should be finished in case the user needs to finish the optimization earlier than expected and decide a solution.

During the run, a report website is generated, and it can be updated at any time so the user can look at the results of the iterations in the optimization that have already been performed. The report website serves as a presentation of results and a decision support tool (marked in green in Fig. 2) and allows the user to analyse the results from the optimization. In order to support the user to select a solution, the report website has five sections: General information (Fig. 10), Results overview (Fig. 11), Charts (Fig. 12), Solution analyser (Fig. 13 and Fig. 14) and Discussion (Fig. 15).

The General information section (Fig. 10) shows general information about the optimization objectives, variables, additional outputs, relations and the number of iterations performed from the defined ones in the previous tasks (1–6).

In the Results overview section (Fig. 11), the user can see the lowest values for minimisation objectives and the maximum values for maximisation objectives that have been reached in the solutions. Also, the solutions in the Pareto front are offered to the user.

In the Chart section (Fig. 12), the user can create 2D scatter plots of

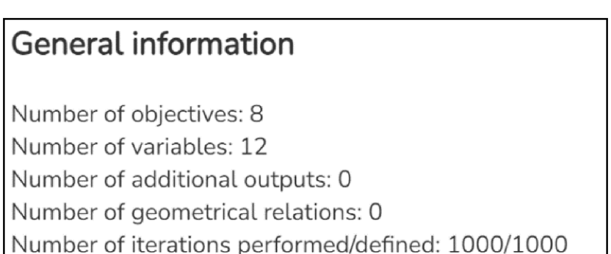

Fig. 10. Report website – General information of the optimization previously defined and performed.

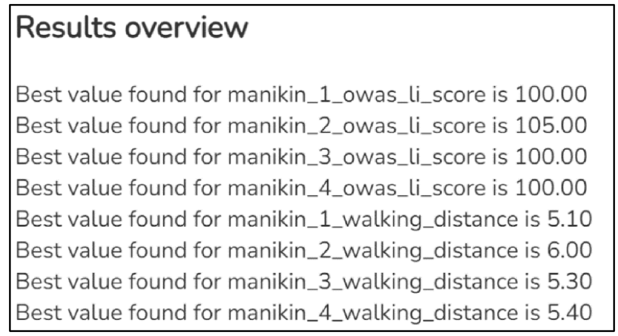

Fig. 11. Report website – Results overview – Example showing eight objectives: four walking distance calculations and four OWAS Lundqvist index calculations, each corresponding to a different manikin performing a different task.

all the solutions by selecting variables or objectives. The solutions in the Pareto front are marked in green to support the user select optimal solutions from the solution space. Hovering a solution also shows exact values for the selected variables or objectives and the number of iterations. In addition to that, the user can select a solution to mark it in yellow and change the selected variables or objectives to see the solution in different dimensions of the design or objective space. The user can also create several charts, and the selected solution is synchronised for all the charts.

Once a solution has been chosen, to further analyse it, the user can use the Solution analyser (Fig. 13 and Fig. 14). The chosen solution is automatically analysed against other available solutions from the optimization, and the values for all objectives are shown as percentile values in a bar chart (Fig. 13). This allows the user to balance the results from different objectives, supporting consideration of both productivity and worker well-being for all manikins that have been included in the optimization.

In addition to the bar chart, the user can analyse the exact value for all objectives, variables and additional outputs for the selected solution (Fig. 14).

The process done in the previous tasks is iterative, where users can discuss and select different solutions to reach a better balance between objectives. Also, they can automatically load the selected solution in the DHM tool to further analyse the design solution. The balance between objectives and selection of a solution is left to the decision makers. Once a final decision has been chosen, the report website section Discussion (Fig. 15) allows to input comments regarding the discussions taken to ensure that the solution is balanced and both productivity and worker well-being have been considered.

When the discussion section is finished, the user can automatically print the report website in PDF to store all the solution decision process.

4. Results from usability evaluation of EPP

The SUS method provides answer alternatives on a Likert scale: 1 – Strongly disagree, 2 – Disagree, 3 – Neither agree or disagree, 4 – Agree, 5 – Strongly agree. The questions in SUS are stated as positive questions for odd numbers (e.g. Question 1. I think I would like to use EPP frequently) and stated as negative questions for even numbers (e.g. Question 2. I found EPP unnecessarily complex). The questions were presented to the participants in their original form (Section 2.3). However, in Fig. 16, the results of the SUS questionnaire are reverse coded for the even questions for easier interpretation, i.e. for the odd numbered questions, dark green represents 5 – Strongly agree, whereas in even numbered questions, dark green represents 1 – Strongly disagree. Fig. 16 presents the answers of each participant to each question.

Following the calculation procedure described in [21] gave the average SUS score 66.25 for EPP. According to [31], a SUS score of 66.25

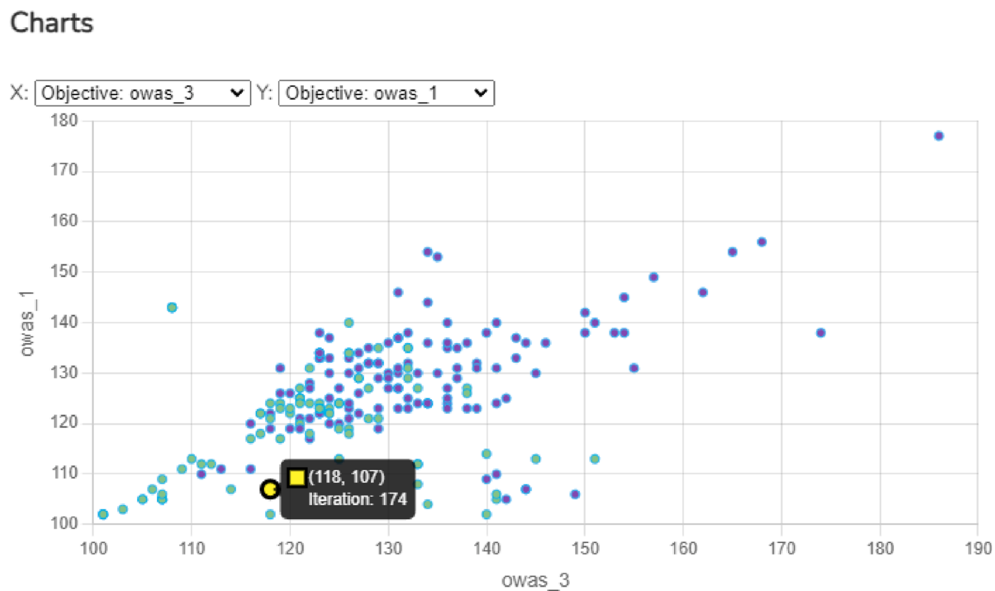

Fig. 12. Report website – Charts.

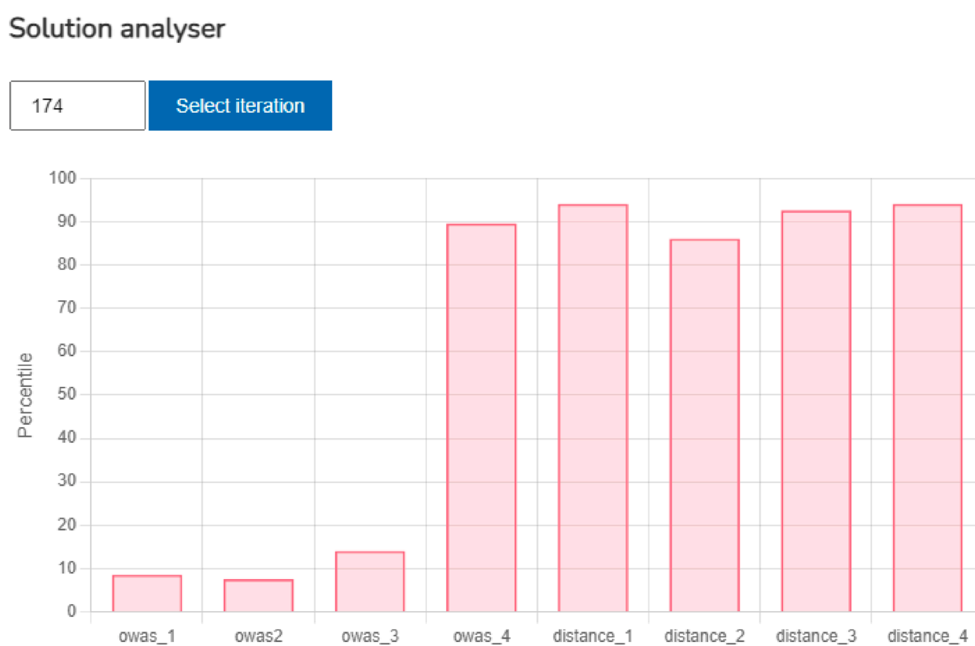

Fig. 13. Report website – Solution analyser balancing charts.

is considered to be in the D rating of the grade scale, rather close to the C rating, and the adjective to describe it would be "OK" (or "acceptable") and close to "good" (Fig. 17).

The following section presents findings from analysing the outcomes of the interviews. The findings from the interviews are structured according to the ten questions in the SUS questionnaire. This is to facilitate easier comparison with the SUS results and also to present a richer view of the issues covered by each question in SUS.

- **Question 1 – I think that I would like to use the digital tool (EPP) frequently**: the use of optimization was mentioned on several occasions in the interviews. Participants mentioned that while the use of optimization could help in projects where a new production line or workstation is being designed, and it has clear issues from a productivity and worker well-being point of view, many everyday tasks are straightforward and do not require optimizations. Also, in the interviews with ergonomists, they mentioned they would not use EPP directly but rather discuss the results with engineers who perform the optimizations. Overall, most of the participants noted that with enough resources, using optimization could benefit the results in the factories.
- **Question 2 – I found the digital tool (EPP) unnecessarily complex**: most of the participants commented that while performing optimizations is a complex task by itself, EPP made performing optimizations an easier task. Some participants also mentioned that they had never performed optimizations with algorithms earlier, but they could see themselves performing them by using EPP. A few participants were not experienced in the use of DHM tools and simulation and perceived optimizations as a very complex task that they would struggle with, even with the use of EPP.
- **Question 3 – I thought the digital tool (EPP) was easy to use**: comments from **Question 2** also apply. The participants mentioned

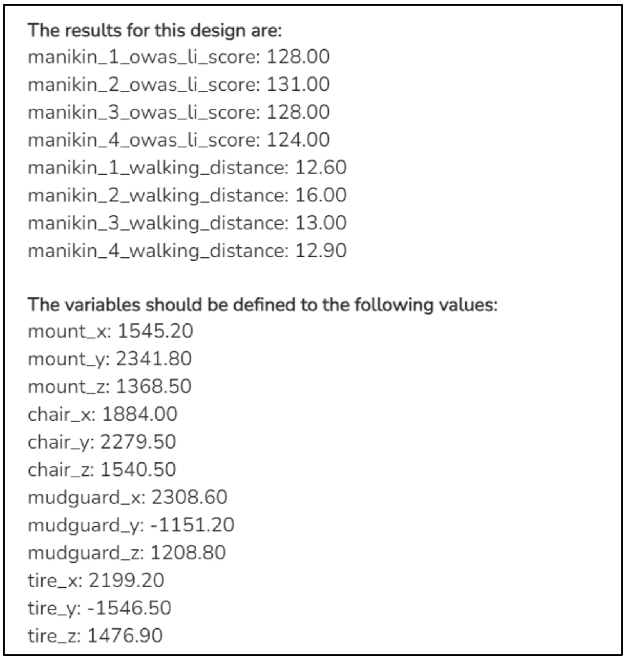

Fig. 14. Report website – Solution analyser solution description.

that they could see themselves using EPP for optimization tasks and that they did not find the tasks of setting up an optimization, running an optimization and visualising the results particularly difficult. The same participants who found optimizations overall a very complex task mentioned that EPP was difficult to use since they were not used to optimizations in general.

- **Question 4 — I think that I would need the support of a technical person to be able to use the digital tool (EPP)**: most of the participants mentioned that they understood the question as "I need the support of a technical person to use EPP at the beginning". They also mentioned that after a short learning process, they would not need more support. A few participants mentioned that an optimization engineer should lead the process while other engineers and ergonomists would input their requirements in the optimization.
- **Question 5 — I found the various functions in the digital tool (EPP) were well integrated**: overall, all participants felt that EPP was well integrated and synchronised with the DHM tool, as well as providing enough functions to perform optimizations. However, some of the participants mentioned that EPP was lacking some "smart functions" that would help setting up optimizations, such as creating multiple optimization variables and objectives with fewer clicks.
- **Question 6 — I thought there was too much inconsistency in the digital tool (EPP)**: no participant mentioned inconsistencies in EPP, and there were no specific comments on the topic.
- **Question 7 — I would imagine that most people would learn to use the digital tool (EPP) very quickly**: most of the participants felt that it would be easy to learn to use EPP, which related the answers to **Question 3** and **Question 2**. While some of the participants did not have a technical background, they mentioned that they felt that EPP was easy to learn, and since the question mentioned "most people" rather than "myself", and they felt they would not be direct users of EPP, they based their answer by relating it to colleagues that would have the technical background to learn fast how to use EPP.
- **Question 8 — I found the digital tool (EPP) very cumbersome to use**: most of the participants commented that EPP was straightforward and simple to use. However, in a similar way to **Question 5**, some participants mentioned that some operations were repetitive and that EPP would be easier to use if some "smart functions" were implemented to avoid repetitive tasks.
- **Question 9 — I felt very confident using the digital tool (EPP)**: many participants felt that EPP would be straightforward to use; however, during the interviews, the interaction was done by discussing with the interviewee and not by directly using EPP. Therefore, participants had a mostly neutral response to this question and mentioned that they would like to obtain and test EPP by themselves.
- **Question 10 — I need to learn a lot of things before I could get going with the digital tool (EPP)**: all participants mentioned that they would need a stronger background to use EPP with confidence. While they mentioned that they could use EPP and perform optimizations without having a deep knowledge of optimizations, they also mentioned that they would initially use default settings for optimization algorithms and avoid advanced functionalities.

In general, all participants made similar comments about EPP, even if they had different backgrounds and worked at different companies. They all mentioned that optimization is used at their company, but there are a few experts that lead the projects of optimization, and other engineers and ergonomists are usually not involved in the process. Participants also mentioned that EPP could be beneficial by supporting the collaboration between ergonomists and engineers. Some participants described the design process as an iterative process between engineers only, and ergonomists were invited at two or three occasions to ensure that the design fulfilled requirements related to worker well-being to an appropriate degree. However, the outcome of such meetings is sometimes that design changes are required to successfully fulfil worker well-being requirements. All participants meant that such design changes

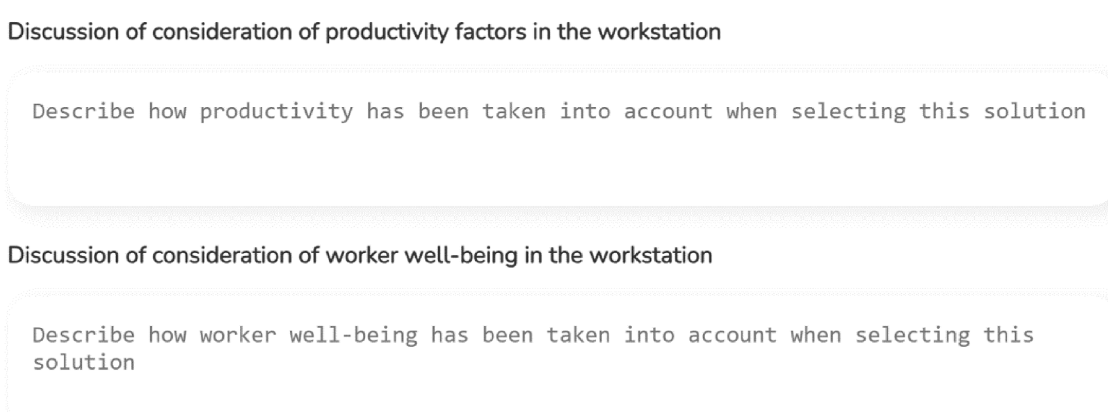

Fig. 15. Report website – Discussion – Example of how the report website suggests content of text input, to eventually be filled in by the decision makers.

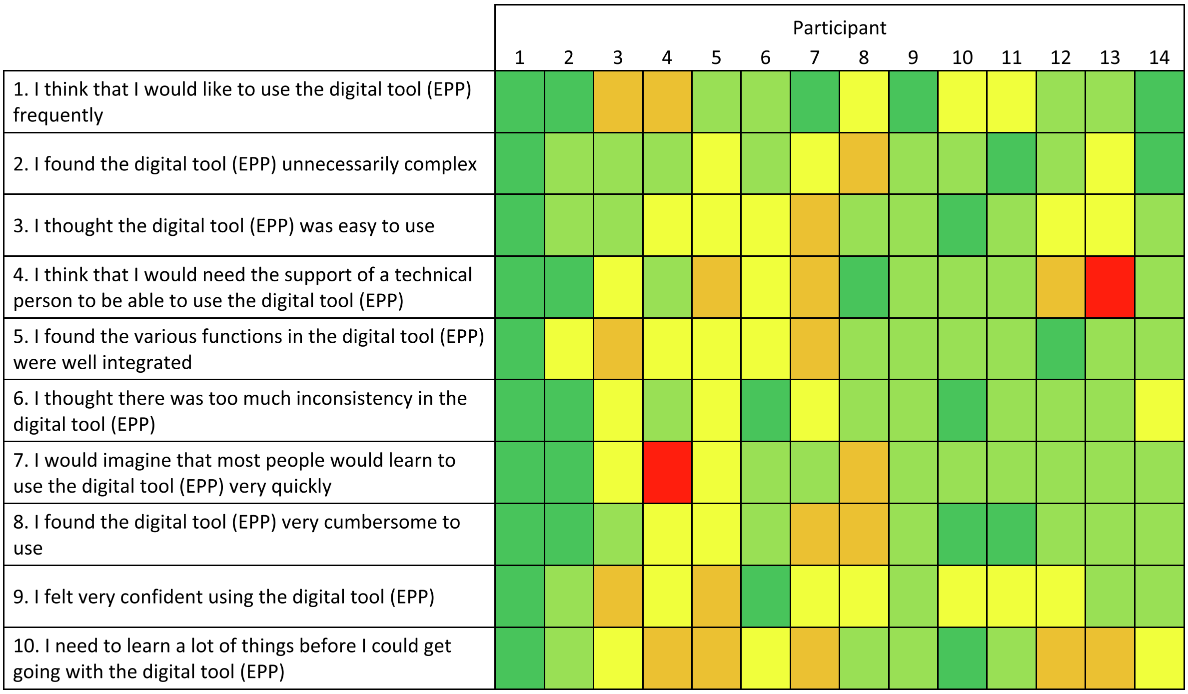

Fig. 16. Answers of each participant to the SUS questionnaire with even questions reverse coded (odd numbered questions: 5 = dark green, 4 = light green, 3 = yellow, 2 = orange, 1 = red; even numbered questions: 1 = dark green, 2 = light green, 3 = yellow, 4 = orange, 5 = red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

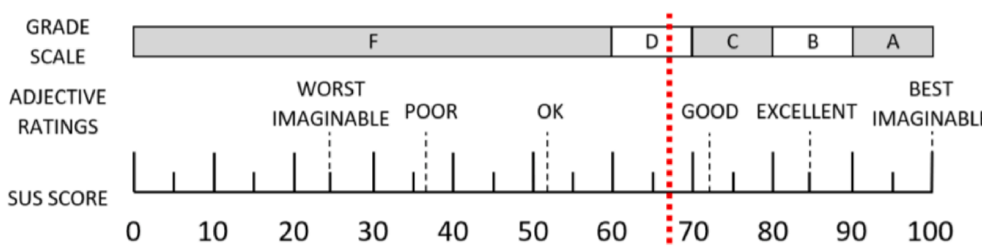

Fig. 17. Average SUS score 66.25 for EPP, marked with red dotted line, and compared to adjective ratings and grade scale according to [31]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

often cause iteration loops that are time-consuming, and that deadlines makes it very complicated to implement all needed changes while considering productivity and worker well-being. The follow-up question (or similar variation of it) "Does this process lead to suboptimal solutions in both productivity and worker well-being?" was then asked to the participants. All participants answered "yes", which, in some cases, was followed with an explanation of their own ideas for how to improve the collaboration and the process to achieve better designs.

Ergonomists mentioned they would like to be more included in the design process, but that it was difficult to follow the complete process and understand all the requirements of engineers. Engineers mentioned that including ergonomists in the processes would reduce the number of iterations as well as their workload on making continuous adjustments to the design; however, among other difficulties, it was difficult for engineers to include ergonomists in the design process due to the lack of tools that cover both productivity and worker well-being aspects in the same tool. The question (or similar variation of it) "Could EPP help improve the collaboration between engineers and ergonomists?" was then asked to the participants. In this case, participants with a stronger technical background answered "Yes", while participants with a lower technical background did not find themselves involved in the optimization definition tasks, but found the analysis in EPP and the report website to be the tools they would use the most to increase the collaboration. Also, some participants mentioned that EPP had the necessary functionality to improve their design processes but that EPP would benefit from having a better user interface (referring to the user experience of EPP).

5. Discussion

EPP has been created in an iterative collaboration process with the industry and by combining ergonomics evaluation methods and evolutionary algorithms in order to perform multi-objective optimizations of productivity and worker well-being. However, during this research project, several challenges have arisen. The first challenge relates to the idea of comparing and balancing productivity and worker well-being. This task is complicated, since choosing a solution that benefits productivity could affect the workers' well-being. However, improving workers' well-being can also lead to better worker productivity, and therefore increase the productivity of the overall system. While the increase in productivity in the long-term due to a more sustainable work life is proven [32], it is not possible to quantify the increase in productivity in the long-term related to the improvement of worker well-being in an objective manner so that it can be an input for DHM tools. At the same time, poor fulfilment of ergonomics requirements can lead to lowered productivity and quality risks [33]. Due to the complexity of the interaction between productivity and worker well-being, considering productivity and worker well-being, and obtaining balanced solutions, has been a challenge in this research project. For the development of EPP, the worst scenario has been considered, where no increase in productivity is expected due to improvement of worker well-being; however, in real-world applications, the improvement of worker well-being has, in many cases, lead to increased productivity [34].

The second challenge, as mentioned in Section 3.2 is that worker well-being cannot be treated in the same way as productivity. While productivity evaluations are easily quantifiable, ergonomics evaluation methods, in many cases, offer qualitative information, and are often evaluated with subjective criteria. In addition to this, ergonomics evaluation methods are most often applicable to certain cases, being dedicated to a specific type of work task, or to specific parts of the body. This leads to difficulties when using ergonomics evaluation methods in applications that require numerical data. Techniques for optimizations of productivity are well known; however, the techniques cannot be applied in the same way for worker well-being. There are ergonomics optimization studies [9]; however, it is not so straightforward to know what methods are applicable in a certain case, how they can be used in an appropriate manner (e.g. subjective measurements in ergonomics evaluation methods), and how can they be used in an optimization context (e.g. results might not be quantitative). In addition to that, many ergonomics evaluation methods offer a short range of resulting scores (e.g. RULA provides a final score between 1 and 7). Studies done in this research project has shown that using ergonomics evaluation methods that provide outcomes with a short range perform poorly in optimizations compared to using ergonomics evaluation methods that provide outcomes with a longer range (e.g. OWAS with Lundqvist index has a range of 300 possible results). Some studies have tried to find suitable ways to use ergonomics evaluation methods in optimizations by analysing different ergonomics evaluation methods, but they have also found the process complex due to the number of ergonomics evaluation methods and their suitability depending on the task performed by the operator [35,36]. In addition to that, simulations can be discrete (facilitating analysis of workload at certain instants in time) or continuous (facilitating analysis of workload over time); therefore, there is a need to use ergonomics evaluation methods for optimization that can consider both discrete and continuous evaluations. Thus, the complexity of finding and/or adapting an ergonomics evaluation method suitable for automated optimization is considered a challenge in this research field. To meet this challenge, a variety of ergonomics evaluation methods and productivity measures have been implemented in EPP. By implementing the static ergonomics evaluation methods RULA and REBA, and the productivity measures of time and walking distance, it is possible to perform discrete evaluations of productivity and worker well-being. The implementation of ergonomics evaluation methods RAMP and OWAS with the Lundqvist index statistical approach allows to perform time-based ergonomics evaluations and continuous evaluations. Having a variety of ergonomics evaluation methods, in combination with the functionalities that EPP provides, it is possible to combine several ergonomics evaluation methods as optimization objectives or constraints, as well as using statistical approaches such as the Lundqvist index to convert static ergonomics evaluation methods into time-based ergonomics evaluation methods. Hence, a way forward could be to extend and generalize the approach of how Lundqvist index handles OWAS assessments to other observational based methods (e.g. RULA and REBA) to also include time index values.

The third challenge of the research has been to include the functionality to automatically perform the optimizations with evolutionary algorithms, but without creating confusion and overloading the users, who are not always experts in multi-objective optimizations. Therefore, implementing the optimization steps of the framework in a digital tool is not a straightforward process, but a process of adapting, combining, and implementing optimization algorithms and ergonomics evaluation methods while considering the natural workflow of users and guiding them through the tasks of performing multi-objective optimizations of productivity and worker well-being. This challenge has been evaluated in this research project. Although the results from the usability study show that both novice and expert DHM tool and optimization users considered EPP fairly easy to use and navigate, and were able to understand the process of performing multi-objective optimizations of productivity and worker well-being in EPP, there are still room for development of functionality and usability of EPP.

Finally, it is possible to add worker well-being to the optimizations both as objectives and as constraints. These approaches present different benefits and downsides depending on the optimization problem. Adding worker well-being to the optimizations as objectives allows to further explore how to minimize the risk scores of ergonomics evaluations and allows a balanced trade-off between productivity and worker well-being. However, adding worker well-being to the optimizations as objectives can result in an increased complexity in the optimization. If, for example, anthropometric diversity is considered in the optimization, the number of optimization objectives can rapidly increase and it would be necessary to perform more evaluations. Adding worker well-being as a constraint to the optimizations allows ensuring acceptable risk scores of ergonomics evaluations and reduces the number of objectives, reducing the complexity of the optimizations. However, adding worker well-being as a constraint may limit the improvement of worker well-being to the definition of the constraint. Also, adding worker well-being as a constraint could result in an over constrained optimization and consequently limit the productivity improvements. Both approaches offer advantages and disadvantages, and their use should be determined based on the specific optimization problem and the preferences of the decision-makers.

6. Limitations and clarifications

The digital tool Ergonomics in Production Platform (EPP) obtains manikin characteristics, task times, manikin postures and motions, scores from ergonomics evaluation methods (as an option to doing the ergonomics assessments within EPP), from the digital human modelling (DHM) tool it is connected to, i.e. those aspects are dependent on the functionality of the DHM tool being used, and not of EPP per se. Hence, the optimizations performed with EPP will vary depending on the DHM tool used. In addition to that, different DHM tools offer different approaches for connecting and extracting data, which can limit the capabilities of EPP. The use cases performed in the development of EPP have been done with the DHM tool IPS IMMA [37]. IPS IMMA utilizes a quasi-static approach to model and predict human postures during different tasks, utilizing a task definition editor, inverse kinematics and an optimization-based comfort function that takes into account joint angles, joint torques and external forces, while preserving static equilibrium and non-collision. The capabilities in predicting human posture can vary with different DHM tools.

Moreover, EPP evaluates physical ergonomics, and more specifically, postural and force-related biomechanical loads with the ergonomics evaluation methods implemented. Other evaluations such as cognitive loads are not considered in the actual status of EPP.

Also, EPP uses existing optimization algorithms and allows connecting to other optimization tools to use additional algorithms. During this study, no specific optimization algorithm has been created for simulation-based multi-objective optimizations of productivity and worker well-being.

Finally, the challenges presented in the discussion have limited the development of EPP. Regarding the first challenge, while the long-term increase in productivity due to a more sustainable work life is well-documented [32], the current version of EPP cannot predict this long-term increase and instead uses metrics that reflect short-term productivity. Additionally, some ergonomic evaluation methods may not be implementable due to the limitations highlighted in the second challenge. Furthermore, as EPP achieves higher software maturity, the initial usability evaluation conducted in this study should be expanded. Future evaluations should involve direct interaction between users and the tool to better capture their experiences and provide a more comprehensive SUS evaluation.

7. Future work

This study presents a usability evaluation with 14 participants that are engineers in the areas of design engineering, production engineering, and ergonomics. In the future, it would be interesting to perform a deeper study with participants of different expertise areas to identify the possibilities to extend Ergonomics in Production Platform according to their specific needs.

Additional ergonomics evaluation methods could be implemented in EPP, such as the Arm Force Field method [38], LM-MMH equation [39], and the oxygen consumption prediction models [40], so that optimizations that further consider forces and energy expenditure can be performed with EPP.

8. Conclusions

The development of EPP has been carried out during four years of collaboration with the industry. By an iterative development of EPP, and feedback from industrial partners, it has been possible to improve the functionality and usability of EPP. In this paper, the development and evaluation of EPP is presented. The overall results from the SUS evaluation, and the discussion in the interviews, are positive. Both novice and expert DHM tool and optimization users considered EPP fairly easy to use and navigate, and were able to understand the process of performing multi-objective optimizations of productivity and worker well-being. The participants with more experience in DHM tools said that EPP could support in the design stage of production systems, and that EPP could benefit in the collaboration between engineers and ergonomists in the production development process. Also, engineers discovered that the automatic generation of design solutions, and the reusability of solutions that EPP offers, could greatly support and reduce their design efforts. The participants with less experience with DHM tools mentioned that they would not be direct users of EPP, but noticed the potential and the applicability of EPP for the more DHM tools experienced engineers in their company. The participants with less experience also said that EPP could benefit the collaboration between engineers and ergonomists.

The usability evaluation of EPP shows positive results, but also notices needs for improvements. While EPP supports to define optimizations, the participants provided useful feedback for possible functionalities that could further automate several tasks of the optimization definition. Hence, it is expected that EPP will be further developed in future research projects.

CRediT authorship contribution statement

Aitor Iriondo Pascual: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Dan Högberg:** Writing – review & editing, Writing – original draft, Supervision, Methodology. **Anna Syberfeldt:** Writing – review & editing, Supervision, Funding acquisition. **Erik Brolin:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code is available in a referenced DOI in the article.

References

[1] W. Kuhn, 'Digital Factory - Simulation Enhancing the Product and Production Engineering Process, in: Proceedings of the 2006 Winter Simulation Conference, Dec. 2006, pp. 1899–1906. doi: 10.1109/WSC.2006.322972.
[2] D.L. Fisher, M. Rizzo, J. Caird, J.D. Lee, Handbook of Driving Simulation for Engineering, Medicine, and Psychology. CRC Press, 2011.
[3] M. Oppelt, L. Urbas, 'Integrated virtual commissioning an essential activity in the automation engineering process: from virtual commissioning to simulation supported engineering', in: IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society, Oct. 2014, pp. 2564–2570. doi: 10.1109/IECON.2014.7048867.
[4] E. Kılıçaslan, H.I. Demir, A.H. Kökçam, R.K. Phanden, C. Erden, Ant Colony optimization application in bottleneck station scheduling, Adv. Eng. Inform. 56 (Apr. 2023) 101969, https://doi.org/10.1016/j.aei.2023.101969.
[5] S. Scataglini, G. Paul, DHM and Posturography. Elsevier Academic Press, 2019.
[6] J. Village, C. Searcy, F. Salustri, W. Patrick Neumann, 'Design for human factors (DfHF): a grounded theory for integrating human factors into production design processes, Ergonomics 58(9) (2015) 1529–1546, doi: 10.1080/00140139.2015.1022232.
[7] A. Azadeh, N. Shabanpour, M. Soltanpour Gharibdousti, B. Nasirian, Optimization of supply chain based on macro ergonomics criteria: a case study in gas transmission unit, J. Loss Prev. Process Ind. 43 (2016) 332–351, doi: 10.1016/j.jlp.2016.05.024.
[8] D. Battini, X. Delorme, A. Dolgui, A. Persona, F. Sgarbossa, Ergonomics in assembly line balancing based on energy expenditure: a multi-objective model, Int. J. Prod. Res. 54 (3) (Feb. 2016) 824–845, https://doi.org/10.1080/00207543.2015.1074299.
[9] M. Butlewski, W. Czernecka, A. Pajzert, M. Radziejewska, M. Suszynski, C. Feniser, 'Ergonomic Criteria in the Optimization of Assembly Processes', in: Performance Management or Management Performance?, I. Abrudan, Ed., Cluj-Napoca: Todesco Publishing House, 2018, pp. 424–431.
[10] M. Dalle Mura, G. Dini, Optimizing ergonomics in assembly lines: a multi objective genetic algorithm, CIRP J. Manuf. Sci. Technol. 27 (2019) 31–45, doi: 10.1016/j.cirpj.2019.08.004.
[11] Y. Harari, A. Bechar, U. Raschke, R. Riemer, Automated simulation-based workplace design that considers ergonomics and productivity, Int. J. Simul. Model. 16 (Mar. 2017) 5–18, https://doi.org/10.2507/IJSIMM16(1)1.355.
[12] M. Bortolini, M. Faccio, M. Gamberi, F. Pilati, Multi-objective assembly line balancing considering component picking and ergonomic risk, Comput. Ind. Eng. 112 (Oct. 2017) 348–367, https://doi.org/10.1016/j.cie.2017.08.029.
[13] S.E. Moussavi, M. Mahdjoub, O. Grunder, A multi-objective programming approach to develop an ergonomic job rotation in a manufacturing system, IFAC-Pap. 51 (11) (Jan. 2018) 850–855, https://doi.org/10.1016/j.ifacol.2018.08.445.
[14] A. Iriondo Pascual, D. Högberg, D. Lämkull, E. Perez Luque, A. Syberfeldt, L. Hanson, 'Optimization of productivity and worker well-being by using a multi-objective optimization framework', IISE Trans. Occup. Ergon. Hum. Factors (2021) 1–11, Nov. 2021, doi: 10.1080/24725838.2021.1997834.
[15] C. Pole, S. Hillyard, Doing Fieldwork, SAGE, 2015.
[16] A. Iriondo Pascual, D. Högberg, A. Syberfeldt, F. García Rivera, E. Pérez Luque, L. Hanson, Implementation of ergonomics evaluation methods in a multi-objective optimization framework', presented at the 6th International Digital Human Modeling Symposium, August 31 - September 2, 2020, Skövde, Sweden, IOS Press, 2020, pp. 361–371. Accessed: Feb. 24, 2021. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:his:diva-19010.
[17] A. Iriondo Pascual, E. Mora, D. Högberg, L. Hanson, M. Lebram, D. Lämkull, Using time-based musculoskeletal risk assessment methods to assess worker well-being in optimizations in a welding station design, in: Proc. 7th Int. Digit. Hum. Model. Symp. 7(1) (2022), Art. no. 1, doi: 10.17077/dhm.31746.
[18] A. Iriondo Pascual, A. Lind, D. Högberg, A. Syberfeldt, L. Hanson, Enabling concurrent multi-objective optimization of worker well-being and productivity in DHM tools, SPS2022, 2022, pp. 404–414, doi: 10.3233/ATDE220159.
[19] A. Iriondo Pascual, H. Smedberg, D. Högberg, A. Syberfeldt, and D. Lämkull, Enabling knowledge discovery in multi-objective optimizations of worker well-being and productivity, Sustainability 14(9) (2022), Art. no. 9, doi: 10.3390/su14094894.
[20] B. Oates, Researching Information Systems and Computing, SAGE, 2005.
[21] J. Brooke, 'SUS: A "Quick and Dirty" Usability Scale', in: Usability Evaluation In Industry, CRC Press, 1996.
[22] L. McAtamney, E. Nigel Corlett, 'RULA: a survey method for the investigation of work-related upper limb disorders', Appl. Ergon. 24(2) (1993) 91–99, doi: 10.1016/0003-6870(93)90080-S.
[23] S. Hignett, L. McAtamney, Rapid entire body assessment (REBA), Appl. Ergon. 31 (2) (Apr. 2000) 201–205.
[24] V. Louhevaara, T. Suurnakki, S. Hinkkanen, P. Helminen, OWAS: a method for the evaluation of postural load during work. Institute of Occupational Health. Centre for Occupational Safety, Helsinki, 1992.
[25] C. Lind, M. Forsman, L. Rose, Development and evaluation of RAMP I : a practitioner's tool for screening of musculoskeletal disorder risk factors in manual handling, Int. J. Occup. Saf. Ergon. (2017) 1–16.
[26] T.R. Waters, V. Putz-Anderson, A. Garg, L.J. Fine, Revised NIOSH equation for the design and evaluation of manual lifting tasks, Ergonomics 36 (7) (Jul. 1993) 749–776, https://doi.org/10.1080/00140139308967940.
[27] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Trans. Evol. Comput. 6 (2) (Apr. 2002) 182–197, https://doi.org/10.1109/4235.996017.

[28] K. Deb, H. Jain, An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, Part I: Solving problems with box constraints, IEEE Trans. Evol. Comput. 18 (4) (Aug. 2014) 577–601, https://doi.org/10.1109/TEVC.2013.2281535.

[29] T. Robič, B. Filipič, 'DEMO: Differential Evolution for Multiobjective Optimization', in: Evolutionary Multi-Criterion Optimization, C. A. Coello Coello, A. Hernández Aguirre, and E. Zitzler, Eds., Berlin, Heidelberg: Springer, 2005, pp. 520–533. doi: 10.1007/978-3-540-31880-4_36.

[30] A. Höldrich, 'Work load examinations at the log wood production', Tarım Makinaları Bilimi Derg 7(2) (2011) Art. no. 2.

[31] A. Bangor, P. Kortum, J. Miller, Determining what individual SUS scores mean: adding an adjective rating scale, J. Usability Stud. 4 (2009) 3.

[32] S. Sattar, K. Laila, M. Z. H. Khan, G.M.A.M. Khan, Relation of job related factors with different dimensions of quality of work life, World J. Public Health, vol. 3, no. 1, Art. no. 1, May 2018, doi: 10.11648/j.wjph.20180301.13.

[33] A.-C. Falck, R. Örtengren, D. Högberg, The impact of poor assembly ergonomics on product quality: a cost–benefit analysis in car manufacturing, Hum. Factors Ergon. Manuf. Serv. Ind. 20 (1) (2010) 24–41, https://doi.org/10.1002/hfm.20172.

[34] A. Chintada, V. Umansakar, Improvement of productivity by implementing occupational ergonomics, J. Ind. Prod. Eng. 39 (1) (Jan. 2022) 59–72, https://doi.org/10.1080/21681015.2021.1958936.

[35] P. Drinkaus, et al., Comparison of ergonomic risk assessment outputs from rapid upper limb assessment and the strain index for tasks in automotive assembly plants, Work 21 (2) (Jan. 2003) 165–172.

[36] T. Jones, S. Kumar, Comparison of ergonomic risk assessment output in four sawmill jobs, Int. J. Occup. Saf. Ergon. 16 (1) (Jan. 2010) 105–111, https://doi.org/10.1080/10803548.2010.11076834.

[37] L. Hanson et al., 'Industrial Path Solutions – Intelligently Moving Manikins', in DHM and Posturography, Elsevier, 2019, pp. 115–124. doi: 10.1016/B978-0-12-816713-7.00011-8.

[38] N.J. La Delfa, J.R. Potvin, The "arm force field" method to predict manual arm strength based on only hand location and force direction, Appl. Ergon. 59 (Mar. 2017) 410–421, https://doi.org/10.1016/j.apergo.2016.09.012.

[39] J.R. Potvin, V.M. Ciriello, S.H. Snook, W.S. Maynard, G.E. Brogmus, The liberty mutual manual materials handling (LM-MMH) equations, Ergonomics 64 (8) (Aug. 2021) 955–970, https://doi.org/10.1080/00140139.2021.1891297.

[40] P.G. Dempsey, V.M. Ciriello, R.V. Maikala, N.V. O'Brien, Oxygen consumption prediction models for individual and combination materials handling tasks, Ergonomics 51 (11) (Nov. 2008) 1776–1789, https://doi.org/10.1080/00140130802331625.