

# AUTOMATED SIMULATION-BASED WORKPLACE DESIGN THAT CONSIDERS ERGONOMICS AND PRODUCTIVITY

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## Abstract

When designing a workplace with manual material handling tasks, it is important to consider both production and ergonomics. We developed an automated workplace design methodology that addresses production and ergonomics for tasks involving a handled mass of up to 23 kg. This process combines optimisation and a Digital Human Modelling (DHM) simulation, which yield the production and ergonomic measures. The task cycle time in current DHM simulations is based on Predetermined Motion Time Systems (PMTS). To address reservations about the time prediction accuracy of PMTS, we developed a new time prediction model that takes the influence of the handled mass into consideration. Our model and optimisation process were evaluated by using a case study of a box conveying workplace design. The time prediction model results did indeed agree with the real mass handling behaviour. Three design approaches (objective functions) were compared: considering only production, only ergonomics and both production and ergonomics. Each approach resulted in a different optimal solution.

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**Key Words:** Workplace Design, Optimisation, Simulation, Ergonomics, Predetermined Time Prediction

## 1. INTRODUCTION

An important trend in industrial workplace design [1] is the growing focus on both economic and ergonomic measures [2]. Against this background, the most desirable design would be the one that gives a combination of the highest production rate (*PR*) [3] and a minimum risk for musculoskeletal disorders [4]. Because such disorders constitute a large financial burden on industries [5], many ergonomic assessment methods have been developed to reduce the risk of injury. Common ergonomic assessment methods include: the National Institute for Occupational Safety and Health (NIOSH) lifting equation [6], which determines the recommended weight limits; Lower Back Analysis (*LBA*), which estimates the spinal compression and shear forces acting on the worker's lower back [7-9]; and Rapid Upper Limb Assessment (*RULA*), which provides an assessment of neck, trunk and upper limb posture [10]. All these assessments can be executed using Digital Human Modelling (DHM) simulations, e.g., Jack<sup>TM</sup>, AnyBody<sup>TM</sup>, and Delmia<sup>TM</sup>, all of which are effective for workplace design [11, 12]. By using DHM, it is possible not only to design a workplace but also to assess the effects of the workplace design by using operational and ergonomic measures [13, 14]. DHM software usually predicts the duration of tasks executed by a virtual worker using Predetermined Motion Time Systems (PMTS), such as Methods Time Measurement (MTM) and the Maynard Operation Sequence Technique (MOST).

However, several studies have questioned the prediction accuracy of PMTS as compared to the actual performance of real workers [15, 16]. Genaidy et al. [17], for example, concluded that one of the major disparities occurs in tasks involving the handling of a heavy

mass, and that in most cases the time prediction overestimates the human physiological capability. A few studies have offered solutions to the overestimation issue by inserting fatigue allowances [18] or adjusting the standard times of tasks [19]. However, these time corrections were specifically tailored to limited number of tasks (e.g., changing an oil filter), and therefore could not be applied to other tasks. To overcome these limitations, our research proposes a model that predicts the task time based on the handled mass and the lifting and lowering heights for handling the mass.

Previous studies that focused on improving workplace design for manual handling exhibited additional limitations. The limitations of studies that have addressed both production and ergonomic aspects [20-24] lie in the fact that they did not consider all possible solutions. In addition, the handled mass in the simulated tasks was low and constant and the task duration was calculated using PMTS. Therefore, this approach may lack validity for cases that involve handling of heavier masses [16, 17, 25]. To address these issues, our proposed optimisation process considers a broader range of solutions, while allowing for modification of the object's mass.

Finally, past research has suggested that ergonomic improvement will result in increased productivity [4, 20]. We argue, however, that this may not be the case when the mass of the handled object changes during the design process. Consequently, our research compares three different objective functions: to obtain optimal ergonomics, to focus on optimal production and to consider aspects of both production and ergonomics. We therefore use multi-objective optimisation and DHM simulation to develop an optimisation process for workplace design that takes into consideration both ergonomic and production measures. The innovations of this research thus lie in the development of a task time prediction model for different object masses and station heights, and the development of a workspace design optimisation procedure that considers solutions based on different objective functions (optimal ergonomic, optimal production, and a combination of the two). This research also extends past studies as it considers a wide range of workplace design configurations.

The remainder of this paper is organised as follows. In the next section (section 2), we give an overview of the simulation approach for workplace design, and then we describe the examined case study, the DHM simulation, and the analyses performed in the study. In section 3, we describe the development of our new biomechanical time prediction model. In section 4, we present the optimisation process. In section 5, we present the results and discussion. Section 6 includes conclusions, and a discussion of the limitations and future directions.

## **2. METHOD**

### **2.1 Overview**

We developed an automated process to determine the best workplace design and object mass (Fig. 1). This process uses a multi-objective optimisation combined with a DHM simulation (Jack<sup>TM</sup>). To execute the process, the following code components were written in Python<sup>TM</sup>: 1) the main program that manages the communication between the code functions and runs the optimisation algorithm; 2) a simulation function that sends the workplace design parameters required by Jack<sup>TM</sup> for each run (e.g., conveyer height, distances, etc.); 3) a new time prediction model that reads the joint motion from Jack<sup>TM</sup> after each run and then calculates the task Cycle Time (*CT*); and 4) an objective function that calculates the score based on the ergonomic Performance Measures (PMs) and the *CT*. The main program runs this process for each set of workplace design parameters and then determines the best solutions. All of the automated processes were performed on a Lenovo G550 PC with an Intel® Pentium® Processor T4300 (1M Cache, 2.10 GHz, 800 MHz FSB).

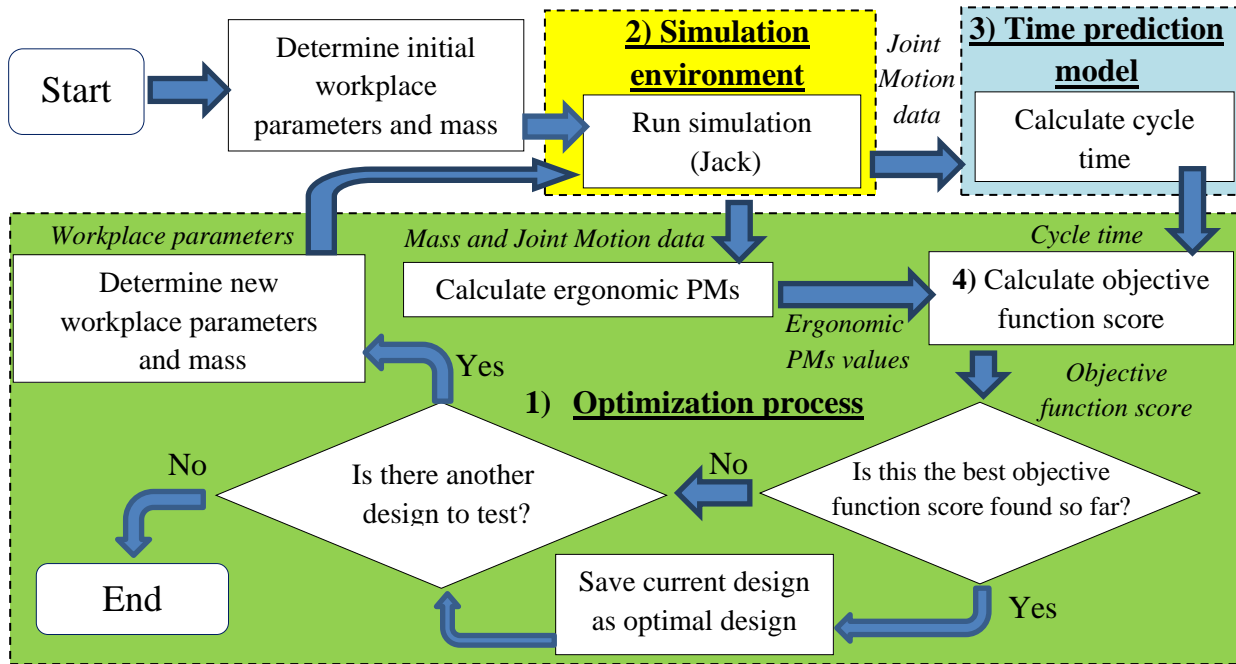


Figure 1: Automated workplace design based on an optimisation approach.

## 2.2 Case study: Box conveying work process

As a case study to demonstrate and assess our approach for determining an optimal workplace design, we chose a box conveying work process, which is a common task in agricultural packing houses and in warehouses. The process includes four basic tasks: (1) lifting a box from a conveyor; (2) carrying the box to a platform; (3) lowering the box onto the platform; and (4) returning to the conveyor to lift a new box. The digital workplace was designed in Jack<sup>TM</sup> and consisted of a roller conveyor, a shipping platform, a box, and a worker (Fig. 2). For our study, we chose the anthropometric worker data for a median male from the ANSUR database [26] (height of 1.75 m and weight of 79 kg). The walking distance between the conveyor and the platform was set at 5 m.



Figure 2: Box conveying workplace designed in Jack<sup>TM</sup>.

## 2.3 Digital human modelling simulation

The workplace was designed and the work process simulated using Jack<sup>TM</sup> (Siemens PLM) software for generating virtual 3D work environments and analysing the ergonomics of the task. The inputs for each simulation run (i.e., the independent variables) were the mass of the handled box and the heights of the shipping platform and of the conveyor in the workplace. After each simulation run, Jack<sup>TM</sup> yielded the worker's temporal joint angles and the *LBA* values in each time frame during the task.

## 2.4 Analyses

### *The effect of the workplace design parameters on the time predictions*

To gain insights into the utility of our time prediction model, we examined the data from the simulation in order to answer the following questions: How do the time predictions for the lifting and lowering tasks change as a function of the conveyor/platform height? How do these time predictions change as a function of the box mass?

### *Assessment of the biomechanical time prediction model*

To assess our time prediction model, two comparisons to previous publications were made. In the first comparison, the metabolic rate of the worker was calculated using the results of our simulation and the new time predictions as input to the equation of Garg et al. [27]. Then, these metabolic rate predictions were compared to the metabolic rate recommended by Chaffin [28]. This assessment was performed three times for conveyor and platform heights of 20 cm and three box masses of 2, 10 and 23 kg. In the second comparison, we compared the time predictions of our model with the results of Lee's experiments [29] for box lifting and lowering.

### *Investigation of the objective functions and optimisation algorithm*

To analyse how variations in the optimisation parameters change the objective function score, two tests were performed. First, the conveyor and platform heights were manipulated and the box mass was kept constant. Second, we examined how variations in the box mass change the score of three objective functions. Finally, for a better understanding of the effect of user preferences on the final design and PMs, we compared the optimal solutions obtained using the three objective functions.

## **3. DEVELOPMENT OF THE BIOMECHANICAL TIME PREDICTION MODEL**

For optimizing a workplace design involving different masses of the handled object, it is important to use a time prediction model that captures the characteristics of the changes in the times of lifting, lowering and carrying tasks as a function of the handled mass. Therefore, our aim was to develop a model that can calculate the total *CT* of a manual material handling work process consisting of lifting, lowering, carrying and walking (the last of the four stages with no mass). The model must include tasks in the simulation; thus, we proposed the following formulation to calculate the *CT*, Eq. (1):

$$CT = t_{bend} + t_{reach} + t_{lift} + t_{carry} + t_{lower} + t_{release} + t_{rise} + t_{walk} \quad (1)$$

where  $t_{bend}$ ,  $t_{reach}$ ,  $t_{lift}$ ,  $t_{carry}$ ,  $t_{lower}$ ,  $t_{release}$ ,  $t_{rise}$  and  $t_{walk}$  are the times required to bend, to reach for the mass and grasp it, to lift the mass, to carry the mass, to lower the mass, to release the mass, to stand erect and to walk with no load, respectively. In the reaching, grasping and releasing activities, there is no mass involved, therefore the times ( $t_{reach}$  and  $t_{release}$ ) were taken to be 1 s, according to MTM tables. For the remainder of the task elements, time prediction equations were developed separately, based on experimental results found in previous publications [29-36]. These equations combined with motion data from the simulation provide the task time prediction.

### **3.1 Lifting time**

For the lifting task with trunk extension and flexion, the time duration of the trunk extension element ( $t_{lift}$ ) was calculated as the change in trunk angular extension from the initial to the

final trunk angle ( $\Delta\theta_T$ ), based on data from the DHM, divided by the trunk average angular velocity ( $\omega_T$ ). To determine  $\omega_T$ , the relation between the peak trunk velocity and the mass handled was calculated using data from the studies of Davis and Marras [30] and Marras and Davis [31] for different masses. A linear regression curve fit estimating the trunk angular velocity was obtained, with  $R^2 = 0.913$  and a high level of significance ( $p$ -value  $< 0.001$ ; Fig. 3).

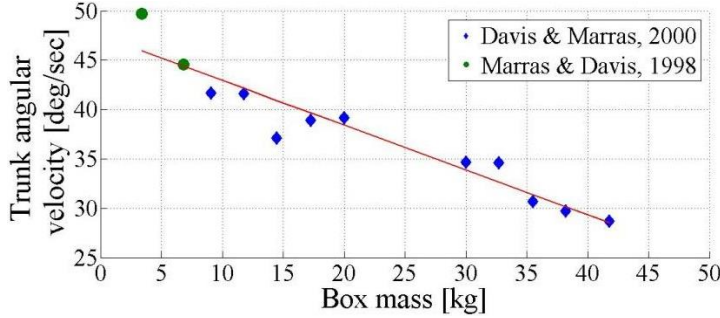


Figure 3: Relation between the lifted mass and the trunk peak angular velocity.

The average trunk velocity during the lifting activity was found to be 69.7 % smaller than the peak velocity, based on the results of Allread et al. [32]. Thus, a linear model describing the relation between the object mass,  $m$ , and the average trunk angular velocity was developed, Eq. (2):

$$\omega_T(m) = -0.137662 \cdot m + 14.3881 \quad (2)$$

Thereafter, the box lifting time,  $t_{lift}$ , was calculated using the trunk extension angle ( $\Delta\theta_T$ ) and the average angular velocity ( $\omega_T$ ):

$$t_{lift} = \frac{\Delta\theta_T}{\omega_T(m)} \quad (3)$$

For a worker height of 1.75 m (median male in ANSUR database; [26]) and an initial height of the object to be lifted that is more than 100 cm from the floor, no trunk extension is required for the lifting. In this case, the worker lifts his/her arms to the height of the object, and then lowers them while bringing the object closer to his/her body. The time prediction for this case was calculated using the shoulder rotation angle  $\Delta\theta_S$  and the shoulder angular velocity  $\omega_S$ , Eq. (4):

$$t_{lift} = \frac{\Delta\theta_S}{\omega_S(m)} \quad (4)$$

Since, to the best of our knowledge, there are no published studies referring to the shoulder flexion velocity during the lifting of different masses, we assumed that the effect of the mass would be similar in shoulder and trunk extensions, and therefore the trunk velocity could be calculated using Eq. (2).

### 3.2 Mass carrying time

To determine the relation between the handled mass and the carrying velocity, the findings of Goldman [33] and Hughes and Goldman [34] are used. These studies found that soldiers performing combat (e.g., carrying out an uphill assault, clearing mines) and load carrying tasks, and being allowed the liberty of working/walking at a self-selected pace, unconsciously adjusted their pace to maintain a metabolic rate of 7.29 W/kg. However, this metabolic rate is considered to be the exertion level of combat soldiers [33], and may not be suitable for manufacturing workers during a continuous eight-hour work shift. For such cases, Chaffin [28] recommended a metabolic rate during physical work of 5.34 W/kg. Assuming that

employees work at a pace that does result in this recommended metabolic rate, we determined the walking speed by using findings from two studies. First, we used the study of Schertzer and Riemer [35], who calculated the metabolic rate for a mass carried on the back ( $MR_{back}$ ) as a function of the carried mass,  $m$ , and the carrying velocity,  $v$ , Eq. (5):

$$MR_{back} = e^{0.518479+0.220584 \cdot v+0.011237 \cdot m} \quad (5)$$

Second, we used the findings of Datta and Ramanathan [36], who found that the metabolic rate for carrying a mass in the hands is higher than that, carried on the back, and can be represented in the following relation, Eq. (6):

$$MR_{hand} = MR_{back} \cdot (1 + 0.01067 \cdot m) \quad (6)$$

where  $MR_{hand}$  is the metabolic rate for the mass ( $m$ ) carried. Then, using Eqs. (5) and (6), the walking velocity as a function of the carried mass is given by Eq. (7):

$$v = 5.229512605 - 0.09390347244 \cdot m \quad (7)$$

The box carrying time,  $t_{carry}$ , is given by Eq. (8):

$$t_{carry} = \frac{d}{v} \quad (8)$$

where  $d$  is the carrying distance, and  $v$  is the carrying velocity in Eq. (7).

### 3.3 Lowering time

Using the results of Lee's [29] experiment of box lifting and lowering, we revealed that the average time for box lowering is 13 % less than that for lifting under the same conditions. Thus, using the change in trunk angle and the angular velocity for lowering, the lowering time  $t_{lower}$  was calculated as Eq. (9):

$$t_{lower} = \frac{\Delta\theta_T}{1.13 \cdot \omega_T} \quad (9)$$

For cases where trunk flexion is not needed and the lowering is performed using a shoulder extension, the time was calculated using the shoulder rotation angle and velocity, described above for lifting and in Eq. (4).

### 3.4 Return walking

The return walking velocity (with no mass carried) was determined to be 5.22 km/h, based on a metabolic rate of 5.34 W/kg and Eq. (5).

### 3.5 Bending and arising times

The bending time ( $t_{bend}$ ) includes trunk flexion without carrying a mass (before grasping the box) and is calculated using Eq. (9). The arising (standing up) time ( $t_{rise}$ ) includes trunk extension without carrying a mass (after releasing the box) and is calculated using Eq. (2).

## 4. DEVELOPMENT OF THE OPTIMISATION PROCESS

The purpose of the optimisation process is to find the best workplace design. The process consists of: defining the PMs for the optimisation, formulation of the objective function, and running of the optimisation algorithm. Our optimisation method consists of a two-stage grid search. In the first stage a coarse grid search of the entire solution span is conducted, and in the second stage a fine grid search is conducted in the proximity of the best solution obtained in the first stage. The best solution found in the second stage is determined as optimal.

#### 4.1 Performance measures (PMs) of the optimisation

##### *Ergonomic PMs*

The *LBA* and *RULA* were chosen to be the ergonomic PMs, since each evaluates different body parts and each evaluates a different ergonomic aspect (forces and postures, respectively). The lower back compression force was determined using the *LBA* tool in Jack<sup>TM</sup> [9]. The *RULA* score was calculated by using the code we developed in Python<sup>TM</sup>. This code reads the temporal joint angles for various body parts of the virtual worker (e.g., shoulder) from Jack<sup>TM</sup> and then calculates the *RULA* score. The maximum *LBA* and *RULA* values during the task were used as PM input for the optimisation objective function that was developed in this study. We used the maximum value that occurred during the work process, as this is the common practice in compliance assessments [37], especially for *RULA* which is recommended for evaluating the 'worst posture' [10], and for the *LBA* which requires that compression forces not exceed a maximum value of 3400N during the entire work process. Therefore, both PMs were calculated at highest sampling rate available by Jack<sup>TM</sup> (0.033s).

##### *Production PM*

The production rate (*PR*) was defined as the production PM. The *PR* is the total mass that was handled per unit time. The *PR* is calculated as a function of the handled mass and the *CT* (Eq. 10):

$$PR = \frac{m}{CT} \quad (10)$$

where  $m$  is the mass handled per work cycle and  $CT$  is the cycle time. Jack<sup>TM</sup> is able to calculate the  $CT$  based on the MTM method. However, since MTM may not provide a good representation of the change in the human working pace when heavy objects are handled [17], we used our new time prediction model developed in section 3 for calculating the  $CT$ .

#### 4.2 Formulation of the objective function

An objective function that combines the three PMs to evaluate a workplace design was developed based on the 'product of powers' formulation [38], Eq. (11):

$$U = \prod_{i=1}^n PM_i^{w_i} \quad (11)$$

where  $U$  is the objective function score;  $n$  indicates the number of PMs (3); the  $i$  index indicates the PM type:  $i = 1$  for *LBA*,  $i = 2$  for *RULA*, and  $i = 3$  for *PR*; and  $w_i$  represents the PM weights. This formulation enables the combination of PMs with different scales (e.g., *LBA* and *RULA*) without the need for normalization of the values. By controlling the weights' values, we determine the relative importance and influence of the PMs on the objective function score. In this study three objective functions, representing different user preferences, were used: 1) considering only ergonomic PMs – the 'Ergonomic Function' ( $w_1 = 1$ ,  $w_2 = 1$ ,  $w_3 = 0$ ); 2) considering only the production PM – the 'Production Function' ( $w_1 = 0$ ,  $w_2 = 0$ ,  $w_3 = -1$ ); and 3) considering both production and ergonomic PMs – 'Combined Function' ( $w_1 = 1$ ,  $w_2 = 1$ ,  $w_3 = -1$ ). The aim of the optimisation is to find the lowest objective function score that corresponds to the optimal workplace design.

#### 4.3 The optimisation algorithm

The optimisation process was executed using our specially developed Python<sup>TM</sup> code. The optimisation variables that determined the workplace design were: 1) the handled mass and 2) the heights of the conveyor and shipping platform. Before each simulation run, a new set of

variables was assigned to Jack<sup>TM</sup>. After each simulation run, Jack<sup>TM</sup> outputs were used to calculate the *PR* and *RULA* values and the objective function score. To reduce the computing time, the optimisation was executed in two stages (coarse and fine).

In the first optimisation stage, the handled mass was altered with increments of 1 kg in a range between 2 and 23 kg. The lower limit represents a very light box and the upper limit was set at 23 kg, since this is the maximum lifting mass recommended by NIOSH [6]. The heights of the conveyor and platform were altered by increments of 10 cm in the range of 20 to 160 cm measured from the floor. These mass and height limits were chosen in order to explore a large, feasible solution span while not exceeding the workers' capabilities. However, in the future the decision maker can narrow the span according to his/her subjective preferences, or due to specific operational and design constraints. After all workplace combinations (a total of 4950) had been examined, the workplace design that generated the lowest objective function score was designated as the best solution in the first stage. In the second stage, the mass and height of objects in the workplace were changed by increments of 0.5 kg in a range of  $\pm 1$  kg and 2 cm in a range of  $\pm 10$  cm, respectively, from the best mass/heights obtained in the first stage (an additional 605 combinations). If at the end of the first stage several optimal solutions are found, the second stage fine search is conducted around each of them, and the best solution found in all of the fine searches is determined as optimal. If at the end of the second stage several optimal solutions are found, all of them are presented to the decision maker to choose from.

The computational time for examining each design lasts 5 seconds, thus for the current case study the optimisation process, which included the examination of 5555 solutions, lasted 7 hours and 42 minutes. The workplace combination that generated the lowest objective function score was taken as the best solution of the optimisation process.

## 5. RESULTS AND DISCUSSION

### 5.1 The effect of the workplace design parameters on the time predictions

In the lifting and lowering tasks, a greater height of the conveyor or platform required less trunk extension and flexion, and thus the task duration was shorter (Figs. 4 a, 4 b, 4 c).

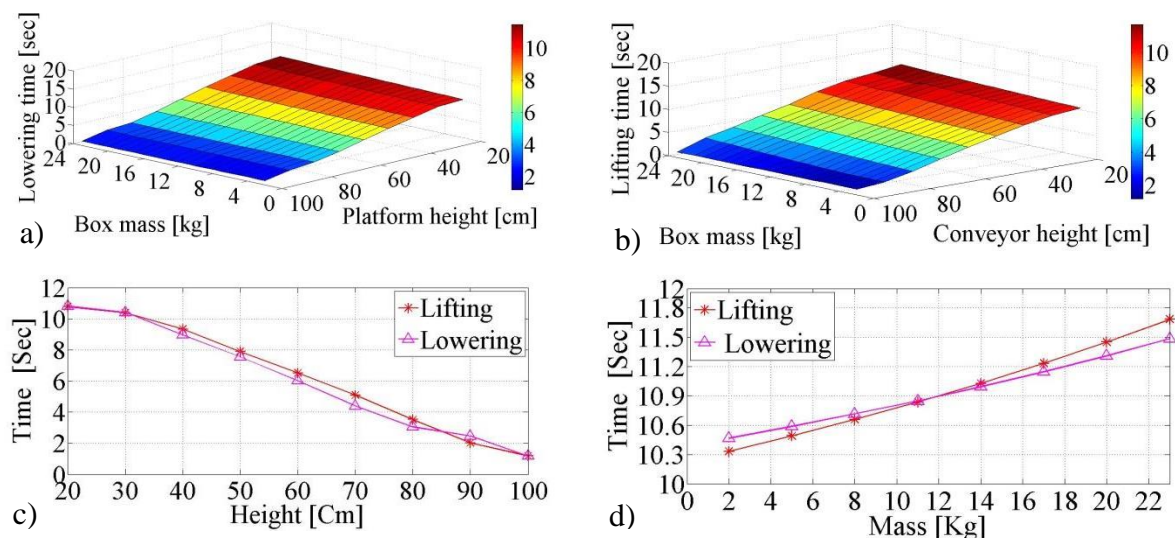


Figure 4: a) Lowering duration as a function of the platform height and the box mass; b) Lifting duration as a function of the conveyor height and the box mass; c) Lifting and lowering duration as a function of the lifting starting height or lowering ending height; box mass fixed at 10 kg; d) Lifting and lowering duration as a function of the box mass, conveyor and platform heights fixed at 20 cm.



The relation between the task duration and the lifting or lowering distance was not linear, especially at the edges (Fig. 4 c). This is because the virtual worker's lifting or lowering motion in Jack<sup>TM</sup> software changes as a function of the height of the conveyor or platform. As reported previously in the literature [30, 31], the results of the lifting and lowering times showed that an increase in the box mass reduced the trunk angular velocity, and thus increased the lifting and lowering durations (Figs. 4 a, 4 b, 4 d). It was also found that an increase in the box mass increased the maximal trunk bending angle which was higher for the lifting task and lower for the lowering task (see Fig. 4 d).

## 5.2 Assessment of the biomechanical time prediction model

Two evaluations were made to assess the correlation between the time performance predicted by our model and actual human behaviour. First, by using metabolic rate prediction equations [27] and times for each task as predicted from our model, the metabolic rate was calculated for different box masses with conveyor and platform heights fixed at 20 cm. The findings indicate metabolic rates of 4.7, 5.57 and 5.36 W/kg for box masses of 2, 10 and 23 kg, respectively. The average predictions of metabolic rate is 5.21 W/kg which is close to the desired metabolic rate recommended by Chaffin [28] for 8 h of continuous work (5.34 W/kg), with a maximum deviation of 14 %. Second, we compared results for the lifting times as obtained using our prediction model (see Eq. (2)) with the results of Lee [29] for box lifting from the floor to knee level for boxes with masses of 10, 15 and 20 kg. This comparison revealed that the CTs from Lee's experiment and from our model showed similar behaviour ( $R^2 = 0.99$ ). This consistency of the findings suggests that the influence of the object mass on the lifting time as calculated by our biomechanical time prediction model does indeed capture the behavioural characteristics of real people.

## 5.3 Investigation of the objective functions and the optimisation algorithm

The scores of the three objective functions (i.e., Production Function, Ergonomic Function and Combined Function) as a function of the platform and the conveyor heights for a fixed mass of 10 kg are presented in Figs. 5 a, 5 b and 5 c. The results show that for all three objective functions the score decreased with an increase in the conveyor and platform heights from 20 cm to 100 cm. The minimum score was achieved for conveyor and platform heights in the range of 100 to 120 cm. For heights above 120 cm, the worker was required to raise his/her arm in order to reach the box, which caused a moderate increase in the *CT*, *LBA* and *RULA* values, and resulted in a slight increase of the objective function score. The Production Function changed at a moderate rate, probably due to the relation between the height of the conveyor and the platform and the lifting and lowering durations, as presented in Figs. 5 a, 5 b and 5 c.

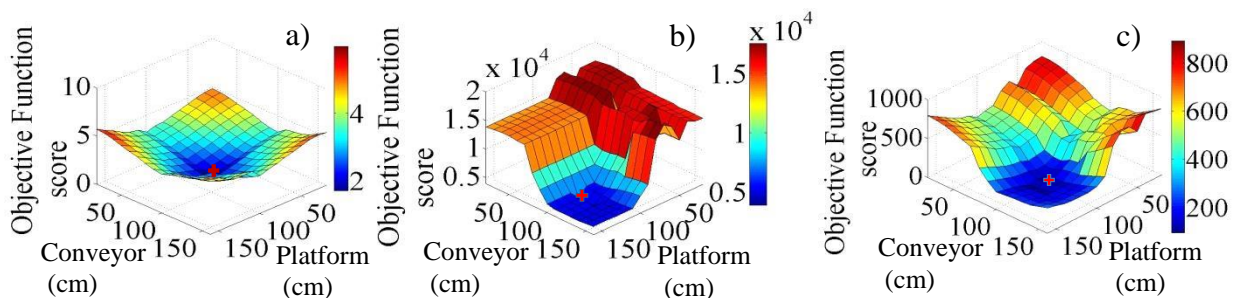


Figure 5: Effect of changes in the conveyor and platform heights on the objective function score for: a) the Production Function; b) the Ergonomic Function; c) the Combined Function (mass fixed at 10 kg).  $\oplus$  = the optimal solution.

Evaluation of the Ergonomic Function revealed that the objective function score improved significantly between the heights of 60 to 90 cm. This change can be explained by the considerable improvement in the *RULA* score in this range, and also suggests a nonlinear relation between the height changes and the lower back forces acting on the worker. In addition, when examining the effect of changes in the platform height on the Ergonomic Function, a local minimum was found at a height of 50 cm, due to an improvement of 1 point in the *RULA* score caused by the occurrence of smaller wrist and shoulder rotation angles in the lowering posture.

The effect of the box mass on the PM values, and thus on the objective function score, was examined separately for each of the three objective functions (Fig. 6 a). For the Production Function, the score decreased (improved) with an increase in the mass. For the Ergonomic Function, the score increased (deteriorated) with an increase in the mass; at a mass of 11 kg the *RULA* score increased from 4 to 5, due to additional negative points that were added to its inner calculations. This 'jump' at 11 kg demonstrates the importance of combining several ergonomic measures in the objective function. While the *LBA* is a forces-based measure and is continuously affected by changed in the box mass, and is sensitive to small mass changes, the *RULA* is a posture-based measure and only differs between masses above or below 10 kg, thus creating the 'jump' in Figure 6 a. For the Combined Function in the mass range between 2 and 10 kg the increase in the *PR* was higher than the increase in the *LBA* and *RULA* values and, thus, the objective function score decreased (improved). At 11 kg, the *RULA* score increased from 4 to 5, which explains the jump in the curve (Fig. 6 a); from 11 kg to 23 kg the increase in the mass caused an increase not only in the *PR* but also in the lower back forces (whereas the *RULA* score remained at 5).

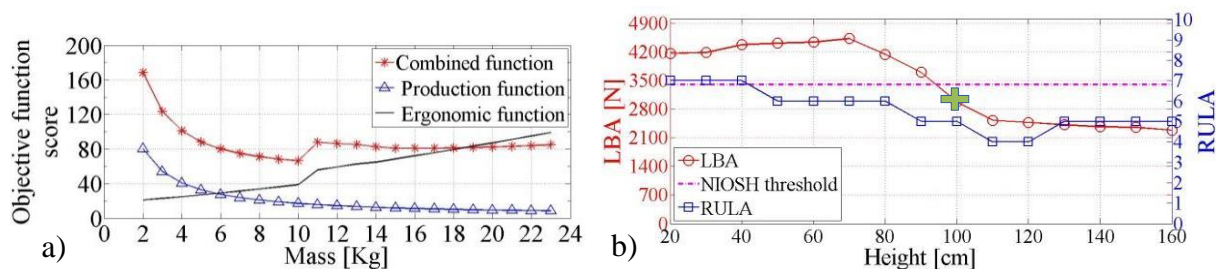


Figure 6: a) The objective function scores as a function of the box mass; b) *LBA* and *RULA* values as a function of the conveyor and platform heights, for a box mass of 23 kg. + = the optimal heights using the Production Function.

Next, the optimal design solutions (heights and box mass) for each of the three objective functions are presented and analysed (Table I). For the solution of the Production function, the *RULA* score was 5, which indicates that for this mass the work postures requires further ergonomic investigation and improvements. Also, the combination of heavy box mass (23 kg) and optimal lifting and lowering postures resulted in an *LBA* value of 2981 N. Although this *LBA* value is below the NIOSH threshold of 3400 N, it may still increase the risk of back injuries [6]. The *LBA* value is influenced by both the box mass and the work postures; for this solution, lowering the conveyor height by as little as 10 cm resulted in an *LBA* value that exceeded the NIOSH threshold (Fig. 6 b).

A comparison of the optimal solution for the Production Function with that for the Combined Function showed a carrying time that was shorter by 29.5 % and a total task *CT* that was shorter by 13.2 % in the latter. This, in turn, reduced the *PR* by 49.9 % and improved the ergonomic PMs by reducing the *RULA* score by 20 % and reducing the *LBA* value by 53.7 %.

Table I: Design solutions and time prediction of the task elements for the three objective functions.

Objective function	Conveyor height (cm)	Platform height (cm)	Box mass (kg)	<i>RULA</i>	<i>LBA</i> (N)	<i>CT</i> (s)	<i>PR</i> (kg/min)	Lifting time (s)	Carrying time (s)	Lowering time (s)	Return walking time (s)
Production	100	100	23	5	2981	11.83	116.6	1.19	5.86	1.33	3.44
Ergonomic	116	120	2	3	699	16.16	7.42	4.56	3.57	4.58	3.44
Combined	100	100	10	4	1379	10.27	58.39	1.32	4.19	1.31	3.44

- Lifting time =  $t_{bend} + t_{reach} + t_{lift}$ ; Carrying time =  $t_{carry}$ ; Lowering time =  $t_{lower} + t_{release} + t_{rise}$ ; Return walking time =  $t_{walk}$

Optimisation with the Ergonomic Function resulted in a low *LBA* value and *RULA* score, and platform and conveyor heights that do not require trunk bending. In comparison to the optimal solution of the Production Function, the *PR* was lower by 93.6 %.

The optimal solutions of the Ergonomic and Production Functions might be impractical for an industry environment, since they may either lead to a very low production rate (the Ergonomic solution) or to a high risk of injuries (Production solution). These results show the benefit of using the combined approach (i.e. using the 'Combined Function'), which offers a solution with both acceptable productivity and ergonomic values.

Since both *LBA* and *RULA* deteriorate with the increase of handled mass, it is expected that the optimal mass using the Ergonomic Function would be the lowest possible. Therefore, the limit values of the design's lowest mass should be considered by the decision makers. Note that regarding production rate, the maximum mass does not guarantee the maximum production rate, since an increase in the mass reduces the lifting, carrying and lowering velocities, and therefore increases the cycle time of the worker. Therefore, an increase of the mass can result in a reduction of the production rate.

For demonstration purposes, equal weights were assigned to the measures in the 'Combined Function'. However, in future use of the proposed methodology the weights should be carefully determined according to the decision maker's preferences.

## **6. CONCLUSIONS**

This study presents an automated workplace design process that addresses both production and ergonomics aspects by using DHM simulation and multi-objective optimisation. The design approach can help in improving workers' productivity and in reducing the risk of injury. This design process extends previous studies [20, 23], in that it includes the object mass as a variable in the optimisation process and tests a much larger number of designs; it is therefore likely to achieve a better workplace.

It has been proposed that design solutions with improved ergonomics, especially for improving working postures and for tasks that are performed over longer periods of time (e.g., a few hours or more), will result in increased productivity [4, 20]. However, these studies were performed with fixed mass, and our study shows that when the handled mass changes, the improvement of ergonomic values may cause deterioration in the production measure. In the presented case study, considering only ergonomics resulted in a workplace design which improved the ergonomic values by 76.5 % yet caused deterioration in the production rate by 93.6 %, which would probably not be acceptable to the decision maker. Thus it is important to consider both ergonomic and production in the optimisation process, as offered by our Combined Function.

Finally, the time prediction model developed in this work captured the characteristic behaviour of real humans by considering the influence of changes in the handled mass on the

work pace of the worker. The time predictions of our model resulted in an average predicted metabolic rate of 5.21 W/kg, which is only 2.5 % lower than the recommended value of 5.34 W/kg.

## 6.1 Limitations and future directions

The developed biomechanical time prediction model aims to capture the characteristics of changes in time for lifting, carrying, lowering and walking tasks, as a function of the handled mass. Such a model is appropriate for the workspace design optimisation process as long as the characteristics of real people are captured. However, while the model's predictions are in agreement with previous experiments [29] and models [28], additional validation is necessary concerning its ability to predict work rate in a real working environment.

The results of the simulation depend on the representation of generic human motion prediction by Jack<sup>TM</sup>. Yet, there is always individual variability in motion [39] and strength [40], and therefore the workplace design configuration obtained by the optimisation might need to be further adjusted for a given individual.

The current study considered task design by using the maximum value of the *LBA* and *RULA* during the work process. Future work should investigate the effect of a long-term ergonomic analysis (i.e., the duration of an entire shift, year, etc.) using criteria for evaluating cumulative trauma disorder.

Finally, due to the simulation processing time of Jack<sup>TM</sup>, 5 s on average were required for the execution of each iteration in the optimisation process. Therefore, the optimisation of complex workplaces or optimisation with higher accuracy could result in long computation times. The results of this case study and the use of ergonomic guidelines could be used to narrow the search span and reduce the optimisation time in future studies. Moreover future research should consider an additional optimisation algorithm to reduce the run time.

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