ERGONOMIC EVALUATION OF BASIS MANUAL ASSEMBLY OPERATIONS WITH INTEGRATION OF SIMULATION TOOLS

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Abstract: *This paper describes the development of a simulation model. The model deals with the role of assembly worker in the virtual environment with an emphasis on ergonomics and time analysis. Firstly, we analyse time reports of common tasks in manufacturing processes like reaching, lifting etc. We receive time reports from three different methods: analytical MTM method, Siemens JACK 8.4 simulation and practical experiment. Secondly, we look into influential parameters, dimensions and mass of object, which affect the time reports. The results of our research show us that the parameters have different weight of importance. The main goal of this paper is to propose suggestions and guidelines for a worker-friendly environment from an automated generated ergonomic report of JACK simulation. We also ergonomically evaluate the task of lifting with the NIOSH method and propose improvements.*

Keywords: SIMULATION TOOL, MANUAL OPERATIONS, COMPUTER AIDED MANUFACTURING, DIGITAL HUMAN MODELLING, TIME ANALYSIS, ERGONOMICS EVALUATION.

1. Introduction

Due to an increasing competition on the global market, industrial companies are confronted with new challenges, such as higher productivity, new product design, shorter lead times and better quality. Companies need to provide ergonomically designed manual assembly workplace that support productivity, quality and promote the health of workers and potential new employees [Törnström, 2008].

In the early stages of manual workplace design the workers are not effectively considered which is one of the top challenges in the factories of the future. However, the use of digital human modelling (DHM) tool can enhance quality by minimizing changes, promoting security and eliminating ergonomically related problems [Onan, 2007]. The main advantages of DHM tools are representative simulation and associated graphics for ergonomics analysis of products and workplaces [Chaffin, 2005; 2007]. The focus in Technomatix Jack software is on improving the design with emphasis on product, ergonomics and human factors by using DHM [Onan, 2007]. Siemens Jack simulation tool use MTM time standard for all time reports [Siemens Technomatix JACK TSB User's Guide, 2015].

Ergonomics (or human factors) is defined by the International Ergonomics Association as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to this design in order to optimize human well-being and overall system performance. Ergonomists contribute to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people [Karwowski, 1999].

The National Institute for Occupational Safety and Health (NIOSH) in the US published an equation for setting weight limits for lifting tasks in 1981. The equation applies to symmetric lifting tasks [Dempsey, 2015]. The equation was then reformed in 1991 and was called the revised NIOSH lifting equation. The revised NIOSH lifting equation includes aspects such as asymmetry, coupling, frequency etc. for manual lifting [Sahni, 2016]. The objective of both equation is to prevent or reduce the occurrence of lifting-related low back pain (LBP) among workers and others musculoskeletal disorders [Waters, 1993].

The activities we have dealt with in our research are common in an industrial environment. By analysing the activity of lifting the load that is dangerous to the worker's health, we can reduce the number of injuries in the workplace, which is relevant for the industry. The goal of all manufacturing companies is that work does not affect worker's health, so they must provide enough time to rest during the activities. In the literature, we found some scientific articles that deal with a similar topic as our case study. Agosta et al. [Agosta, 2016] focused on the simulation of the upper limbs by comparing the real and abstract movement. Macaluso et al. [Macaluso, 2016] also deal with the upper limbs. They research arm movement underwater and the results were compared with the results obtained on land. The emphasis of their research was on the kinematics of the arm at the pace. Other researchers also focused on other parts of the body. Cheng [Cheng, 2018] was studying the lower body, Padula et al. [Padula, 2003] the trunk. They researched the movement of the trunk while lifting the load to different heights. The experiment was conducted on different population groups (female, male, students, workers with and workers without musculoskeletal symptoms). The only work [Harari, 2018] that deals with the same topic as our research covers the MTM experiment and MOST analysis, but does not include any computer simulations. The emphasis is on the whole body of workers and their aim were to develop a new time prediction model. Authors Polašek et al. in their work focus on comparing digital simulation tools (JACK, Delmia) to assess ergonomics in practical cases. Three analyses focused on carrying, lifting (NIOSH) and biomechanical conditions were carried out. The results of both digital tools were compared and concluded that both tools are suitable for ergonomic simulation of the work environment. The authors of Okun et al. [Okun, 2017] have developed a new framework of fundamental workplace safety and health knowledge and skills (the NIOSH 8 Core Competencies) based on the Health Belief Model (HBM), which examines how the social and physical environment affects young workers. The aim of the research is to provide young people with knowledge and skills on safe and healthy work.

The paper describes step by step an assessment methodology for basic tasks, which we are used in an assembly processes. The comparison of time reports based on MTM method and JACK simulation tool was made. Our research focuses on the evaluation of the impact of two different parameters of the box (dimension, mass) on the total time in the worker`s lifting procedure. After that, we perform a practical experiment of the same sequence of tasks and compare time results with time reports from MTM method and JACK simulation. Finally, we assess ergonomic report of the tasks with emphasis on lifting task. We use NIOSH lifting equation tool to evaluate influence of different parameters (load weight, frequency, asymmetry etc.).

2. Methodology

2.1 The MTM method

The MTM method is a process that analyses any manual operation or the method of basic movements necessary for its implementation [Laring, 2002].

Predetermined time standard prescribes each movement. Time standard is defined by the nature of the movement and with its conditions. The MTM methodology is based on the following five basic movements: to reach, to grasp, to move, to position and to release. These movements compose 80 % to 85 % of the procedure wholly influenced by human beings [Ferreira, 2009]. Six different moves can describe the movement of the body: sitting and getting up, sidestepping, turning, bowing, squatting and getting up, kneeling and walking [Krager, 1961].

2.2 The simulation tool

The Task Simulation Builder (TSB) is the part of Siemens Jack 8.4 software. In it, you can create a simulation, where humans and objects can be fully animated. Firstly, the user selects type of activity from the existing task list and works through the wizard-style user interface, to enter each task's parameters. Secondly, when a simulation is complete, you can generate a timing report. Time report breaks each task down into actions and provides time estimates. In TSB, you can also select one of the several real time ergonomics analysis tools to review the simulations. Predetermined task, that we can use are; to go, to get, to put, to pose, position, regrasp, wait, touch and apply force. Mid-simulation we can swap between sitting and standing. This task does not include any type of motion for the worker, it simply changes the state so that all tasks added afterwards will know the worker is sitting (or standing) [Siemens Technomatix JACK TSB User's Guide, 2015].

2.3. NIOSH analyses tool

The NIOSH Lifting Analysis tool (part of Siemens JACK 8.4) is based on the NIOSH lift equation, which was developed by a committee of experts who evaluated research findings from a wide range of worker performance studies. The lifting guideline reflects biomechanical, psychophysical and metabolic (energy) data.

You use the NIOSH Lifting Analysis Tool when you need to: estimate the injury risk of two-handed, manual lifting tasks, evaluate a job characterized by multiple lifting tasks, evaluate a lifting task characterized by trunk rotation, different types of hand coupling, repetitiveness, and duration, determine a relatively safe load weight for a specific task, decide the appropriate style of intervention/abatement for a task that has demonstrated a lifting hazard, compare the relative risk of two lifting task configurations, prioritize jobs for further ergonomic analysis.

The model concepts give us a simple linear equation that yields a Recommended Weight Limit (RWL) and Lift Index (LI) or Cumulative Lift Index (CLI). RWL is defined for a specific set of task conditions as the weight of load that nearly all healthy workers could perform over a substantial period of time (up to 8 hours) without increasing risk of developing lift – related lower back pain.

Recommended Weight limit (RWL) is calculated as:

RWL = LC x HM x VM x DM x AM x FM x CM

Where: LC is the load constant, determined to be 23kg, HM is the horizontal multiplier (the horizontal location of the hands), VM is the vertical multiplier (the vertical location of the hands from the floor), DM is the distance multiplier (the vertical lift distance), AM is the asymmetry multiplier (the asymmetry angle in degrees), FM is the frequency multiplier (lifts/min), CM is the coupling multiplier (between 1.00 ("good") and 0.90 ("poor")).

The lifting index (LI) is calculated simply as:

LI = Actual Task Load Weight / RWL

From the NIOSH perspective, it is likely that lifting tasks with a LI > 1.0 pose an increased risk for lifting-related low back pain for some fraction of the workforce. NIOSH considers that the goal should be to design all lifting jobs to achieve a LI of 1.0 or less. Experts agree that nearly all workers will be at an increased risk of a work-related injury when the LI exceeds 3.0 [Siemens Technomatix JACK NIOSH Lifting Analysis Tool, 2015].

The NIOSH Lifting Analysis Tool does provide specific recommendations in reports for each of the equation multipliers (see Table 1).

Table 1: *Interpretation of the recommendations [Siemens Technomatix JACK NIOSH Lifting Analysis Tool, 2015].*

HM < 1	- Bring the load closer to the worker by removing any horizontal barriers or reducing the size of the load - Avoid lifts near the floor - If lifts near the floor can not be avoided, the load should fit easily between the legs.
VM < 1	- Raise/lower the origin/destination of the lift - Avoid lifting near the floor or above the shoulders.
VM < 1	- Reduce the vertical distance between the origin and the destination of the lift.
AM < 1	- Move the origin and destination of the lift closer together to reduce the angle of twist - Move the origin and destination further apart to force the worker to turn the feet and step, rather than twist.
FM < 1	- Reduce the lifting frequency rate - Reduce the lifting duration - Provide longer recovery periods.
CM < 1	- Provide new containers with better handles - Improve the handles on the containers being used.
RWLD < RWLO*	- Eliminate the need for significant control of the object at the destination through job redesign or modifying the container/object characteristics.

*D – Destination (Final state of worker while lifting), O – Origin (Initial state of worker while lifting)

3. Case Study

Our case study is an example of common used sequence of tasks in industrial manual assembly process. The goal is to compare time reports from the MTM method and JACK simulations software tool, respectively. The problem is posed, like an example of lifting the box with the mass of 13.6 kg and size of 406.4 mm from the floor to the table. At the start, the worker stands in front of the table facing it, and the box stands on the left side of the table. The worker must go to the box, take it and put it on the table. In order to bring our case study closer to the industrial environment where these activities are common (lifting, carrying, etc.), we set up a laboratory experiment and performed the same sequence of movements. The experiment includes 10 students. Additionally, we perform ergonomic analysis on origin tasks simulation. After that, we adjust critical joints and perform another analysis for comparison. Then we use NIOSH analysis tool for lifting task. Based on recommendations, we improve critical parameters and get worker friendly lifting task.

Fig. 1: *Some tasks from the sequence (go, bend, turn).*

Our case study includes next sequence of tasks (Fig. 1). Firstly, from the initial state the worker turns the body by 90°. After this, the worker starts walking parallel to the edge of the table towards to the box. He walks the distance of 1200 mm. The worker performs two sidesteps to reach the gap between his feet for easier lifting of the box. When the worker is in the balanced position, he bends to the box and prepares for the next move that is reaching for the box. The worker picks up the box in the middle of the bottom edge. He grasps it with both hands and applies force according to the load. The worker lifts the box and regrasps it for easier carrying. After that, he straightens his body to the neutral position. Than he takes the turn by 180° and walks back in a straight line towards the table. The distance he walks is 1200 mm. The worker turns his body to face the table. Then he puts the box on the table. The position of the box on the table is not important and for this reason, we use the "put" movement and not the "position" movement. After putting the box on the table, the worker returns to the neutral pose facing the table.

We perform 25 versions of simulation with different combinations of mass and dimensions of the box. We compare all versions of simulation by the MTM method and JACK simulation tool with an emphasis on the duration of tasks.

For the given sequence of tasks, we make ergonomic report. We focus on posture demands. The analysis includes joints angle summary for neck, back, wrists, shoulders and elbows. After origin analysis, we adjust the most strained joints and observed improvements.

After that, we make NIOSH analysis for lifting task. From the origin simulation, according to the simulation tool suggestions, different combinations of parameters were taken into consideration, so that we received ergonomically appropriate execution of the task.

4. Results

In this section, we present results of time analyses. First results are from analytical method MTM, second are from automatic generated Jack simulation tool and third from laboratory experiment. In this section, the results of the ergonomic analyses (posture demands and NIOSH lifting equation) are also presented.

4.1. Time analyses of tasks

Table 2 presents all basic movements for task sequence of our case. Time for each movement is given by the MTM method, the JACK simulation and through experimental approach. Time of all movements is not completely consistent. We can note that different movements contribute different share to the total time. According to the JACK software, for example, lifting time is twice as long as the time for the same movement, according to the MTM method. Therefore, the same movement has a greater or lesser effect on the total time, if we use different methods.

***Table 2**: Comparison of basic movements between MTM method, JACK simulation and practical experiment.*

	MTM method	**JACK simulation**	**Practical experiment**
Description of basic movements	**Time [s]**	**Time [s]**	**Time [s]**
Turn body by 90°	0.67	0.2	0.97
Walking	0.76	1.34	1.97
Sidestep	0.64	0.64	0.78
Bend towards the box, reach and	1.30	2.54	1.02
Force application	0.38	0.38	0.59
Straighten the body	1.38	3.16	1.55
Turning by 180°	2.01	0.781	1.47
Walking to the table	0.67	0.95	1.37
Turning by 90	1.34	0.17	0.61
Put the box on the	0.35	1.76	1.25
Neutral position	0.52	0.5	0.87
Total times [s]	**10.12**	**12.42**	**12.45**

If we focus only on total times by each method, we can see that all tasks by MTM spend 10.12 s, by JACK simulation 12.42 s and the total time of the practical experiment is 12.45 s.

Human being and avatar never perform task in the same way, because we always use different trajectories, joint`s angles, path walks, etc. In this matter, the simulation and experiment are the same and this is the reason why they give us the same result of total time. We can note from table 2 that MTM method spend 20% less time for the whole sequence of tasks.

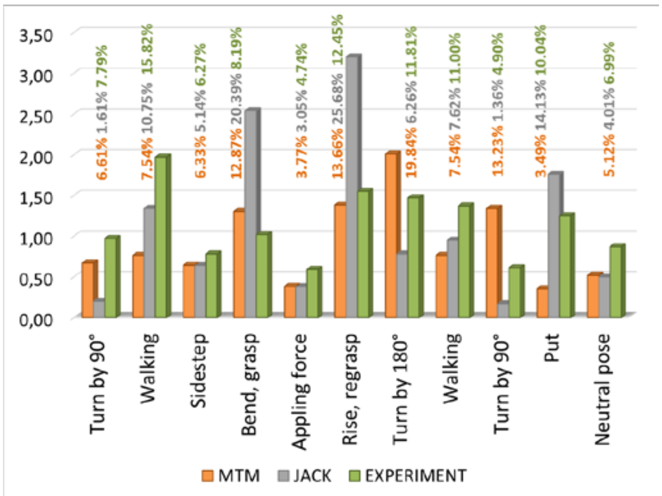

***Fig. 2:** Comparison of the time analysis.*

Fig. 2 represents time difference for each task between different methods. The percentage above the columns shows the proportion of each task according to the total time, so if we look closer the first column, 6.61% is the time share of task "turn the body" by 90° by MTM method. We note that there is a huge deviation in percentage, especially for the task of bending towards the box and grasping it (bend, grasp) and for the task of straightening the body and regrasping the box. Task "rise and regrasp" represent 25% of total time by Jack simulation. Another interesting task based on time analysis is turning; the Jack simulation needs less time for avatar to turn, compared to the MTM method, which requires more time. The practical experiment shows that the human spends the longest amount of time on walking.

4.2 The Influential parameters

This sub-chapter focuses only on time analysis by the MTM methods and by the Jack simulation. Work methodology is the main difference between both methods. "What-if" scenarios can be used in JACK for different movements and tasks. With this option, we can quickly change various parameters of the object (mass, dimensions) and the avatar (sex, anthropometric features).

Table 3 and Table 4 represent results of total time for all dimensions and mass combinations of the box for the MTM method and JACK simulations. Total times of tasks, mass and dimensions in MTM method are linearly dependent.

***Table 3:** MTM total time analysis for different dimensions and masses of the box.*

		Mass of the box [kg]				
		4.5	**9.1**	**13.6**	**18.1**	**20.4**
Dimension of the box [mm]	**203.2**	9.32	9.60	9.89	10.17	10.34
	304.8	9.43	9.72	10.01	10.29	10.44
	406.4	9.54	9.83	10.12	10.42	10.56
	508.0	9.66	9.95	10.24	10.54	10.68
	609.6	9.77	10.06	10.36	10.66	10.80

The analysis of the results shows that the mass of the box has no effect on the total time of simulations, which is not logical. The time is changing only because of the prolongation of waiting time so that the worker gets accustomed to the mass of the box (apply force task). In reality, we need more time to lift a heavier box. In result analysis, we also discovered that dimensions have no effect on total time. The adjustment of the body and joint position for each task separately is necessary when changing the dimensions of the box. The total time is different because joints can never be adjusted identically.

Table 4: *JACK total time analysis for different dimensions and masses of the box.*

		Mass of the box [kg]				
		4.5	**9.1**	**13.6**	**18.1**	**20.4**
Dimension of the box [mm]	**203.2**	12.06	12.20	12.34	12.51	12.57
	304.8	12.18	12.31	12.43	12.56	12.62
	406.4	12.15	12.28	12.41	12.54	12.60
	508.0	12.05	12.17	12.30	12.43	12.47
	609.6	12.36	12.48	12.60	12.72	12.79

In conclusion, the JACK software does not take into account the different dimensions and masses of the object when performing the same movements, although in the reality lifting bigger and heavier objects takes more time.

4.3. Ergonomic analyses

The analysis was made for all the joints of the body, and the paper presents only joints where the parameters were the most critical. The entire pie diagram represents the time of the working cycle. The green colour represents the time when a worker is in an acceptable position in which almost every healthy worker can perform tasks completely. Yellow represents the time when the worker is in a conditionally acceptable position, while orange represents a time of posture that is unacceptable. Figure 3 shows a flexion of the back. The left part of figure 3 is an analysis of the ergonomics of the initial simulation state, and the second part of figure 3 represents an improved version of the simulation. We note that we reduced the time of an unacceptable position of back flexion at the new simulation by almost 5 times. On the left side of Figure 4, we see an indication of the radial bending of the wrist. With an improved simulation, the unacceptable position of the joint was reduced by almost 5 times. In Fig. 5, we can see the flexion of the back and wrist in the initial and improved version of the simulation.

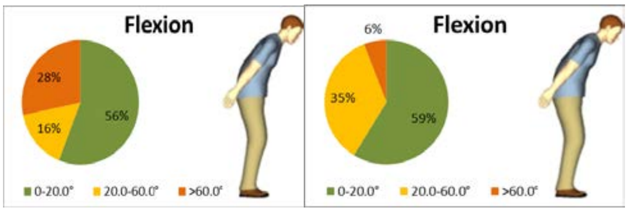

Fig. 3: *Time spent for work cycle in each posture range for back flexion.*

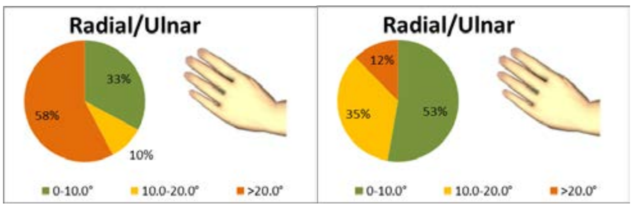

Fig. 4: *Time spent for work cycle in each posture range for radial bending of wrist.*

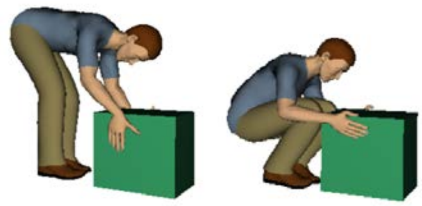

Fig. 5: *Initial and improve version of simulation.*

The simulations of lifting the box were carried out according to the NIOSH methodology. We made seven simulations, some were ergonomically acceptable and the others not (see Table 5). The parameters for calculating RWL, which are not in the table, are therefore constant in all versions of simulation (LC = 23 kg, HM = 0.64, VM = 0.86, DM = 0.89, CM = 0.95, Coupling = poor).

In the first version (task named 1), when worker lifts a box of 13.6 kg (AL) and his body is twisted (O.A., D.A.), we obtained results that are completely unacceptable (red colour; STLI). The program gives us recommendations to reduce the rotation of the body to reduce the distance between the worker and the box and to reduce the frequency of the lifting.

Table 5: *NIOSH results of various simulation.*

TASK	AL	O.A.	D.A.	F	D	AM	FM	FIRWL	STRWL	FILI	STLI
1	13.6	180.4	4.7	4	4	0	0.7	0	0	****	****
2	13.6	0	0	4	4	1	0.8	10.7	8.01	1.26	1.7
3	13.6	0	0	2	4	1	0.8	10.7	8.68	1.26	1.6
4	10	0	0	4	4	1	0.7	10.77	8.01	1.26	1.3
5	8	0	0	4	4	1	0.7	10.77	8.01	1.26	1
6	7	0	0	4	4	1	0.7	10.77	8.01	1.26	0.9
7	7	0	0	2	4	1	0.8	10.77	8.68	1.26	0.8

In the next version of simulation (task named 2), we eliminated the rotation and obtained a conditionally acceptable result (yellow colour; STLI). The program has proposed reducing the frequency of work and providing a longer recovery period. We got a slightly better result, but it is still unsuitable for the whole duration of the job (8 hours). The next improvement was the reduction of the box weight to 10 kg. We got a better LI, but still unacceptable. By reducing the weight to 8 kg, the index LI was 1, which is the first acceptable result. This result tells us that this task has a nominal risk for lower back injury from physical stress. Then we reduced the mass to 7kg and performed two versions of simulation with different frequencies and obtained the results shown in tasks named 6 and 7. We can note that the biggest improvements were brought by a reduction in back rotation and lighter load

5. Conclusions

Nowadays, the need for restructuring of companies is shown with the aim of providing higher productivity, shorter lead time and lower costs for the same or better quality of products. Despite the modernization and automation of the production, there are still many manual assembly workstations in the industry. For a better condition and worker-friendly environment, the assembly needs to be adapted to the worker`s needs in order to prevent injuries and work related diseases. Ergonomic design for workers should be introduced into the initial stages of process development. For easier and faster design, the most appropriate use is simulations and digital human modelling (DHM). As a result, we get an ergonomic and time-equivalent simulation of the avatar, as in a real environment.

A practical experiment was conducted and a simulation with the MTM method and the Siemens Jack 8.4 software was made. The problem described is composed of the usual tasks that are common in an industrial environment, such as lifting and lowering the load. In our case, the load was transferred from the initial point on the floor to the final point on the table. The first goal was to identify, using MTM method and simulations, how and if the different dimensions and masses of the load affect the total time of the described case. In the following, we compared the times of individual tasks and the total times according to all three methods. The benefit of this paper is an example of how modern technology, such as ergonomic tool Siemens Jack, can help. It allows us to evaluate the workplace, if it is well organized for humans and if working positions are acceptable. We can determine which factor may cause a health risk. This is the reason why we conduct ergonomic analysis and different “what if” scenarios for NIOSH lifting tasks.

Using the MTM method and the Jack simulation, we analysed the effect of the mass and dimensions of the box on the total time. We carried out 25 different combinations - five different masses and 5 different dimensions of the box. The total time range by MTM analysis was between 9.32 and 10.80 seconds. The mass and the dimension of the box linearly affect the total time. The range of total times by the Jack simulation was between 12.05 and 12.79 seconds. By changing the weight and size of the box, the total time according to the Jack method does not change. In the real environment, the mass or/and the size of the box surely affects on the duration of total times.

Our research work has shown that the total times of practical experiment and simulation match. The difference between the MTM method and the practical experiment comes from the fact that a worker always chooses a different point of grasp, a trajectory, a walking speed and adapts it to the conditions in the environment. In addition, in the simulation, the programmer puts the avatars in different positions similar as in experiment, so between those two analyses there are minimal deviations in total time. From a practical point of view, we can conclude that the total times of all methods are the same, but the times of individual tasks vary. For the industrial environment, only the total times are important, and the difference in the times of the individual tasks is not significant. However, if we want to optimize sequence of tasks, it is necessary to do detailed research of each task separately.

For the sequence of tasks, we performed an ergonomic analysis. We found out that in the given sequence the worker's back and wrist are most affected. According to the results, we retake the simulation by relieving the back and arms and re-creating the ergonomic report. The new report shows that the time when the worker was in an unacceptable position was reduced by 5 times for both strained joints.

The obtained results of all analyses are comparable and acceptable. From an industrial point of view, this means that we can use a simulation tool to determine the optimal sequence of operations. It makes the design of manual assembly easier and faster. The great advantage of simulation tools is also “what – if” scenarios that can be used to determine the time standard for each individual worker and the load, respectively. As a result of the simulations, we obtain a time and ergonomic reports that are consistent with the real environment. An additional advantage is animation of work, which facilitates the understanding of manual assembly for both workers and managers. Further work in the field of simulation should include a detailed analysis of the correlation between the duration of the task and the different load parameters and its implementation in a virtual environment.

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