Digital production planning and human simulation of manual and hybrid work processes using the ema Software Suite

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Abstract

For planning and designing production and work systems, a holistic approach is necessary that considers both levels of factory planning and workplace design. Currently, separate digital tools are mostly used for the design of factories and the detailed planning of work systems. That leads to workers being considered inadequately or too late in the planning process of production. The consequence can be a time-consuming and costly replanning to solve problems in existing production and work processes. Using the example of an assembly of washing machines, an iterative approach is presented for a combined digital planning on factory and workplace level. A holistic design of the assembly line is carried out using the ema Software Suite, consisting of the ema Plant Designer (emaPD) and ema Work Designer (emaWD). In the case study, emaPD is used to optimize production elements such as operating resources, layout, and logistics by considering the material flow, throughput times, and production costs. These results are applied for detailed planning and design at the workstation level with emaWD, which uses an algorithmic approach for self-initiated motion generation based on objective task descriptions. The generated simulations are examined and optimized based on production time estimation (MTM-UAS) and ergonomic risk assessments (EAWS, NIOSH, reach and vision analysis) as well as workers' abilities (age, anthropometry). As a result, an efficient factory with an optimized material flow could be planned while minimizing the manufacturing costs and throughput times while complying with the space specifications and ergonomics. The takeover of ergonomically unfavorable processes by robots as hybrid workstations enables, among other things, an improvement in ergonomics. The digital planning approach of combined factory (emaPD) and workplace design (emaWD) also enable early, coordinated, efficient planning of economical and ergonomic production.

Keywords: Ergonomics 4.0, Industry 4.0, Digital Factory, Digital Human Modeling (DHM), human-robot-interaction

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1. Challenges of design of economical and ergonomic factory and work systems

Increasing cost pressure from competition, labor and material costs, greater variety and shorter product life and market launch cycles require that production and work systems must be planned and reconfigured faster and more frequently (Spath et al. 2017, Bracht et al. 2018). When planning and designing production and work systems, in addition to costs, times, quality, time-to-market and flexibility, the ergonomic design for the user group as well as the skill-based deployment of the workforce must be considered (Schenk et al., 2014; Schlick et al., 2018). Different departments are usually involved in planning the factory / production respectively work system design. At the factory planning level, the focus is on the production program, the dimensioning, as well as the structuring and design of the factory and production systems. Work planning deal with the design of the workplaces and processes e.g., design of the workplace heights or the design of the human-machine / robot interaction according to economic and ergonomic criteria. Early, coordinated, and efficient planning of factory design as well as production and individual workplaces is important, but is often not done sufficiently (Bracht et al., 2018).

Many companies use digital design and simulation tools for their factory as well as work planning processes (Wiendahl et al. 2015, Bracht et al. 2018, Burggräf et al. 2021) The available software provides more and more functionalities such as Integrated Factory Modelling (IFM) model which offers the advantage of being able to access more detailed information than a pure 3D visualization (Burggräf et al. 2021). However, digital tools are mostly used separately for designing factories / logistics and for detailed planning of work systems (Bracht et al., 2018, Gunther, 2021). These software systems differ, amongst others, in functional scope as well as in the software handling. A common data basis is not available and must be achieved through data conversions. This is a time-consuming process and can lead to errors. Companies invest a lot of money for the software operation and must have design and simulation experts for the different applications who are expensive too. Not all software systems offer the appropriate interfaces to one another, so that factory and workplace planning often must be carried out separately. That can lead to that worker are considered inadequate or too late in the planning process of production. The consequence can be a time-consuming and costly replanning to solve problems in existing production and work processes.

For planning and designing production and work systems, a holistic approach is necessary that considers both the level of factory planning and workplace design to improve the quality of results and to reduce the effort. In the following, an iterative approach to continuous digital planning between the factory and workplace levels using the EMA Software Suite is presented.

2. Digital factory & work planning for economic and ergonomic production design

A procedure for iterative, combined factory and work planning using the software system 'EMA Software Suite' is described on the example of a washing machine production and assembly project. The aim is to redesign the assembly line and optimization the production line. It also should be checked whether the planned production program can be realized with the existing machines and assembly and how an improvement in the economic efficiency of the overall production could be realized next to good ergonomic condition for the worker on the single workplaces.

Based on the production program and range, the target quantities, the planning period and requirements for the quality and quantity of the production are to be defined. The product must also be analyzed, since the single components determine the manufacturing methods, the handling technology, etc. and the product structure the assembly sequence too. Product changes such as simplifying or merging functional units can also affect the technical, economic as well as ergonomic conditions (e.g. weight, forces, grasping) of the production (Schenk et al., 2014; Bracht et., 2018).

The washing machine consists of 86 components including a washing machine frame, washing machine drum, drain pump, various cables, hoses, and screws (see Fig. 1). The parts vary in shape, dimensions, and weight. The total weight is 82.95 kg and the individual weights vary from a few grams to more than 10 kg. The washing machine is produced in three color variants (white, blue, orange).

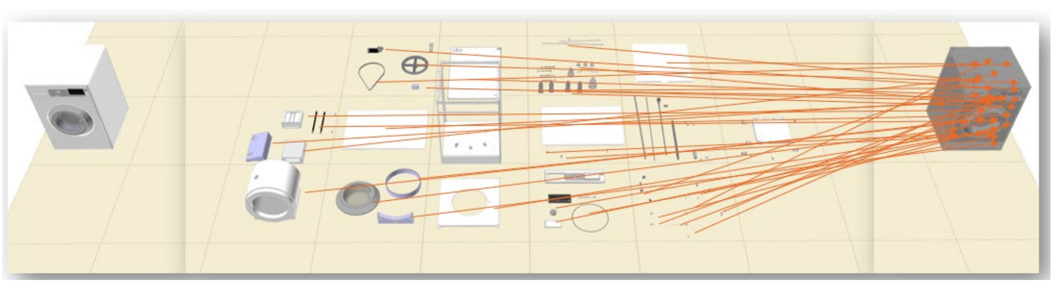

Figure 1. assembled washing machine (left) and individual parts of the washing machine (right)

Figure 2 illustrates the goals and functions of the EMA Software Suite with its two software systems EMA Plant Designer (emaPD, left side) and EMA Work Designers (emaWD, right side). The systems emaPD and emaWD can be used independently or together in one interface. In emaPD the planning of production and assembly takes place at the factory level (macro level) and in emaWD the exact 3D visualization and designing of production lines up to the workplace level are done according to economical, time and ergonomics criteria. The current planning statuses can be exchanged directly and synchronously via the bidirectional interface between emaPD and emaWD to update and refine the planning data.

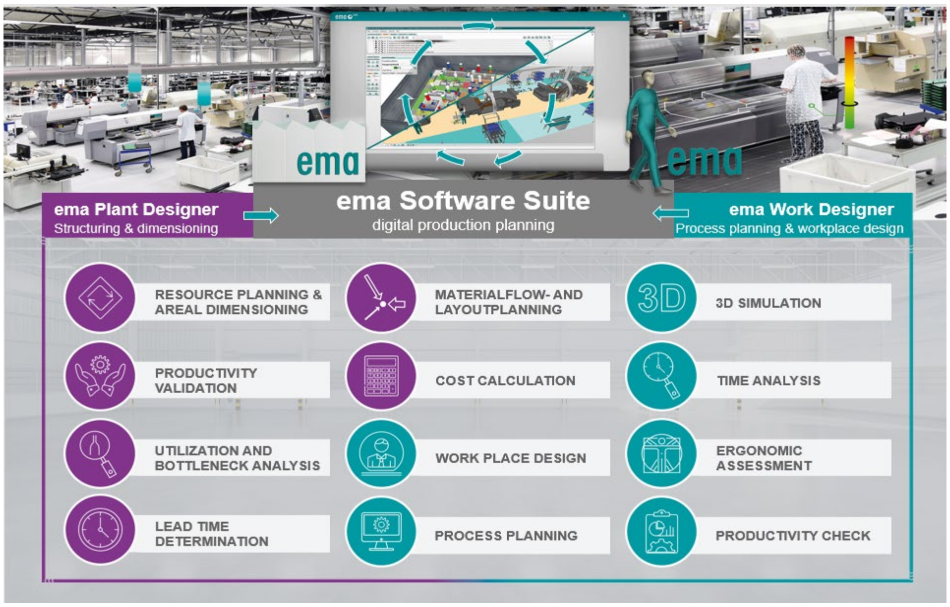

Figure 2. goals and functions of EMA Software Suite with emaPD (left) and emaWD (right).

On the basis of mathematical-analytical calculation methods (e.g. queuing theory (Manitz 2008)), computer-aided modeling, analysis and optimization of production with regard to throughput times, space requirements and manufacturing costs are carried out in the emaPD. Product data (planned quantities, parts list, lot sizes), process data (work plans, container data) and resource data (availability, costs, areas, shift models), which can be transferred via intersection, serve as inputs. As first step it is to be determined whether the production program (target: 80,000 washing machines per year) can be realized under the existing conditions (e.g. number, types of machines). Possible bottlenecks, space requirements or the critical path of production can be identified so that measures for improvement (e.g. adding more machines, buffer spaces) can be derived. Furthermore, a decision must be made about the proportion of in-house production and external procurement, as well as the equipment (machines) to be used and the work processes to be defined. Alternative machines and work plans can be created for the factory / production and variants can be calculated for the overall production plan considering output quantity, costs, utilization, space requirements and throughput times. Possible problems for workers in space, ergonomics aspects as well as a specification of the time requirements can be determined by transferring the results of emaPD to the emaWD. The interaction between the human using a digital human model with various characteristics and the workplace can be analyzed in emaWD and can be adapted according to ergonomic and economic requirements.

By calculating the overall equipment effectiveness (OEE) in the emaPD, the productivity and any losses of the machines can be determined. Set-up and processing times, scrap and rework rates, resource time, availability, planned downtimes can be defined and optimized by suitable measures. In emaWD, the production and assembly times can be specified at the work process level using the standard time method such as MTM-UAS (Bokranz & Landau, 2012). Another important point concerns the analysis of the costs of production and investment. The material and manufacturing costs can be calculated in emaPD considering the cost of material storage, the machines (hourly rates or fixed/variable costs), purchased and raw parts. In combination with emaWD, investment costs can be included for the resources, which in turn affect the costs of production.

At the overall production level in the emaPD, the total utilization of the machines and the available space in the factory must be included. Based on the entries, various scenarios can be set up and evaluated and compared according to KPIs such as required space, production volume and costs. For the dimensioning of the areas, among other things, operation areas are defined in the emaPD. A precise design of the layout (exact arrangement of machine, workplaces) and the creation of path maps can be specified in emaWD and can be returned to the emaPD. This allows the optimization of material flow based on transport intensity and effort. In addition, physical strain on humans could be also included in the planning process. For the creation and design of the layout in 3D, standard machines and workplaces can be defined in emaPD (left) and automatically imported into emaWD (right).

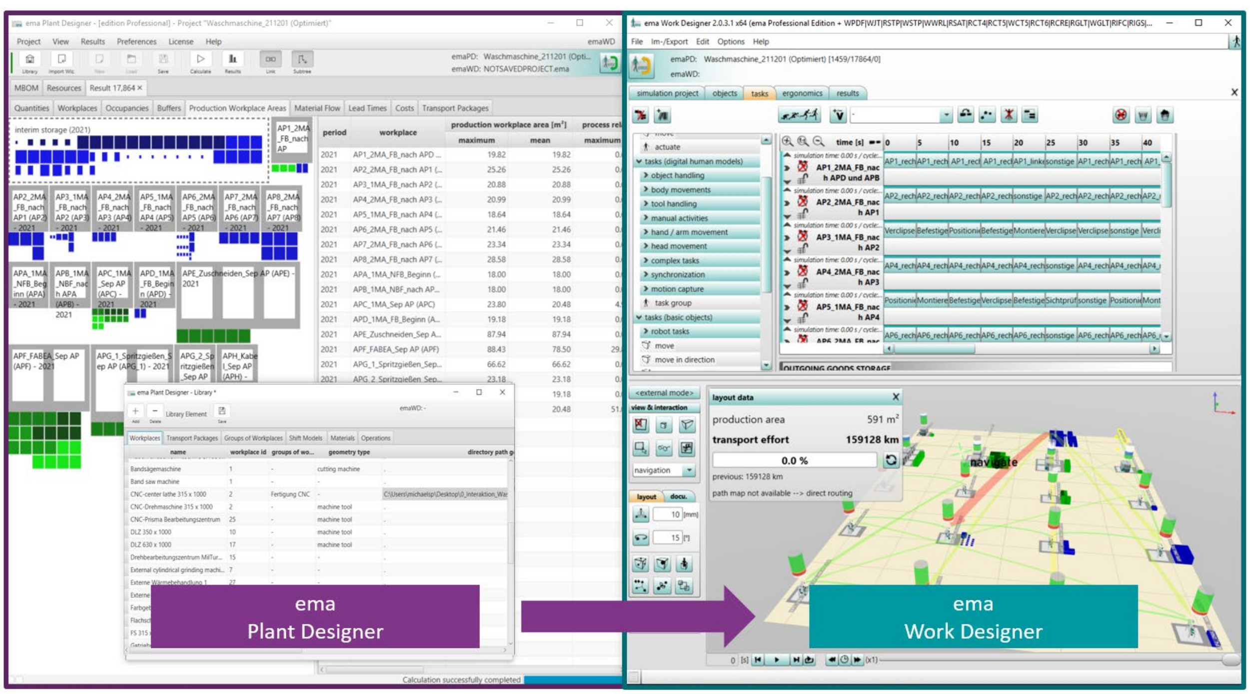

Figure 2. Transfer of washing machine production from emaPD (left) to ema WD (right).

In emaWD, the workstations can be supplemented with additional external objects via command CAD-formats such as *step, *jt, *dae, *obj, *wrl, *CATProduct and many more. Parameterizable objects such tables, tools, robots can also be used from the built in ema object library to expand or rebuilt the factory and the single workplaces.

The detailed planning and design of the workplaces is carried out in emaWD using anthropometric human models from small women (F05) to large men (M95) with different abilities (age-dependent flexibility, forces) for the design of economical, ergonomic, and ability-based work processes (Ullmann & Fritzsche, 2021). The human model configurator (cp. fig. 3) allows the user to add manikins in the 3D-environment. Digital human models in emaWD can be varied in the anthropometry related to different populations (e.g. German, Chinese, Mexican), different body dimensions (e.g. body height: 5th, 50th, 95th percentiles), gender and age groups (20, 40, 60 years), which based on anthropometry database and standards such as DIN 33402-2: 2020 for German population. The selection of an age-related average or restricted range of motion can also be selected (Spitzhirn 2017). Furthermore, the age group have an impact to the maximum forces in the ergonomic assessment (Ullmann & Fritzsche, 2017).

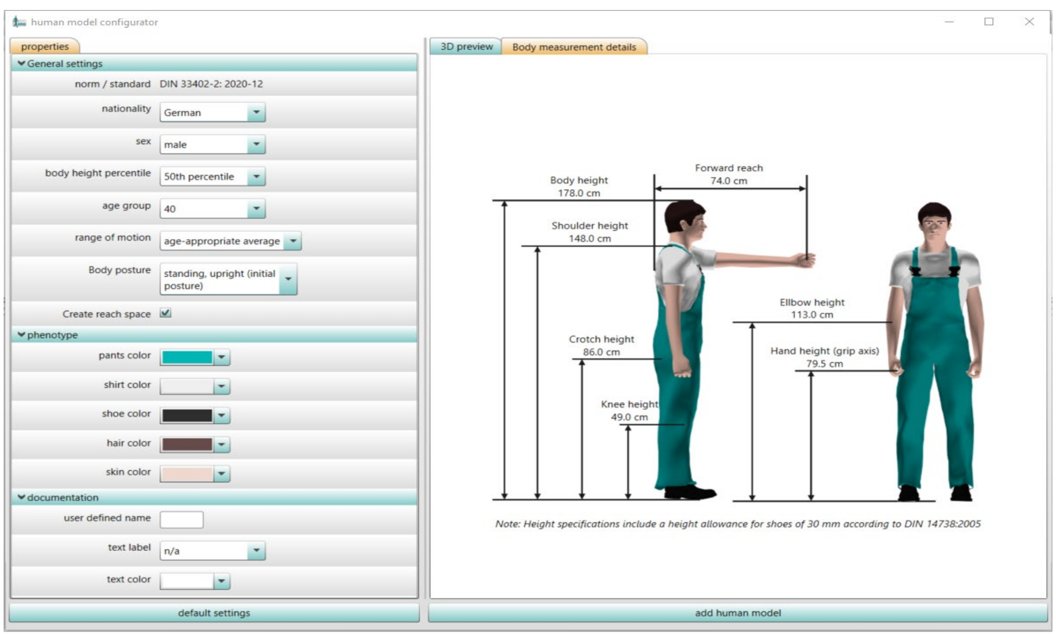

Figure 3. Human model configurator with 3D-Preview in emaWD.

The planning of manual and partially automated processes as well as human-robot interactions is possible using the process simulation in emaWD. To specify the work processes, the path and movement execution of the digital human model is automatically generated on the basis of a parameterized activity description (ema task library) with specification of basic work conditions (e.g. objects to be handled, target positions).

The user can use a lot of different and well know analysis methods such as standard execution time according to MTM-UAS (Bokranz & Landau, 2012), walking distances, proportion of value-adding activities as well as ergonomic analyzes of feasibility (reachability, visual analysis) and ergonomics and health risk assessment according to EAWS (Ergonomic Assessment Worksheet, Schaub et al., 2012) and NIOSH lifting index (Waters et al. 1994) in the emaWD to identify economic and ergonomic problems (Fritzsche et al., 2019b, Spitzhirn et al. 2022). Improvements can be made by changing the environment (e.g. table height), by transferring unfavorable activities from humans to the robot or by shifting work content between workstations. Different human-robot task distributions can be evaluated according to ergonomics and time, so that the best variant can be determined.

The changes can be examined via the bidirectional intersection for their effects at the factory level in the emaPD and thus an iterative optimization process can be carried out. The final concept is documented in the EMA software suite using reports, images, videos and the simulation of the production scenario.

3. Results of digital iterative production planning using digital factory and work planning

A production of 80,000 washing machines in three color variants (white: 55k, blue: 15k, orange: 10k) is planned. Fig. 4 shows example results for washing machine production.

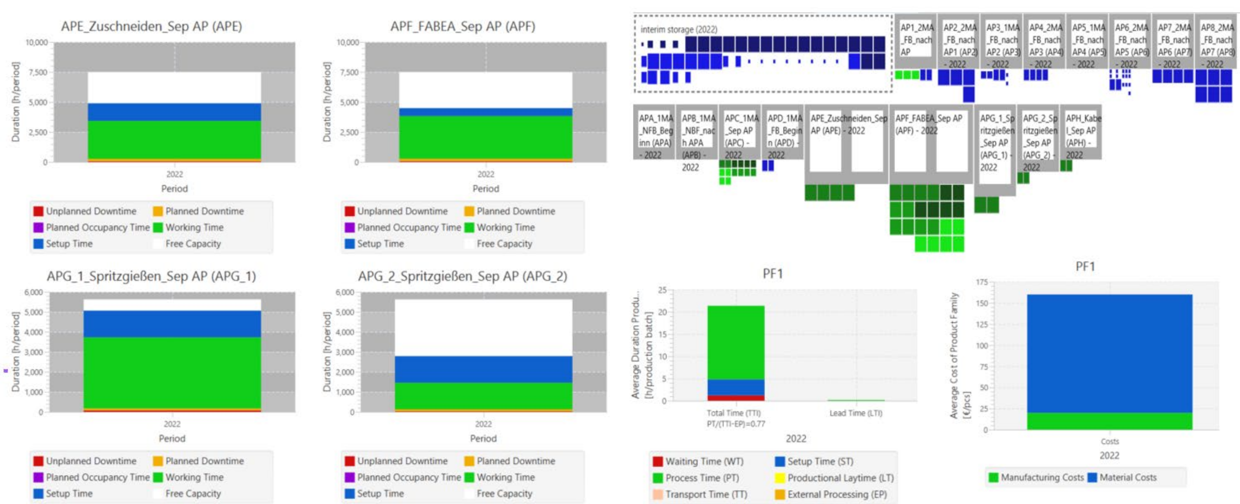

Figure 4. example results for washing machine production using emaPD.

Taking into account the availability of the machines as well as delivery costs, times and availability, 23 parts are manufactured in-house and 63 parts are purchased. The calculation of the current situation resulted in a deficit of 7,587 units. By increasing the number of cutting machines from 2 to 3, adjusting and harmonizing batch sizes and optimizing execution times (reducing waiting times, shifting orders to other machines), it was possible to achieve the production volume in production. In the assembly line, consisting of 8 linked workstations with a total of 14 employees, the blocking times at APB was decreased from 348 hours to 180 hours and at AP1 from 133 hours to 60 hours as well as the idle times on AP1 from 86h to 0h by integrating buffer areas between APB & AP1 (5 buffer areas), AP1 & AP2 (8 buffer areas). The production area is 530.06 m² with production costs of €159.98. The utilization of individual workstations differs from 98.6% for the assembly line to 48.6% for the injection molding machine type A.

The production and assembly line were transferred from emaPD to emaWD. In emaWD the material flow, including the route network, was rearranged (see Fig. 5, left) and the assembly was simulated in emaWD (see Fig. 5, right). New objects such as conveyor belts, shelves, and boxes as well as necessary input variables (weights, forces, placement accuracy) for ergonomics and time evaluations were added.

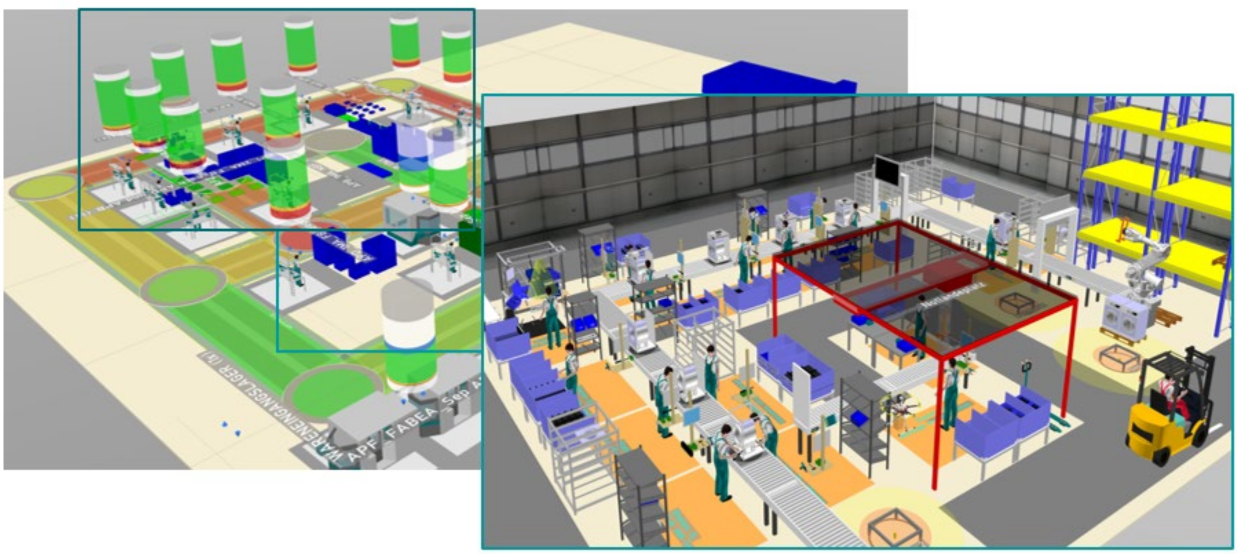

Figure 5. Layout optimization of production (left); simulation of the washing machine assembly (right)

The analysis of the current assembly stations using an average 50th percentile male digital human model (M50-AK40: age group: 40 years, 50th percentile body height: 178 cm according to DIN 14738:2005, age appropriate avenge range of motion and force) showed that there are 4 red workplaces, 7 yellow workplaces and 3 green workplaces according to EAWS (red > 50 points, yellow >25 points, green ≤ 25 points). The red and yellow workplaces mean an increased risk of getting musculoskeletal disorders. In addition, an age-appropriate work evaluation was done by adding different human models - small old women (F05-AK60: age group: 60 years; 5th percentile body height 60: 154 cm, age appropriate reduce range of motion), an tall young man (M95-AK20: age group: 20 years 95th percentile body height: 194 cm, age group: age appropriate avenge range of motion and force) and a tall old man (M95-AK60: age group: 60 years 95th percentile body height: 183,5 cm, age group: age appropriate reduce range of motion and force) to the simulation.

The feasibility test showed that the middle-sized man (M50-AK40) and the tall sized man young (M95-AK20) and tall sized old man (M95-AK60) can carry out all activities. However, the small woman (F05-AK60) cannot reach all locations that are needed for the activities on the washing machine assembly line. Figure 6 shows an excerpt of the activities that cannot be carried out by the woman F05 (age group:60). For example, the woman F05-AK60 cannot push the washing machine drum into the frame (workplace 1R). This also affects workplace 1L, as workers 1R and 1L work together to fasten the drum.

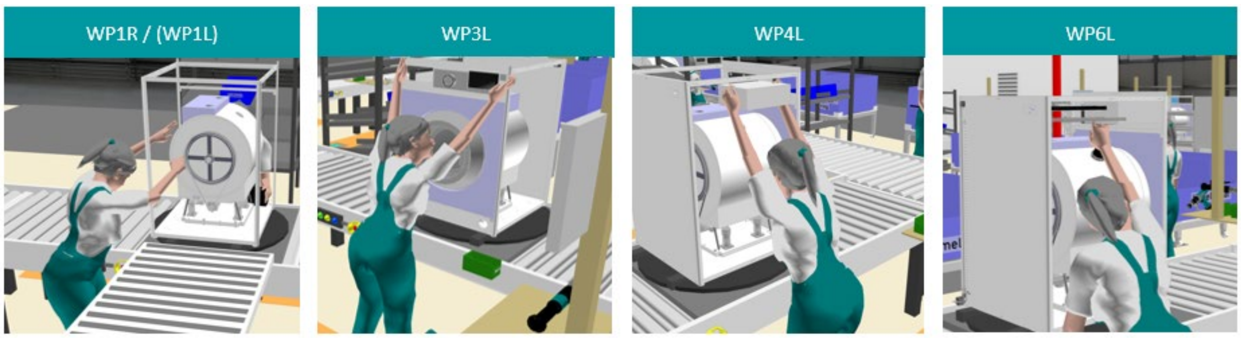

Figure 6. Non-executable activities (woman F05, age group: 60 years) by using emaWD feasibility check

The different characteristics of the people (different anthropometry, mobility, maximum strength) also affect the workload assessment and biomechanical risk score according to EAWS. Tab. 1 shows that the physical strain according to EAWS at workplaces 1R, 2R and 4L is higher for the small woman F05-AK60 than for the men M50-AK40 and M95 AK60. In addition, the feasibility as shown in Figure 6 and table 1 is limited or not feasible for workplace 1R and 4L due to the smaller body size and body reach as well as the age-related reduction of flexibility (Spitzhirn 2017).

Table 1. Excerpt of ergonomic results based on feasibility test and EAWS for workplaces 1R, 2R,4L

	Workplace 1R			**Workplace 2R**			**Workplace 4L**		
	M50-AK40	**F05-AK60**	**M95-AK60**	**M50-AK40**	**F05-AK60**	**M95-AK60**	**M50-AK40**	**F05-AK60**	**M95-AK60**
Feasibility	yes	no	yes	yes	yes	yes	yes	no	yes
= EAWS Points [1]	61,5	(70,0) [2]	68,5	52,5	56,5	52,5	59	(63) [2]	37
+ Body posture points	*6*	*(5,5)*	*7,5*	*2*	*2*	*2*	*24*	*(28)*	*2*
+ Force points	*50*	*(59)*	*56*	*34*	*34*	*34*	*33*	*(33)*	*33*
+ Load handling points	*-*	*(-)*	*-*	*16,5*	*20,5*	*16,5*	*-*	*(-)*	*-*
+ Extra points	*5,5*	*(5,5)*	*5,5*	*-*	*-*	*-*	*2*	*(2)*	*2*

[1]cutline: EAWS (high health risk > 50 points, possible health risk >25 points, low health risk ≤ 25 points)
[2] no executability according to emaWD feasibility check; theoretical points in case of reachability

To improve the ergonomic and economic conditions, the following measures were simulated in emaWD and evaluated using EAWS and MTM-UAS. A Fanuc CR35ia robot, which can carry out a maximum weight of 35 kg (weight of washing drum = 30,7kg), is integrated at workplace 1R (handling the washing drum (EAWS: 61,5 to 23 points), an UR10e robot on workplace 2R (taking over the rear wall EAWS:;52,5 to 32 points) and a pedestal on workplace 4L (EAWS: from 59 to 31,5 points) as well as on workplace 5L (EAWS: from 40,5 to 40,0 points). A relocation of work content (relay assembly from workplace 3L (EAWS: 55,5 to 42 points) to workplace 7R) was also done to improve the ergonomic conditions and make a line balancing. During the redesign, the cycle time according to MTM-UAS could also reduce from 70 s to 60 s and the workstations were rebalanced by shifting tasks from one workplace to another. Figure 7 shows the results of the optimization process for the four red workplaces 1R, 2R, 3L, 4L compared to the initial state according to EAWS.

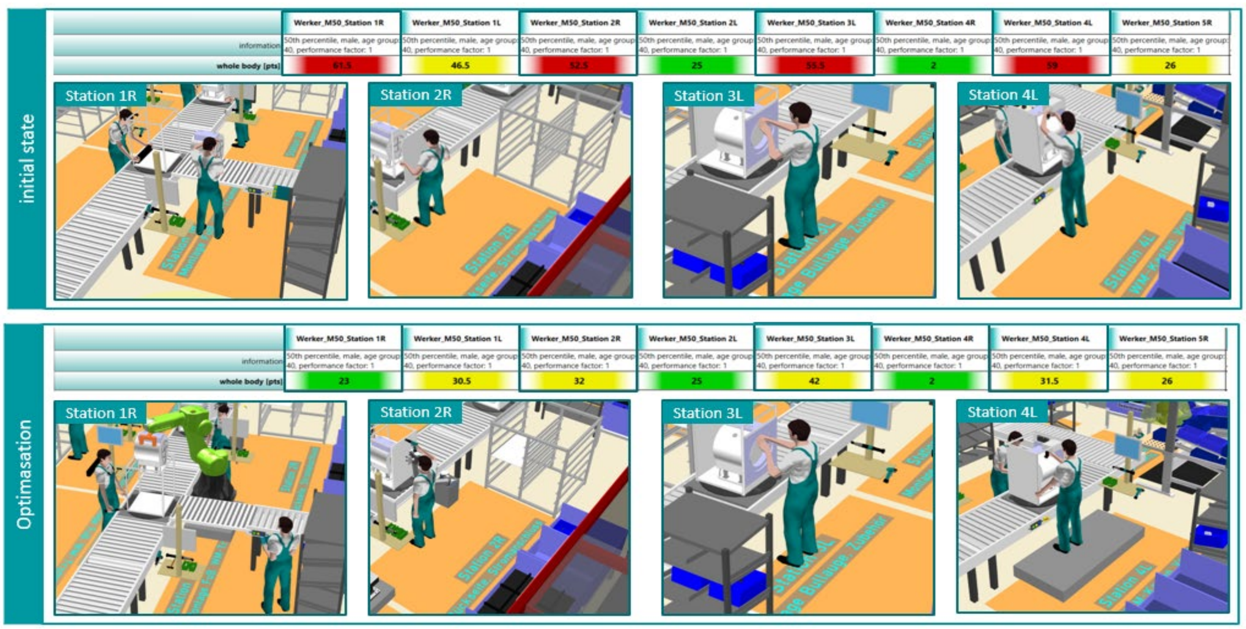

Figure 7. Comparison of ergonomics accord. EAWS in initial state (top) to optimized state (below)

The results of the optimization process in emaWD were transferred back to the emaPD. Due to the line balancing and the other improvements the number of buffer space could reduce signifyingly. Only one buffer space between station APB and AP1 still remains. The idle and blocking times on the assembly line could be reduced to less than 50 h and the manufacturing costs by almost 10 % while at the same time increasing the possible output.

Discussion and conclusion

The combined digital factory and work planning presented made it possible to achieve significant improvements of washing machine production in terms of economic efficiency and ergonomics. Various methods are available in emaPD for an extensive factory planning. By using the emaPD the defined quantities of washing machines are obtained and the space requirements, production costs are reduced significantly as well as material flows are optimized. Compared to a simulation, the mathematical modeling in emaPD offers significant time savings in model creation (-90%) and computing time (-99%), while at the same time there is a high level of agreement in the accuracy of the forecast (approx. 3% deviation according to Bolch et al., 2006). This makes it possible to carry out different variations of the planning in a reasonable amount of time. To calculate the variants, various data such as parts lists are required, which are either entered manually or can be integrated from other systems via an interface, which can significantly reduce the time required.

As other component of the ema Software Suite, the emaWD ensure that the workplaces and processes, are economical, safe, and human-oriented designed. Aspects such as feasibility (visibility or reachability analyses), health risk (e.g. according to NISOH, EAWS) are considered in detail. By integrating different human models (M50-AK40, F05-AK60, M95-AK20, M95-AK60) with the respective characteristics (body height, force, range of motion, appearance related to age, nationality) an age-appropriate work design can be carried out (Spitzhirn et al., 2022). It is important that a representative range of characteristics (anthropometry, mobility, strength) are mapped to ensure broad use by later users. The analysis shows that non-compliance could result in that worker such as F05-AK60 cannot execute all work tasks. This can be avoided by using the feasibility check in emaWD. A further advantage of the combined factory and work planning approach is the detailed simulation and the visualization of the process in emaWD. That ensure, that no necessary process is forgotten by the user. In addition, necessary places can be planned for example for optimization measures such as pedestal (no use for tall men such as M95-AK20 or M95-AK60), manipulators, robots, or seating to prevent expensive corrections in the field. This can save significant time and money. The employees are thus more at the center of the planning. In addition to economic advantages (e.g. avoiding unfavorable and time-consuming movements, reducing the reject rate, increasing motivation), good ergonomic design can achieve greater flexibility and longer employability of employees (Fritzsche et al., 2019a).

The ema software suite supports a new economic and human oriented approach in the field of factory and work planning, and has the potential to improve the cooperation of both disciplines significantly. The direct interaction between emaPD and emaWD enables planning to be detailed and accelerated. This means that extensive data is available for planning that do not have to be obtained from other systems first. A good usability, bidirectional interfaces between emaPD and emaWD as well as integrated methods support an interactive, joint, efficient creation, calculation, analysis and improvement process of the factory and production. An extensive library as well as standard workstations and machines reduce the time for construction of the environment. Furthermore, the assembly times (e.g. MTM-UAS) based on emaWD simulation can be used to specify the planning data in the emaPD. The extensive evaluations (time, ergonomic, material flow etc.) in combination with a graphic user interface including dynamic simulation provide the basis for the discussion and evaluation of various measures with different stakeholders (e.g. planners, works council, production). This increases acceptance and can help improve the planning results. In the example, the manufacturing costs and unplanned downtimes could be significantly reduced, and the ergonomic conditions improved, for example by integrating robots into hybrid workstations. Furthermore, the use of the system should not be viewed in isolation from other software systems in the respective company. For that purpose, ema Software Suite offers extensive interfaces to other systems (import and export of CAD data and movements, process data), which can be used for example for further investigations or visualizations with virtual reality applications.

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