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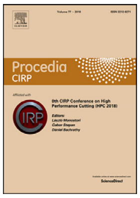

ErgoTakt: A novel approach of human-centered balancing of manual assembly lines

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ABSTRACT

Although the increasing use of automation in industry, manual assembly stations are still common and, in some situations, even inevitable. Current practice in manual assembly lines is to balance them using the takt-time of each workstation and harmonize it. However, this approach mostly does not include ergonomic aspects and thus it may lead to workforce musculoskeletal disorders, extended leaves, and demotivation. This paper presents a holistic human-centric optimization method for line balancing using a novel indicator – the ErgoTakt. ErgoTakt improves the legacy takt-time and helps to find an optimum between the ergonomic evaluation of an assembly station and its balance in time. The authors used a custom version of the ErgoSentinel Software and a Microsoft Kinect depth camera to perform online and real-time ergonomic assessment. An optimization algorithm is developed to find the best-fitting solution by minimizing a function of the ergonomic RULA-value and the cycle time of each assembly workstation with respect to the worker's ability. The paper presents the concept, the system-setup and preliminary evaluation of an assembly scenario. The results demonstrate that the new approach is feasible and able to optimize an entire manual assembly process chain in terms of both, economic aspects of a well-balanced production line as well as the ergonomic issue of long term human healthy work.

1. Introduction

Although industrial processes lead toward extensive use of flexible automation, manual assembly is still inevitable due to the mounting complexity e.g. of cables, hoses or electronics, hard-to-reach places, sensitive surfaces, difficult operations, etc. (Heilala and Voho, 2001). The design and leveling of an assembly line are issues since the beginning of industrial mass production, but it becomes even more critical nowadays. In fact, to compete in the global market, companies need increasing effectiveness and efficiency, especially in high-loan countries. In addition, global policies lead to an increased focus on workers' wellness and safety. In fact, according to the Sixth European Working Conditions Survey (Eurofound, 2019), exposure to repetitive arm movements and tiring positions lead to the development of work-related musculoskeletal disorders (WMSDs) with heavy costs for countries welfare. WMSDs include "all musculoskeletal disorders that are induced or aggravated by work and the circumstances of its performance" (WHO, 2003). WMSDs extend to almost all occupations and sectors, bearing critical physical and economic consequences for the sufferer: workers, families, businesses, and governments. These ailments are considered the most common labor medical problems among workers in the European Union. Furthermore, these issues are amplified by the aging of the workforce; in 2080, about one-third of the European population will be 65 or older (Eurostat, 2019). This involves the need for preserving the operators' wellbeing consistent with their active aging in the production environment. Therefore, the aging society, the lack of specialists or the product quality inevitably lead to high ergonomic requirements for manual assembly processes (Peruzzini and Pellicciari, 2017).

The time-leveling of an assembly line is mostly named in the literature as "assembly line balancing" (ALB). ALB is normally designed and evaluated by means of takt-time. As a matter of fact, takt-time leveling of an assembly line and the worker ergonomics are not directly related. This means that a well-leveled assembly

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line may not be ergonomic, and, conversely, a series of ergonomic workstations does not lead to a well-balanced assembly line.

Ergonomic evaluation of the work shift requires a deep analysis of postures, loads, and frequency of movements. In the industrial field, it is commonly carried out by experts with observational methods that are not supported by instrumental measurements and are affected by subjective bias (Roman-Liu, 2014). This approach is costly and time-consuming; therefore, it is usually carried out retrospectively of an accident and by sampling only the most critical stations/processes and workers. Hence, long term and systemic ergonomic evaluations are difficult due to current tools limitations. These are the main reasons why the ergonomic assessment is not integrated into ALB as a holistic view of the process. The authors want to leverage the 4th industrial revolution, and its integrated technologies for supporting the worker of the future, the so-called "Operator 4.0″ (Romero et al., 2016a). In the operator 4.0, bio-data monitoring (i.e. postures, and workload physiological data), smart solutions (i.e. wearable trackers and sensors) and advanced Human-Machine-Interaction are used for improving, wellbeing, inclusivity, and safety of workplaces without affecting the productivity (Romero et al., 2016b).

In this contribution, we propose a novel approach called "ErgoTakt", which improves the standard, takt-time centered balancing approach by automatic ergonomic evaluation. This is achieved by integrating the ErgoSentinel system (Manghisi et al., 2017) with an optimization algorithm to find the best solution of takt-time and ergonomic score for an entire chain of assembly stations. The approach also considers possible constraints, such as the qualification of the employees for the respective tasks, their physical impairment, etc. The novelty of the contribution is first, the enhancement of the ErgoSentinel Software, which was also developed by the authors (Research group of Politechnico du Bari) (Manghisi et al., 2017). This enhancement contains an additional interface for the data transfer and long-time data storage. Secondly, this extension allows, in addition to the ergonomic evaluation, the balancing of assembly lines by an optimization algorithm. The combination and the algorithmic implementation we call ErgoTakt, as it is now possible not only to evaluate the current ergonomic RULA score of a single task, but also considering takt-time issues and limitation of an entire process chain for a long time period. The contribution shows the concepts, implementation as well as the benefits of considering both dimensions (ergonomics and line balancing), as an enhancement of former objectives, which are generally separated in production line planning or operation.

The paper is structured into a literature review followed by the ErgoTakt concept and the underlying optimization algorithm. The first results of a synthetic virtual simulation in a use-case provide the beneficial aspects of the presented approach due to ergonomic and line-balancing performance indicators of an assembly line. The ErgoTakt approach is then discussed. Finally, the conclusions are drawn in terms of the health of the worker as well as the line efficiency.

2. Brief literature review

The ALB main objective is smoothing production, reducing the cycle time and eliminating bottlenecks. Industrial ergonomics aims to reduce the physical and cognitive strain of the operator. For simplicity, we divided the literature review into two sections: one related to the assessment of ergonomic scores and second to the ergonomic line balancing.

2.1. Methods of ergonomic assessment

Ergonomics assessment methods and tools have been extensively studied and presented in scientific literature, medical knowledge, and working environment rules. One of the first approaches is the Ovako Working Posture Analysing System (OWAS), which divides movements into four body parts (trunk, arms, lower body and neck). It uses a series of instantaneous observations to compile a score of the harmfulness of the activity from defined tables (Karhu et al., 1977). The basic concept of OWAS inspired more complex methods like RULA (Rapid Upper Limb Assessment), REBA (Rapid Entire Body Assessment), and EAWS (European Assembly Worksheet), NIOSH-Eq (Revised National Institute for Occupational Safety and Health - Equation) -, Strain Index (SI) - and OCRA (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000; Schaub et al., 2013; Waters et al., 1993; Steven Moore and Garg, 1995; Occhipinti, 1998; Colombini, 1998). OCRA presents results as a quotient of the theoretically best possible execution of the activity (Occhipinti, 1998; Colombini, 1998). Also the JSI-L (job severity index - lifting) method provides a quotient as a result, which consists out of the possible performance of an employee and the foreseen activity. This method is suitable only indirectly for the evaluation of the activities; the suitability of the employee for a certain activity is evaluated first (Liles et al., 1984). Compared to this basis, the Metabolic Energy Expenditure Rate (EnerExp) method considers the energy consumption of an activity (Garg et al., 1978). For each type of activity is assigned an energy consumption value. Finally, the sum of the used physical energy is compared to the maximum harmless energetic performance of a worker.

The presented methods share a practical limitation. In order to evaluate an activity, an observation must take place, either through direct annotation or video recording, followed by an assessment usually carried by specialized personnel. In order to overcome human error and bias, literature presents different approaches to ergonomic measurement automation. Table 1 summarizes the most relevant ones classified according to the ergonomic score method, captured body area and capturing technology. It is clear from Table 1 that two capturing techniques are common: depth camera and inertial measurement unit (IMU). Nearly all listed approaches use a Microsoft Kinect as a depth camera. The Kinect was originally designed for gaming, but due to its low cost and high performances it became an outstanding tool for researchers in many fields, from medical (Webster and Celik, 2014; Boenzi et al., 2016) to virtual and augmented reality (Cruz et al., 2012; Facchini et al., 2016; Manghisi et al., 2018). Another evidence from Table 1 is that the RULA metric is the most used in the literature as an automated tool. RULA was developed originally for quasi static manual evaluation, however the ErgoSentinel tool, allows real time skeleton tracking and RULA processing (Manghisi et al., 2017). ErgoSentinel was adopted in this research work because along the real time automatic computation, it is also easy to integrate in our existing ALB method.

2.2. Methods of ergonomic line-balancing

The leveling assembly lines is a known challenge in industrial assembly (Boysen et al., 2008). Otto and Battaïa provide an extensive survey of the simple line balancing algorithms (SALB) (Otto and Battaïa, 2017). In order to consider the ergonomic factor classical SALB-algorithms, the ergonomic features are integrated as a normalized value. Battini et al. show a possible solution to a SALB problem by including energy consumption as an ergonomic parameter (Battini et al., 2016).

One optimum is to level the times between the workplaces, the other to reduce the cycle time to a minimum. The same is done for the energy consumption to achieve a leveling between the workplaces once and a minimum of the energy consumption at the individual stations once (Battini et al., 2017). A pareto front is used to evaluate the stress field that occurs between the optima values.

Table 1
automated ergonomic capture methods.

Year	Source	Score method	Score area	Capturing technique
2012	(Martin et al., 2012)	OWAS	Hole body	Depth camera
2013	(Vignais et al., 2013)	RULA	Upper body	Depth camera, IMUs, el. goniometer
2013	(Nguyen et al., 2013)	EAWS	Hole body	Depth camera
2013	(Haggag et al., 2013)	RULA	Upper body	Depth camera
2014	(Battini et al., 2014)	Diverse	Hole Body	IMUs
2014	(Paliyawan et al., 2014)	RULA, REBA	Upper body	Depth camera
2016	(Peppoloni et al., 2016)	RULA, SI	Upper limbs	IMUs, electromyography
2017	(Plantard et al., 2017)	RULA	Upper body	Depth camera
2017	(Manghisi et al., 2017)	RULA	Upper body	Depth camera
2018a	(Bortolini et al., 2018)	REBA	Hole body	Depth camera
2018b	(Bortolini et al., 2018b)	EAWS	Hole body	Depth camera

It was evidenced that the first possible result of one target variable worsens the result of the other target variable. In the subsequent work by Battini et al., the same ergonomic evaluation method is used to optimize part provision in addition to the classic assembly line (Battini et al., 2017). Barathwaj et al. choose a different version of the leveling problem (Barathwaj et al., 2015). They consider the cycle time to be given. The aim is to minimize the number of workstations, the waiting time of products between stations and the ergonomic risk at each station. The optimization algorithm is also extended to include ergonomic components. Ergonomic optimization of assembly lines is also investigated in the literature from a management perspective, evaluating the effects of job rotation policy and material handling equipment selection in reducing ergonomic risk.

From the literature review, we can see that the current evolution of ALB is to include ergonomic evaluations in the optimization process.

However, the presented contributions lack the use of real-time acquisition of ergonomic data in combination with a line balancing optimization. Therefore the advantages of the presented method are two: i) it evaluates postures ergonomics online over an extensive period of time, with all operators and stations and without the time and cost of an expert; ii) it uses the takt-time as the main parameter which is well known by the final users.

3. The ErgoTakt approach

The ErgoTakt approach for an entire assembly process chain is illustrated in Fig. 1. We structured the approach into six layers: data acquisition, operating resources, human resources, economic data, ergonomic data, ErgoTakt layer.

The *data acquisition layer* provides ergonomic data captured by a Microsoft Kinect camera and processed by the ErgoSentinel software, which derives a real time RULA-score as input data for the operator movements. For this reason, every workstation should be equipped with a camera.

The *operating resource layer* contains the technical description of the workstation, which means the tasks to be conducted at the specific workstation. E.g. drilling, gluing, screwing and/or manual assembly. As input data the cycle time of a single task and the needed qualification for each task at the workstation are necessary.

The *human resource layer* characterizes the operator by his qualification level, which is related in a database with the workstation description. Furthermore, the physical impairment is considered as a value [0…1]. This value gives e.g. a disabled or older person more time to fulfill a specified task. Both, the qualification as well as the impairment is used as input data or the underlying calculation of advanced data.

The *economic data layer* and *ergonomic data layer* import and aggregate data from the former three named layers. The balancing chart on the one hand and the ergonomic data, on the other hand, are derived with respect to a work cycle.

The *ErgoTakt layer* computes the optimization of ErgoTakt indicator. All input data and the calculated values are aggregated and feed into an optimization algorithm, which aims to minimize the ergonomic stress of the worker and cycle time per workstation with respect to workers' qualification and physical impairment as well as the mandatory assembly order in the process chain.

After a description of the ErgoSentinel software and its integration in the framework, the optimization approach is presented in detail and validated by an assembly scenario of nine process steps.

3.1. ErgoSentinel

ErgoSentinel was presented at the International Conference of Industry 4.0 and Smart Manufacturing (ISM 2019). It is an evolution of the K2RULA tool (Manghisi et al., 2017) and is the outcome of an Italian national project between INAIL (the Italian National Institute of Occupational Accident Insurance) and the VR3Lab of Politecnico di Bari. This system was developed to provide small and medium enterprises of a simple to use, reliable, and low-cost ergonomic tool for improving the working conditions in small and medium enterprises (SMEs). SMEs, with fewer than 250 employees constitute the backbone of the Italian economy (more than 99% by number) and due to their size cannot afford continuous ergonomic assessment. ErgoSentinel is available for free and aims to be largely used and it may become an institutional ergonomic assessment tool.

In this research work, we use Microsoft Kinect® V2 RGB-D cameras and the Microsoft Kinect for Windows SDK 2.0 for body tracking. An important feature of ErgoSentinel in the context of this research is the capability to work unassisted and acquire in real-time the RULA scores of each working station operator with a frequency of 500 ms. Only the ergonomic data are collected in respect of an operators´privacy.

In addition to this online functionality ErgoSentinel can process continuously a file recorded in the standard Microsoft format (.xef). This is a powerful investigation tool able to scan the acquired tasks and finding critical conditions. The software assesses the instant RULA score for the current posture and visualizes it in the dedicated "RULAwindow" (Fig. 2). This window visualizes the scores of each body section for both body sides (left and right), the computed angles, and the grand-score (i.e. the global score). The severity level is visualized with a color-coded background varying from green (grand score 1 and 2) to red (grand-score 7). The accuracy of the ErgoSentinel results was validated comparable against a much more expensive opto-tracking system (Manghisi et al., 2017). ErgoSentinel was extended to export in a comma-separated the instant RULA values in order to be processed by the optimization layer.

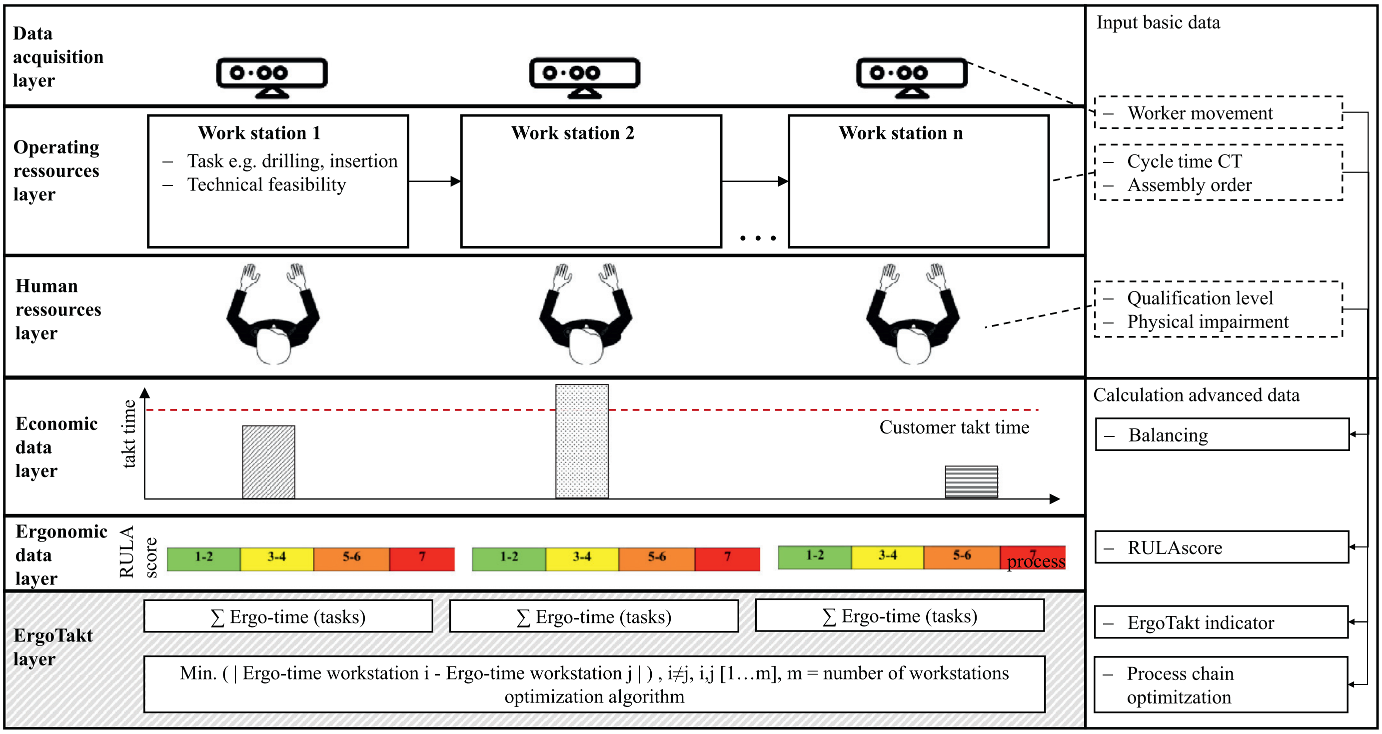

Fig. 1.. General concept of ergonomic line balancing in an assembly process chain.

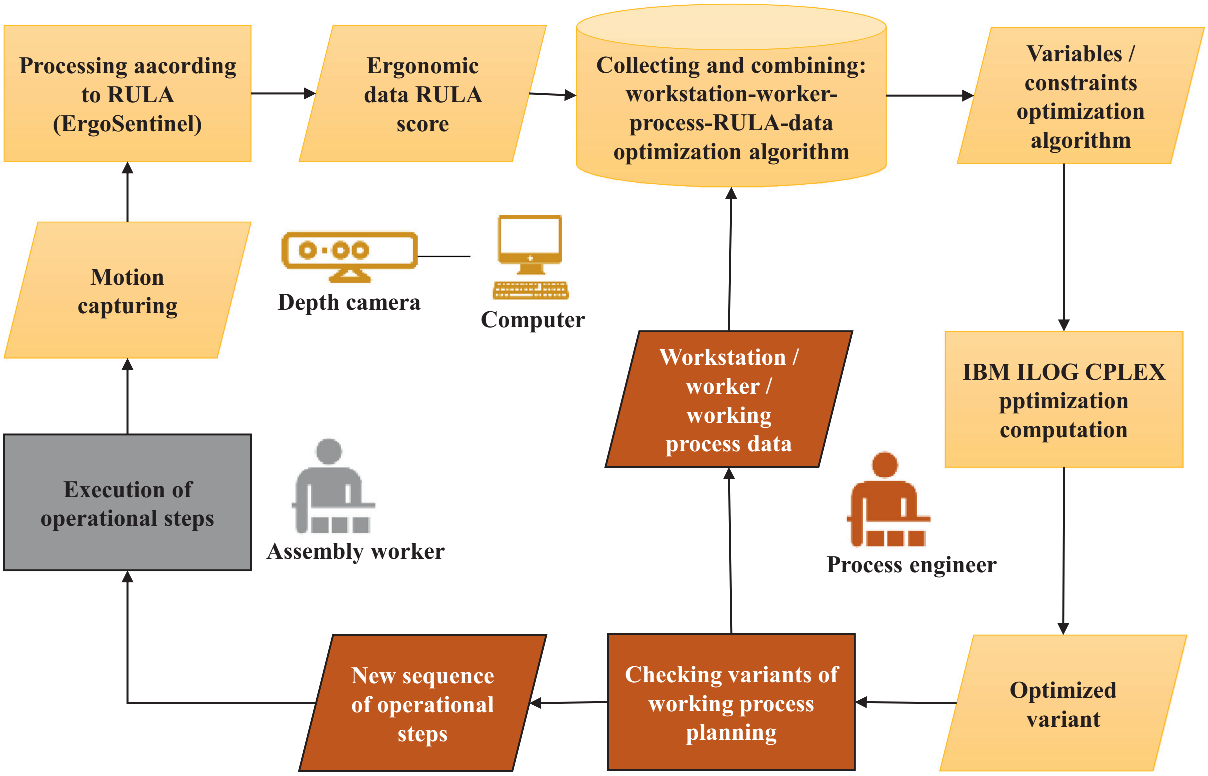

Fig. 2.. Scheme of the work preparation, data collection and optimization.

3.2. Optimization approach

The scheme in Fig. 3 illustrates how the necessary data are provided and used to optimize the assembly process chain with respect to the operators' workload.

Starting from the “process engineer”, the workstation, the worker and the process data are collected, checked and brought into a feasible work sequence before these data were provide to the data-processing system. Then, the “assembly worker” carries out the assembly work. The movements are recorded with the aid of a depth camera and converted into a RULA score by the Er-

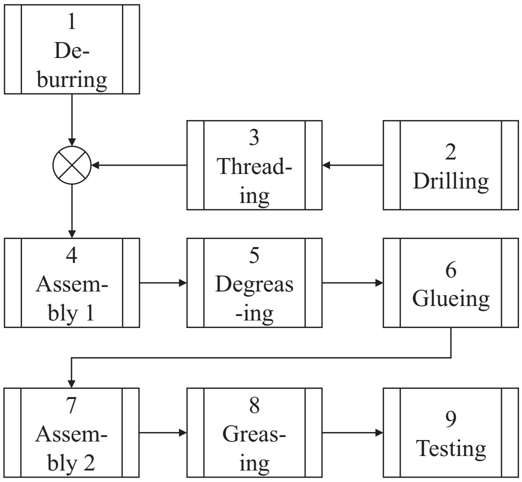

Fig. 3.. Process chain of 9 manual steps.

goSentinel tool. Under the constraints of the mandatory process order, the assembly technology, the worker qualification, and the physical impairment, the algorithm builds variants of the optimized working processes. The ErgoTakt indicator of a workstation j as a sum of the tasks n performed at this workstation is calculated by

$$ErgoTakt_j = \sum_{i=1}^{n} \frac{RULA_i \cdot CT_i}{Res_{W,i}} \tag{1}$$

where $RULA_i$ is the RULA-score derived by ErgoSentinel, CT_i is the cycle time for the task, and $Res_{W\,i}$ is the physical impairment factor for each worker in the interval [0 … 1].

The optimization algorithm is implemented with the IBM ILOG CLPEX [ref]. The objective function is to minimize the difference of the ErgoTakt indicators between workstation i and the other workstations j with $i{\neq}j$ in the process chain.

m is the number of workstations so that i and j are within the interval [1…m]. The optimization function can be described as follows

$$\min\left\{\left|ErgoTakt_i - ErgoTakt_j\right|_{i,j=1}^{m}\right\} \tag{2}$$

Based on the RULA-scores and the worker-workstation-task constraints, which are provided by the assembly preparer as input data, a three-dimensional binary variable containing the assigned worker, task and station is built as a start point for the algorithm. These "lists" of work-preparation contain, which employee may/can do which task, which task can be executed on which station, and the cycle-time for each task. The resulting worker-workstation-task combinations are compared with the following conditions:

1 Is the workstation feasible to fulfill the addressed task(s) and vice versa?
2 Is the worker able to fulfill the task with respect to the qualification level and his/her eventual physical impairment?
3 Is the maximum number of workers per workstation and vice versa one?
4 Is each task only assigned once?
5 Is the sum of all cycle times per task less than the customer takt-time?

The optimization algorithm checks all possible task-workstation-worker combinations regarding the accomplish-ment of the named conditions and the predefined assembly order. Based on these results the tasks are assigned to the workstations according to the minimum ErgoTakt indicator.

Table 2
Task based input data.

Tasks	CT [s]	RULA-score
1 deburring	80	3
2 drilling	150	2
3 threading	120	2
4 assembly 1	200	4
5 degrease	40	2
6 gluing	120	2
7 assembly 2	240	4
8 greasing	60	3
9 testing	180	2

Table 3
Worker based input data.

Worker	Resilience	1	2	3	4	5	6	7	8	9
A	1	1	1	1	1	1	0	1	1	1
B	0,8	0	0	0	0	1	0	0	1	1
C	1	1	1	1	1	1	0	1	1	1
D	0,5	0	0	0	0	1	1	0	1	1
E	1	1	1	1	1	1	0	1	1	1

Table 4
Workstation based input data – initial task time in seconds distribution for the workstation W1–W5 to be optimized by the ErgoTakt.

Tasks	W1	W2	W3	W4	W5
1 deburring	80	–	–	–	–
2 drilling	150	–	–	–	–
3 threading	120	–	–	–	–
4 assembly 1	–	200	–	–	–
5 degrease	–	–	40	–	–
6 gluing	–	–	120	–	–
7 assembly 2	–	–	240	–	–
8 greasing	–	–	–	60	–
9 testing	–	–	–	–	180
Max. cycle time per workstation	350	200	400	60	180

4. Use-case scenario

To illustrate the ErgoTakt approach and its results regarding an assembly scenario, we designed a synthetic process chain as a virtual simulation of 9 tasks configured as shown in Fig. 3.

The tasks can be performed by 5 simulated workers with respect to their qualifications and are distributed over 5 workstations. The assembly/task order is fixed. The cycle time CT for tasks and the average RULA-score are presented in Table 2.

The worker data contain the worker ID from A to E and his/her physical resilience, which is represented by a percentage value (see Table 3). In this case, we supposed that the workers B and D have reduced physical resources, e.g. due to their age or disability. Those employees will get more time to fulfill the task according to their impairment. Furthermore, the qualification for the specified tasks (1–9) is noted as a binary variable.

The initialization of the optimization is done by the allocation of tasks to a workstation (W_i), illustrated in Table 4. As an additional starting condition, we defined that gluing (task 6 in Fig. 4) is only feasible at workstation 4 and worker D is the only one qualified for this task. The sum of the task cycle times per workstation defines its maximum cycle time. It can be seen in Fig. 4 (left), that the resulting leveling is less than ideal.

Based on these input data, the optimization is carried out by the algorithm described in paragraph 3.2. In order to show how the implication of ergonomic assessment influences the optimization results, the assembly scenario has been optimized in two phases.

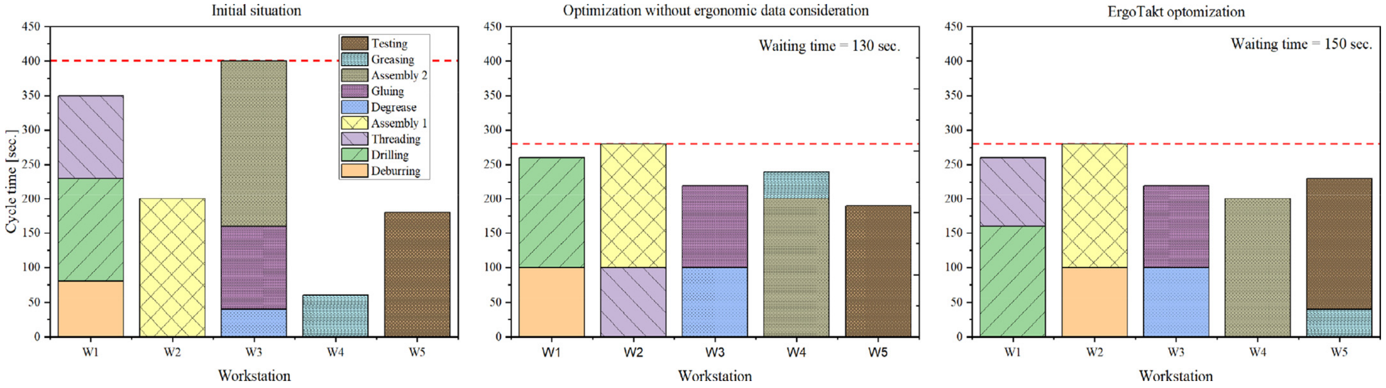

Fig. 4.. Cycle time balancing charts, initial scenario (left), phase 1 optimization without ergonomic (middle), phase 2 ErgoTakt optimization (right).

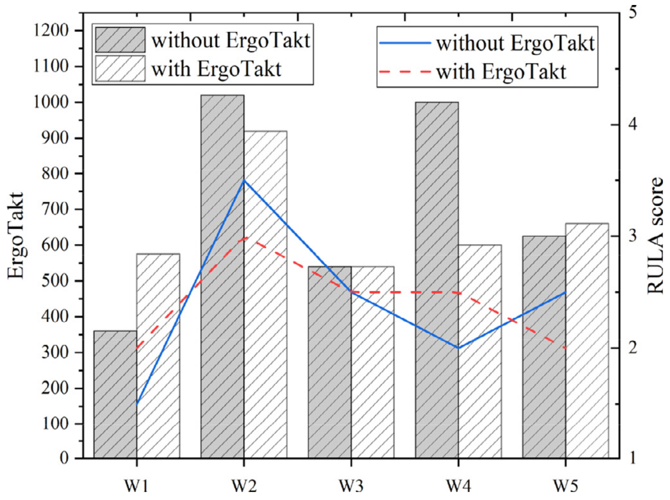

Fig. 5.. ErgoTakt values and RULA scores in relation to the workstations W1–W5.

4.1. Optimization results

The described process chain is modeled with the input data shown in Tables 2–4. The optimization is done in two phases:

In **phase 1** no ergonomic data are considered. Hence, the physical impairment value does not influence the algorithm even if the workers might be burdened by stress or time pressure in real assembly scenarios. The optimization aim is here to optimize the balancing within the entire process chain. Thereby, the target is to lower the maximum cycle time of the ”slowest” workstation in the process chain. The initial scenario gives the start value as 400 s. at W3 (see Fig. 4, left). The result of this optimization phase shows the reassignment of the tasks to the workstations as in the initial scenario and this a “homogenization” of the cycle times. The maximum cycle time of the process chain is lowered to 280 s., the total waiting time between the workstations is 130 s (see Fig. 4, center).

In **phase 2**, the RULA score is considered (Fig. 5 right). The new target value of the optimization algorithm is to minimize the ErgoTakt indicator. As a result, the tasks are also reorganized within the process chain under the given order between W1 to W5. In addition, a technological feasible order is still present. As a result, the maximum cycle time of the process time stays at 280 s., the waiting is 150 s.

Table 5 compares phases 1 and 2 and shows the absolute value of the cycle time of the bottleneck workstation as well as the mean CT_m, the standard deviation σ and the waiting time (WT) between all workstations. The latter indicator shows that the integration of the ergonomic score and resilience to the optimization leads to more WT between the workstations. The mean CT_m as well as the standard deviation σ between both optimization phases differs, which both indicate a homogenization of the assembly line especially when considering σ.

Table 5
Indicators for the optimization results.

Phase	max CT [s]	CT_m [s]	σ [s]	WT [s]
1 without ErgoTakt	280	258	± 57,4	130
2 with ErgoTakt	280	238	± 31,2	150

Furthermore, the average RULA scores, which are known for each task, can be related to both phases even if they are not considered for the optimization in phase 1. The task-workspace- assignments then lead to a RULA scoring for W1–W5. In Fig. 5 also an alignment occurs. The physical exposure of the worker at W2 is brought down from RULA 3,5 to RULA 3, but at the expense of W4 (2,0–2,5). The RULA scores is leveled in a better way by the ErgoTakt approach as in phase for this assembly scenario.

5. Discussion

The results indicate the applicability and the advantages of the approach in a simulated assembly process chain. Based on the virtual scenario simulation, both, the line balancing and the ergonomic scores are improved. The RULA score at the most critical station 2 decrease about 30%. The increase of at station 4 is in a rather uncritical range (2 → 2,5). The benefits of the ergonomic acquisition by the ErgoSentinel software are obvious, long-term evaluation, continuous RULA scoring or low-cost equipment are just some aspects. The combination of automated RULA evaluation and production line balancing makes it possible to optimize both dimensions, economic line balancing and ergonomic posture. It can be seen critically, that actually and, above all, in the existing assembly process chain, many other factors influence the decision of tasks and how they are organized. For instance, the factory layout, the technical flexibility of shifting tasks between workspaces or technological incompatible combinations of workstation and tasks might be a challenge for the implementation of the ErgoTakt approach. Therefore, the first use of the ErgoSentinel/ErgoTakt should already take place in the planning phase of an assembly process chain in order to evaluate the RULA-scores by ErgoSentinel e.g. by card boards. Then, the technical equipment of the workstations and the arrangement of the tasks can be analyzed in advance in terms of ergonomic and line balancing issues.

Nevertheless, the ErgoTakt approach is applicable in an existing assembly line, when the following aspects are fulfilled predominantly:

- Workstation must be compatible with existing skeleton capturing technologies (e.g. postures, tools and safety devices, occlusions., etc.)
- Modular assembly lines with reconfigurable tasks and task technologies
- Re-configurability of the assembly line layout
- Similarity of (assembly) technologies of the workstations
- Low degree of automated workstations within the process chain in comparison to manual assembly tasks.

These conditions are usually verified in normal working environment, thus they not limiting the use of this technology.

6. Summary and outlook

The contribution shows the ErgoTakt approach as a novel method to evaluate assembly lines according to ergonomic and economic KPIs. We integrated human digitalization technologies using a depth camera and the ErgoSentinel software to derive RULA-score in real-time and over a longer period. The utilization of this data in combination with an optimization algorithm are presented in detail. In order to evaluate the initial feasibility of ErgoTakt, a use-case scenario has been developed and performed with and without the integration of ergonomic scores into the optimization. The result shows a improvement of the most critical workstation of about 30% expense of increasing the waiting time by 14%.

Further research has to be done in the evaluation of the approach in real production scenarios, first steps has been already done, but needs to be increased regarding long-term data analysis. Another aspect is the worker acceptance of the system. Here, additional studies are necessary if the behavior of the staff changes by observing the assembly tasks by a camera continuously. Also, the ErgoTakt approach needs to be adopted for assembly lines which contains fully automated processes beside manual workstations.

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