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Multi-objective assembly line balancing considering component picking and ergonomic risk

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ABSTRACT

Aim of the assembly line balancing problem (ALBP) is the efficient and effective assignment of assembly tasks to stations in one-piece-flow production systems. Although this problem has been studied for decades, few contributions consider the component picking at assembly station level. Yet, this activity has relevant and practical implications for ALBPs in the industrial context. This paper proposes an innovative multi-objective optimization model for the ALBP to assign the assembly tasks to stations by distinguishing the assembly activities involved in task execution and component picking. Thus, a function is proposed to relate the time required for component picking with the component storage location at assembly station level and the component features, namely dimensions, weight and handiness. The aim of the developed model for the ALBP is the simultaneous minimization of the assembly line takt time and ergonomic risk, both determined by the task execution and component picking activities. Furthermore, the proposed model not only defines the optimal task assignment to stations, but it also determines the optimal storage location of each component between the locations available at the different assembly stations. The multi-objective optimization model is validated with an industrial case study dealing with a kitchen appliance assembly line. The final assembly line balancing configuration proposed is distinguished by remarkable performance for both takt time and ergonomic risk objective functions. Such a balancing leads to 36% ergonomic risk reduction with just 2% takt time increase compared to the correspondent single-objective configurations. These outstanding results are determined by a proper component disposition in the different station storage locations defined by the model.

1. Introduction

Mass customization is known as the current production paradigm (Hu et al., 2011). Every single customer demands for a complete product personalization in a limited production lead time. To face these challenging market requirements, production processes exacerbate the adoption of just-in-time and assembly-to-order principles (Faccio, Gamberi, Pilati, & Bortolini, 2015; Jainury, Ramli, Ab Rahman, & Omar, 2014). Indeed, modern assembly systems manufacture a huge quantity of similar products united by a common product structure yet differentiated by the mounted components which define the variants and options. Thus, these assembly systems deal with hundreds of different components, each of which is distinguished by a set of features as the volume, the weight, the handiness, the picking frequency, etc. The components required are typically picked by the assembly worker to perform the assigned tasks. Thus, an effective and efficient design of assembly systems should consider the impact that the component picking activities at assembly station level have both on worker productivity and risk of musculoskeletal disorders (Finnsgård et al., 2011; Baudin, 2002). In fact, a properly designed assembly system enables to both maximize the line productivity and minimize the ergonomic risk to which workers are exposed (Savino, Mazza, & Battini, 2016).

Furthermore, aim of the assembly line balancing problem (ALBP) is the tasks to stations assignment (Scholl, 1995). This selection affects the station workload and influences the assembly line productivity. Nevertheless, this assignment univocally defines the station in which each component has to be stored. Every task is distinguished by a corresponding typology and number of components to assemble. Thus, neglecting the influence of component features and storage location (SL) at station level on assembly activities leads to inefficient ALBP solutions. The division of assembly operations into component picking and task execution (i.e. component fastening) enables to assess the impact of component

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Nomenclature

Abbreviations

ALBP	Assembly line balancing problem
MO	Multi-objective optimization
MOST	Maynard operation sequence technique
REBA	Rapid Entire Body Assessment
SL	Storage location
T_{MOST_w}	Component picking time from w-th storage location according to MOST general move sequence
TMU	Time measurement units

Component features

A	component volume parameter
B	component density parameter
C	component shape parameter
D	component damage risk parameter
E	component condition parameter
MAG	magnitude index
V	component volume [cm^3]

Body angles

α	neck bending
β	trunk frontal bending
γ	knee angle
δ	shoulder frontal elevation
η	elbow angle
λ	wrist flexion

Indices

$k = 1, \ldots, K$ assembly stations
$j, i = 1, \ldots, J$ tasks
$w = 1, \ldots, W_k$ storage locations (SLs) within each station
$z = 1, \ldots, Z$ components

Parameters

A_{jz}	1 if task j requires component z, 0 otherwise
AT_j	assembly execution time of task j [s]
AE_j	assembly execution ergonomic risk of task j [REBA score]
CT	maximum assembly line cycle time [s]
HM_{wk}	height of storage location w of station k [mm]
H_z	height of component z (standard bin) [mm]
IE	ergonomic risk of idle worker [REBA score]
IT_k	idle time of worker k [s]
LM_{wk}	length of storage location w of station k [mm]
L_z	depth of component z (standard bin) [mm]
LBK	lower bound of the station number
QM_{wk}	weight capacity of storage location w of station k [g]
Q_z	weight of component z (standard bin and contained components) [g]
PE_{zwk}	picking ergonomic risk of component z from location w of station k [REBA score]
PT_{zwk}	assembly picking time of component z from location w of station k [s]
RM_{wk}	width of storage location w of station k [mm]
R_z	width of component z (standard bin) [mm]
ξ_j	immediate predecessors of task j

Variables

X_{jk}	1 if task j is assigned to station k, 0 otherwise
Y_{zwk}	1 if component z is stored in position w of station k, 0 otherwise

Objective functions

ER	assembly line ergonomic risk [REBA score]
G_s	global function
s	Pareto solution index
TT	assembly line takt time [s]

features and SL on picking activities. The component picking time can represent even a large portion of the task total assembly time (Finnsgård and Wänström, 2013). Fig. 1 presents examples of picking at the assembly station, influenced by the component SL with respect to the assembly workspace.

Fig. 1 suggests a further relevant aspect of component picking at assembly station level. The component features and SL significantly affects the worker ergonomic risk while he is performing assembly activities. Although ergonomic ALBP is nowadays a widely debated topic in industrial engineering research, the proposed approaches and methods aim to minimize the worker risk of musculoskeletal disorders without including any variation in the assembly task duration. Commercial software for the manufacturing industry seek to integrate the ergonomic and time aspects in the ALBP (Cheshmehgaz, Haron, Kazemipour, & Desa, 2012). Siemens Jack™ (https://www.plm.automation.siemens.com/en/products/tecnomatix/manufacturing-simulation/human-ergonomics/-jack.shtml) and Dassault Delmia™ (https://www.3ds.com/products-services/delmia/products/v5/portfolio/) are widespread software to virtually represent the manual manufacturing and assembly activities through digital human modelling. The tasks performed by an operator are simulated by a digital mannequin to assess an extensive range of performance indices. These software offer a wide sets of ready-to-use tools to automatically analyse the operator activities both from the time (MTM motion analysis, MOST, etc.) and ergonomic (REBA index, OWAS, NIOSH, etc.) perspectives. However, these software lack any optimization criteria, thus they do not represent a proper solution for the previously described problem.

Considering the formerly analysed scenario, this paper proposes an innovative multi-objective optimization (MO) model for the ALBP to assign assembly tasks to stations by distinguishing the assembly activities involved in component picking and task execution. The former are the activities to pick components from station SLs which are affected by the component storage position and attributes, such as dimensions, weight, shape and handiness. The latter are the activities for component fastening on the assembly workbench which depend on the task to be performed. Aim of the developed MO model is the simultaneous minimization of the assembly line takt time and ergonomic risk, both of which are determined by the task execution and component picking activities. These optimization targets are those selected between the multitude of criteria for the ALBP, e.g. quality, flexibility, etc. Indeed, the current scenario of assembly industry compels to evaluate both these two performance indicators. Takt time minimization is mandatory to guarantee proper efficiency to the assembly process and adequate utilization of the involved resources. Ergonomic risk reduction is required by the European standards EN 1005-2, 3, 4 and 5 which force the risk assessment of lifting and carrying activities as well of the low load handling at high frequency. Furthermore, the ergonomic assessment of assembly processes is even more relevant considering the industrial environment evolution of the last decade. In the last 10 years the percentage of European employees older than 50 years rose from

Fig. 1. Examples of picking at the assembly station from different component storage locations with respect to the workspace.

21.6% to 30.4% (OECD, 2015). One third of all workers in the EU are involved in painful or tiring postures for more than half of their working day (Paoli and Merllié, 2001) which results in the dramatic amount of 155′639 cases of occupational diseases across Europe in 2014 only (Kieffer, 2016).

The proposed model for ALBP not only defines the optimal task assignment to stations, but it also determines the optimal SL for each component between the locations available at the different stations of the assembly line. Novelty of this research is the integration of traditional ALBPs with logistics and attributes of components at the assembly station level. Between the practical implications of the presented study lies the possibility for practitioners to include important real world assembly aspects, such as component characteristics, SLs and ergonomics, in a unique balancing model. The developed ALBP model is tested and validated with an industrial case study to demonstrate the applicability and relevance of the proposed research. The limitations of this study are related to the use of kanban component feeding policy which requires to use a specific container bin for each picked component filled with a certain quantity of identical items. This component feeding policy requires a wider working space compared to the kitting policy due to a greater quantity of stored materials at assembly station level (Hanson et al., 2012; Boothroyd, Dewhurst, & Knight, 2011). Thus, the influence of component attributes and in-line storage on the picking time and consequently on ALBPs is more relevant when it is adopted the kanban feeding policy (Alnahhal & Noche, 2015; Faccio, Gamberi, Bortolini, & Pilati, in press). A further assumption of the proposed ALBP model is the applicability for single model assembly line, only (Faccio et al., 2015; Chutima and Chimklai, 2012).

The remainder of this paper is organized as follows. Section 2 presents a literature review of the ALBP and the impact of component attributes and storage at station level on assembly line performance. Section 3 describes this problem formulation for component picking activities, proposing an original method to estimate the component picking time as a function of component features and SLs. Section 4 presents a multi-objective assembly line balancing model to simultaneously minimize the assembly line takt time and ergonomic risk. Section 5 describes an industrial case study used to validate the model illustrating the key results, while Section 6 discusses the MO model main outcomes. Finally, conclusions and further research opportunities are drawn in Section 7.

2. Literature review

Since its first formulation in 1955 (Salveson, 1955), the ALBP has been widely analysed and investigated by the international research community. The original ALBP mathematical formulation and solution procedure is aimed at the assignment of assembly tasks to serial workstations to optimize a particular objective function. Considering this problem complexity, several authors proposed different versions of the ALBP, typically focusing on one or more specific features of the analysed assembly system. Boysen, Fliedner, and Scholl (2007) suggest how a relevant number of researchers tackled the ALBP considering the same recurrent features to classify an assembly system as the assembly station or line layout, the stochastic or deterministic assembly times, the buffer presence as well as the targeted objective functions and the selected solving methods. However, it is important to emphasize that few contributions deal with the so-called 'additional aspects of assembly line configuration' as the picking of product components. In particular, the component attributes and storage at assembly station level are typically not considered as one of the most relevant ALBP features. For instance, component picking and in-line storing are not included in the several features listed by Sivasankaran and Shahabudeen (2014) in a recent survey to classify the most relevant ALBP aspects and research directions. A recent trend at early stage seeks to include both time and space constraints within ALBP models, defining the so-called Time and Space ALBP. For instance, Bautista and Pereira (2011) as well as Kucukkoc and Yaman (2013) include space requirements in their ALBP. However, these authors consider the area required to perform the assembly tasks and the space needed by the components and their attributes (i.e. dimensions and weight). Chica, Cordon, Damas, and Bautista (2011), Chica, Bautista, Cordón, and Damas (2016) propose a realistic multi-objective version of the classical ALBP including the space minimization as objective function. Although, these authors do not assess the effects of space minimization on the component picking time.

Recent and promising research directions in ALBP are represented by the inclusion of ergonomic aspects. Otto and Scholl (2011) propose a pioneering contribution in this field of research, proposing an ergonomic objective function for ALBPs. These authors developed several versions of the so-called Ergo-ALBP depending on the ergonomic risk aggregation to the assembly stations. Bautista, Batalla-García, and Alfaro-Pozo (2016) developed an ALBP optimization model which jointly considers the temporal, spatial and ergonomic attributes of assembly operations at once. This model assigns the tasks to the workers considering the task duration, required space and ergonomic risk. Furthermore, some other contributors try to merge the space and time constraints with the ergonomic risk minimization (Bautista et al., 2012; Bautista et al., 2016). However, all these models do not consider the effects of the component features and storage at station level on the assembly time and ergonomic risk (Kara, Atasagun, Gökçen, Hezer, & Demirel, 2014; Otto & Scholl, 2011). Whatever the method proposed and used by the different authors, both the assembly time and risk of musculoskeletal disorder are assessed for each assembly operation considering the component picking activities as defined, fixed and constant for each task (Xu, Ko, Cochran, & Jung, 2012).

A further trend in assembly research is represented by the development of models and methods for assembly station design that consider the impact of component characteristics and logistics on assembly performance. According to the lean production principles, Wänström and Medbo (2008) suggest to distinguish assembly activities into value-adding, i.e. the component assembly, and non-value-adding ones, i.e. the component picking by the workers. As highlighted by Finnsgård et al. (2011), the component picking time can even represent a significant portion of the total assembly time. Furthermore, the picking time is strongly affected by the component SL in the station with respect to the worker and the assembly workspace. Thus, these authors suggest to optimize the component storage strategy at station level to significantly decrease the component picking time. Presenting an industrial case study, Finnsgård and Wänström, 2013 identify which factors have a relevant impact on the manual picking performance of assembly lines. The most significant factors are the component features (size and weight), the offset (the vertical distance between the worker and the component to pick), the orientation angle (the angle between the worker and the stored component), the sideway position (the worker to component direction), the picking height from the floor and the type of storage container bin used at station level. However, no contribution so far integrates the component picking activities at assembly station level influenced by the aforementioned factors into an original ALBP.

Analysing the current state of the art, traditional ALBPs do not consider the effect of component attributes and storage at station level on assembly time. Ergo-ALBP models, too, aim to minimize the assembly line ergonomic risk without including these features. On the contrary, researches on assembly station design clearly present how the picking time at the assembly station level can be significantly decreased by optimizing the component storage along the line. This paper proposes an innovative MO model for ALBP to assign assembly tasks to stations by distinguishing the assembly activities in task execution and component picking. Thus, an original function is proposed to relate the component picking duration and ergonomic risk with the component SL along the line and the component attributes, namely dimensions, weight and handiness. The aim of the developed MO model is to simultaneously minimize the assembly line takt time and ergonomic risk, both determined by task execution and component picking activities. Finally, the proposed model for ALBP not only defines the optimal task assignment to stations, but it also determines the optimal SL for each component among the locations available at the different assembly stations.

3. Problem formulation for component picking activities

This paper proposes to distinguish the assembly activities of each task in:

- a variable component picking time and ergonomic risk, that depends on the component attributes and in which location at assembly station level the component is stored,
- a constant task execution time and ergonomic risk, that uniquely depends on which task has to be performed.

Thus, this Section adopts the method proposed by Bortolini, Faccio, Gamberi, and Pilati (2016a) to relate the component picking time with the SL in which they are stored at assembly station level (Section 3.1) and with the component features (Section 3.2). Furthermore, these two aspects are integrated in a function for picking time estimation (Section 3.3). Finally, REBA (Hignett & McAtamney, 2000) method is exploited to define a procedure for the assessment of the ergonomic risk of component picking as a function of the component attributes and the SL in which the component is stored (Section 3.4). Through the several steps required to assess the component picking activities, the following assumptions are considered:

- Single model assembly line.
- Kanban policy for component feeding.

Table 1
Container bins for component storage at assembly station level.

		Container bin ID					
		1	2	3	4	5	6
External dimensions [mm]	Depth	145	200	300	450	630	800
	Width	90	140	200	300	450	600
	Height	70	130	145	200	300	430
Internal dimensions [mm]	Depth	123	186	284	428	605	755
	Width	80	125	181	277	428	553
	Height	63	110	130	183	275	392

- Divisibility of each assembly task in component picking and task execution (e.g. component fastening) (Wänström and Medbo, 2008).
- The component picking time and ergonomic risk depend on the component features and its SL at assembly station level.
- Container bins to store the components along the assembly line. Proper bins are identified for each component considering its physical dimensions and weight (Table 1).

3.1. Influence of component storage location on picking time

According to Bortolini et al. (2016a), this paper assesses the component picking time starting from the Basic MOST (Maynard Operation Sequence Technique) pre-determined motion time system (Maynard, 1972; Maynard & Stegemerten, 1948) adopting the General Move Sequence model (get, put and return actions). The MOST General Move Sequence evaluates the worker basic movements to pick the component stored in SLs at assembly station level to define the component picking standard time. The MOST General Move Sequence is exploited to assess the component picking time (T_{MOST_w}) from the SLs ($w = 0, \ldots, 3$) which traditionally distinguish industrial assembly stations. Fig. 2a graphically represents these SLs with respect to the assembly workspace, whereas Fig. 2b and c propose the top and side views of the assembly station with the most relevant geometrical dimensions. Table 2 proposes the calculated picking time both in seconds and in Time Measurement Units (TMUs, e.g. 1 TMU = 0.036 s) from the aforementioned SLs.

The estimated component picking time significantly decreases from the least to the most accessible SL (from 5.04 to 1.44 s). Furthermore, as previously described (Finnsgård et al., 2011), the component picking time represents a relevant portion of the total assembly time. Thus, proper ALBP models should consider a variable picking times function of the component SL. However, the MOST technique does not consider any component feature, as dimensions, shape, and weight to estimate the picking time. To overcome this drawback, this research assesses the influence of component features on picking time.

3.2. Influence of component features on picking time

To overcome the aforedescribed MOST limitations, the adoption of the *MAG* (magnitude) concept is proposed. *MAG* is developed first by Pareschi (1994) to assess the influence of component features to manual handling activities. For each component considered, *MAG* is assessed using the following Eq. (1) experimentally determined (Pareschi, 1994).

$$MAG = A \cdot [1 + 0.25 \cdot (B + C + D + E)] \tag{1}$$

This research proposes to exploit *MAG* as a dimensionless index to increase or decrease the component handling time considering its features. Eq. (1) suggests that *A* parameter is the main driver of *MAG* index. This parameter can be determined considering the component volume (V) and exploiting the relation presented in Eq. (2) (Pareschi, 1994).

$$A = \begin{cases} 0.0338 \cdot V^{0.6996}, & V \leqslant 500\ \text{cm}^3 \\ 0.226 \cdot V^{0.3863}, & V > 500\ \text{cm}^3 \end{cases} \tag{2}$$

The values of parameters B, C, D and E are qualitatively assessed analysing the component attributes as listed in Table 3. For instance, flat, stackable and groupable components are distinguished by the shape value of $C = -2$ which lowers *MAG* index, thus the component picking time. On the contrary, long, circular and irregular components have a shape value of $C = 2$ which increases the picking time.

The adoption of *MAG* concept can be implemented to evaluate the handiness of any component. For instance, a wooden cube of side 5 cm is distinguished by $MAG = 1$.

3.3. Picking time estimation as a function of component features and storage location

Following the guidelines proposed by recent literature contributions (Bortolini et al., 2016a), an experimental campaign is developed to measure the picking time of components distinguished by different features, e.g. volume range 15–16,000 cm^3 and B, C, D, E values between −1 and 2, from the representative SLs identified in Fig. 2. During the campaign, several workers performed different picking activities of the identified components from station SLs 0, 1, 2, 3. For each component and SL at least 10 different time measures are performed using expert workers. First, the picking times obtained by the different workers are normalised using the Bedaux method (Bedaux, 1928) considering a Bedaux speed rating of 60 (normal speed). No rest factor is considered to compare these picking times with the one estimated by the MOST method. Furthermore, the picking time average value $\overline{PT}$ and standard deviation σ are calculated for each component and SL. Table 4 proposes the experimental campaign results. The picking time depends both on the component features summarized by the *MAG* index and on the location where the components are stored. The higher the *MAG* index, the longer the picking time is. Similarly, SLs far from the workbench (from SL 0 to SL 3) increase the picking time value. Eq. (3) exploits these considerations to evaluate the picking time as a function of component features and SL at assembly station level.

$$PT = PT(w, MAG) \tag{3}$$

The $PT(w, MAG)$ function is evaluated comparing for a specific SL the measured picking time from the experimental campaign with the one estimated adopting the MOST General Move Sequence (T_{MOST_w}, values presented in Table 2). The former also depends on the features of the picked component represented by the *MAG* index, whereas the latter considers the picking time uniquely depend on the SL. $PT(w, MAG)$ functions are proposed in

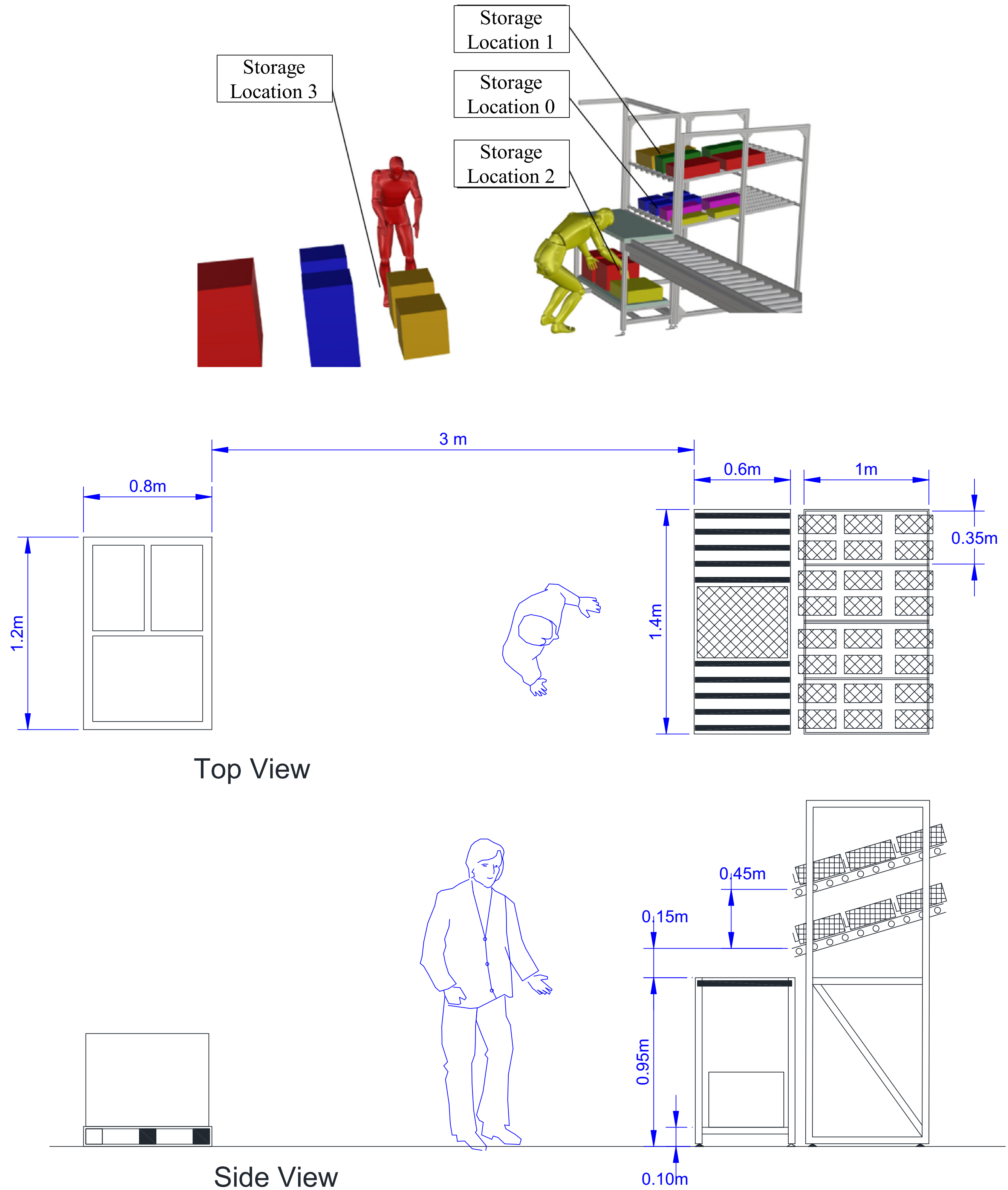

Fig. 2. Typical component storage locations at assembly station level (a). Top (b) and side (c) views with geometrical dimensions.

Table 5, both considering the component features (*MAG*) and SL (w). These functions are 3rd degree polynomial with a correlation coefficient greater than 95% to the measured data.

The next Fig. 3 plots the dimensionless ratio $PT(w, MAG)/T_{MOST}$ for the different SLs ($w = 0, \ldots, 3$) and component features ($MAG = 0, \ldots, 12$) to compare the previously defined $PT(w, MAG)$ function with the traditional MOST General Move Sequence approach for component picking time estimation. This ratio lower or greater than 1 suggests respectively an overrated or underrated

Table 2
MOST general move sequence and component picking time for the considered storage locations.

Storage location w	MOST general move sequence	Picking time	
		[TMU]	[sec]
0	$A_1\ B_0\ G_1\ A_1\ B_0\ P_1\ A_0$	40	1.44
1	$A_1\ B_3\ G_1\ A_1\ B_0\ P_1\ A_0$	70	2.52
2	$A_1\ B_6\ G_1\ A_1\ B_0\ P_1\ A_0$	100	3.60
3	$A_3\ B_6\ G_1\ A_3\ B_0\ P_1\ A_0$	140	5.04

picking time by the MOST approach compared to the measured values.

Fig. 3 suggests how the MOST approach overrates the picking time for every component distinguished by $MAG \leqslant 2$ whatever the SL is. For SL 3 in particular, the MOST methodology overestimates the picking time even for components with higher *MAG* value. Indeed, for this SL, the MOST approach considers the worker walking activity to reach the SL behind the workbench. Furthermore, the greater the *MAG* value, the worse the MOST methodology estimates the component picking time, in particular for SLs close to the workbench (e.g. SL 0). For instance, the real picking time of cumbersome components from these locations is from 50% to 125% higher than the MOST estimation.

3.4. Influence of component storage location and features on picking ergonomics

As suggested by the previous Section 3.3, the picking of components during the assembly tasks is strongly influenced by the component attributes and by the component SL at assembly station level. Thus, it is necessary to evaluate not only the temporal aspect of picking activities but also the ergonomic one. Savino et al. (2016), propose a list of different methods to estimate the risk of musculoskeletal disorders for workers employed in assembly systems. Analysing the proposed methods, it is possible to highlight the major characteristics as well as the most relevant limitations and drawbacks to exploit these methods for the assessment of the ergonomic risk of component picking operations during manual assembly activities.

Table 5
PT(***w***, ***MAG***) functions.

Storage location w	$PT(w, MAG)$
SL 0	$T_{MOST_0}\ (0.0009MAG^3 - 0.0134MAG^2 + 0.1594MAG + 0.7173)$
SL 1	$T_{MOST_1}\ (0.0008MAG^3 - 0.0151MAG^2 + 0.1517MAG + 0.7307)$
SL 2	$T_{MOST_2}\ (0.0008MAG^3 - 0.0162MAG^2 + 0.1466MAG + 0.7397)$
SL 3	$T_{MOST_3}\ (0.0003MAG^3 - 0.0074MAG^2 + 0.0864MAG + 0.7278)$

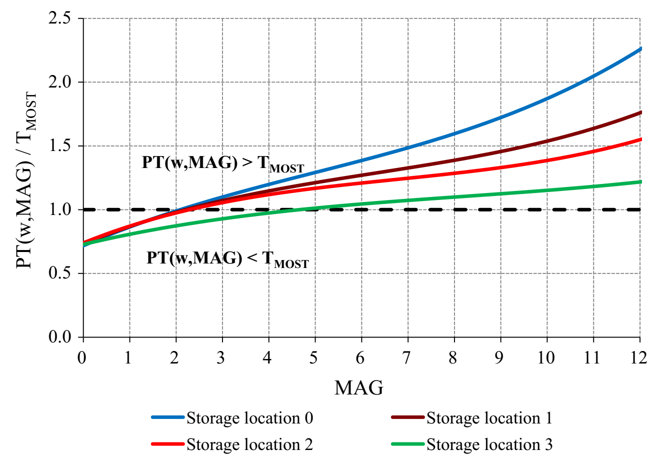

Fig. 3. $PT(w, MAG)/T_{MOST}$ ratio for the identified storage locations as function of *MAG* value.

Table 3
B, C, D, E values determined by the component density, shape, damage risk and condition for ***MAG*** *index calculation* (Pareschi, 1994).

Value	B. Density	C. Shape	D. Damage risk	E. Condition
−3	Extremely light and empty	Extremely flat, stackable and groupable		
−2	Light and empty	Flat, stackable and groupable	Not possible to damage	
−1	Quite light and voluminous	Quite flat, stackable and groupable	Unlikely to be damaged	
0	Reasonably solid	Square and reasonably stackable	Slight risk of damaged	Clean, crushproof and solid
+1	Quite heavy and dense	Quite long, circular, irregular	Susceptible to crushing, breakage or scratch damage	Deformable, unctuous and limp
+2	Heavy and dense	Long, circular, irregular	Susceptible to serious damage	Extremely deformable and unctuous, hot, slick, stinging
+3	Extremely heavy and dense	Extremely long, circular, irregular	Extreme likelihood of irreparable item	

Table 4
Experimental campaign to evaluate the component picking time as a function of component features and storage location.

Component ID	Component volume [cm^3]	A	B, C, D, E	*MAG* index	*PT* location 0		*PT* location 1		*PT* location 2		*PT* location 3	
					$\overline{PT}$	$\sigma(\boldsymbol{PT})$	$\overline{PT}$	$\sigma(\boldsymbol{PT})$	$\overline{PT}$	$\sigma(\boldsymbol{PT})$	$\overline{PT}$	$\sigma(\boldsymbol{PT})$
#1	15	0.22	1, 0, −1, 0	0.22	1.06	0.16	1.37	0.16	2.69	0.20	3.73	0.09
#2	42	0.46	1, 0, −1, 0	0.46	1.22	0.07	1.56	0.11	2.98	0.14	3.85	0.20
#3	121	0.97	0, 1,0, 0	1.21	1.22	0.16	1.62	0.24	3.29	0.24	4.15	0.11
#4	188	1.32	1, 1, −1, 0	1.64	1.34	0.11	1.74	0.14	3.42	0.13	4.39	0.33
#5	1820	4.11	0, −1, 0, 0	3.08	1.48	0.17	1.87	0.17	3.56	0.24	4.52	0.17
#6	360	2.08	−1, 1, 2, 0	3.11	1.68	0.16	2.09	0.22	3.84	0.19	4.75	0.24
#7	1728	4.02	0, 1, −1, 1	5.03	1.80	0.15	2.27	0.18	4.28	0.09	5.03	0.25
#8	1356	3.66	1, 1, 0, 0	5.50	2.09	0.08	2.52	0.13	4.38	0.26	5.22	0.20
#9	51170	14.90	−1,−1, 0, 0	7.45	2.20	0.14	2.62	0.20	4.40	0.14	5.40	0.11
#10	16000	9.51	−1, 2, −1,1	11.89	3.30	0.20	3.67	0.24	5.27	0.32	5.77	0.25

- OCRA (Occhipinti, 1998). This method evaluates the risk of musculoskeletal disorders for upper limbs only. Thus, it is not suitable to assess the ergonomic risk of component picking from SLs close to the floor because these require worker leg bending to be reached.
- OWAS (Karhu, Kansi, & Kuorinka, 1977). OWAS does not assess the movements of lower arms and wrists. A proper evaluation of picking activities have to consider these limbs. Thus, OWAS method is not suitable for this paper purpose.
- NIOSH (Niosh, 1981). This methods determines the recommended load weight limit for human lifting operations. NIOSH is distinguished by major limitations to be exploited for manual assembly operations (e.g. place a screw or mount a cover on a workbench). In particular, this method does not provide any useful information to assess the ergonomic risk of this kind of activities.
- RULA (McAtamney & Corlett, 1993). RULA method is distinguished by a low sensitivity to evaluate the ergonomic risk of the different leg postures that a worker assumes during picking activities.
- REBA (Hignett & McAtamney, 2000). This method evaluates the risk of musculoskeletal disorders of more than 600 working postures determined by the combination of trunk, neck, legs, upper arms, lower arms and wrists postures. REBA considers both the weight of the loaded component and its coupling for handling activities. This method proposes for each identified working posture a score from 1 to 15 distinguished by a risk level of musculoskeletal disorder ranging from negligible to very high.

As a consequence of the list above, the REBA method is adopted in this paper to model the ergonomic risk of picking activities considering both component SLs and component attributes. Fig. 5 summarises the procedure for REBA application to component picking activities. The original REBA procedure is presented in Hignett and McAtamney (2000).

First, the proposed procedure assesses the impact of SL on picking ergonomics. The posture of trunk, neck and legs hold by the worker to perform the picking activity is identified through specific

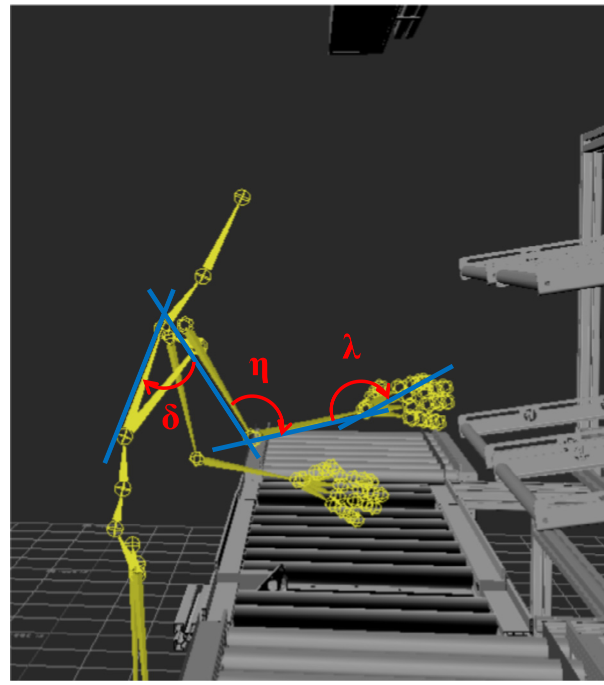

Fig. 4b. Upper arm, lower arm and wrist angles of the worker.

Table 6
Load parameter – component weight (left) and Coupling parameter – *MAG* index (right) relations (from Hignett & McAtamney, 2000).

Weight [kg]	Load	*MAG*	Coupling
<1	0	0.2–5	0
1–5	1	<0.2 OR 5–10	1
5–10	2	10–20	2
>10	3	>20	3

angles (Fig. 4a). Similarly, proper angles measure the upper arm, lower arm and wrist positions (Fig. 4b). Then, the REBA method (Hignett & McAtamney, 2000) exploits these angle values to independently assess the posture of lower and upper limbs, identified by a score from 1 to 9.

Furthermore, the presented procedure includes the component features into the assessment of picking ergonomics. Component weight defines the "Load" parameter (score 0–3) accordingly to REBA method (Hignett & McAtamney, 2000), whereas the aforepresented *MAG* index is considered to assess the "Coupling" parameter (score 0–3) which measures the component handiness for picking activities (Table 6).

Finally, the sum of lower limb posture and load parameter define the lower limb risk, whereas the sum of upper limb posture and coupling parameter represents the upper limb risk (Hignett & McAtamney, 2000). The REBA method is adopted to merge this information and define the final REBA score (range 1–15) which represents the ergonomic risk level to pick up a certain component from a specific SL (from negligible to very high risk) (Fig. 5).

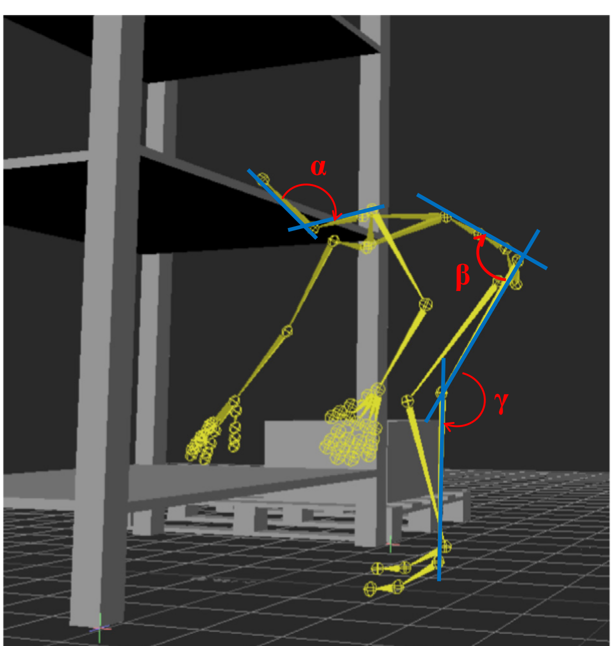

Fig. 4a. Trunk, neck and leg angles of the worker.

4. Multi-objective optimization model for assembly line time and ergonomic balancing

This section proposes an innovative MO model for the ALBP to assign assembly tasks ($j, i = 1, \ldots, J$) to stations ($k = 1, \ldots, K$) by distinguishing the assembly activities involved in component picking and task execution. For each component z required to assemble task j (represented by parameter A_{jz}) the model considers a compo-

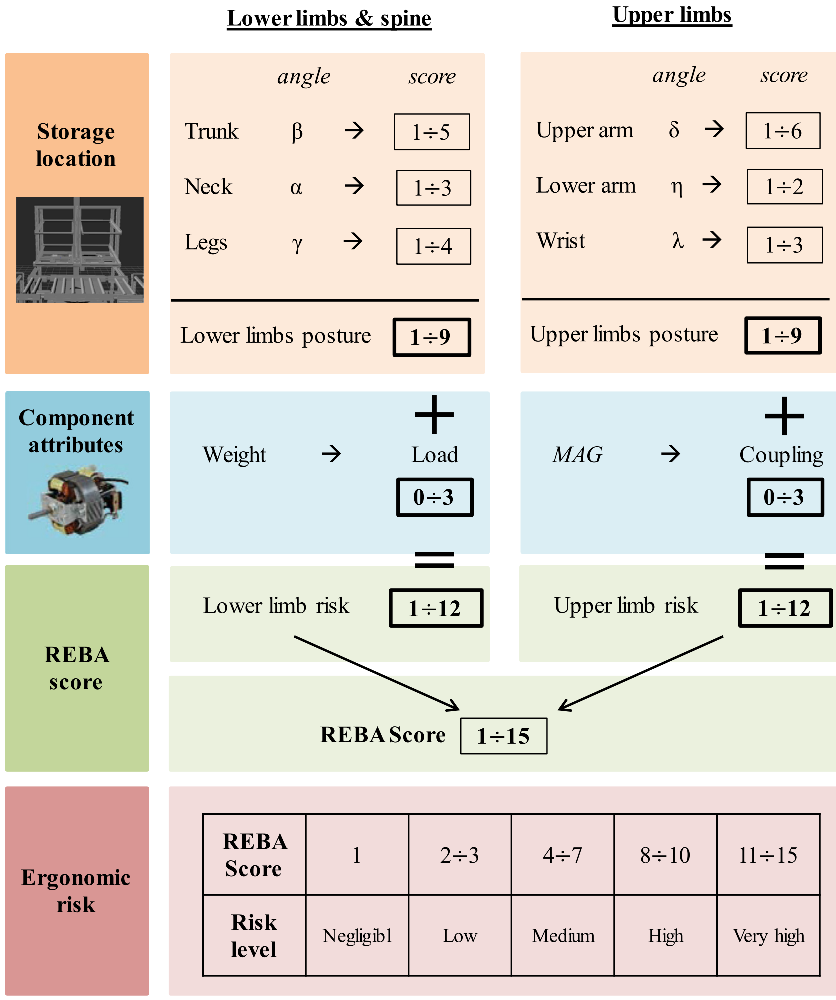

Fig. 5. *Procedure to assess the ergonomic risk of picking activities considering the storage location and component attributes (adapted from Hignett & McAtamney, 2000).* Hignett and McAtamney (2000)[1].

nent picking time PT_{zwk} and ergonomic risk PE_{zwk} which depend on component z attributes and storage location w within the assembly station k. Indeed, the stations do not necessarily have to be distinguished by identical SLs (e.g. $w = 1, \ldots, W_k$). On the contrary, task execution time AT_j and ergonomic risk AE_j uniquely depends on the task j to be performed. The aim of the developed MO model is to simultaneously minimize the assembly line takt time TT and ergonomic risk ER, both of which are determined by the task execution and component picking activities. Furthermore, the proposed model for the ALBP not only defines the optimal task assignment to stations, represented by the decision variable X_{jk}, but it also determines the optimal SL for each component between the locations available at the different stations (decision variable Y_{zwk}). Finally, the proposed ALBP MO model matches the geometrical and load capacity features of the SLs at assembly station level (QM_{wk}, LM_{wk}, RM_{wk}, HM_{wk}) with the dimensions and weight of the components to be stored in (Q_z, L_z, R_z, H_z). The component feeding to the assembly line is managed through standard container bins, one per component type.

The following constraints are defined in the proposed ALBP MO model to ensure these four conditions: effect of tasks to stations assignment on components to SLs allocation and vice versa (Eqs. (4)–(7)), precedence graph and cycle time restrictions (Eqs. (8) and (9)), feasibility of component stocking in storage locations (Eqs. (10)–(13)), congruence conditions of the decision variables (Eq. (14)).

Eq. (4) forces each task to be uniquely assigned to one station. Eq. (5) ensures that each component is stored in a maximum of one location per workstation. Eq. (6) guarantees that the components required by a task have to be stored in locations of the station to which the task is assigned, whereas Eq. (7) enables to assign a task uniquely to these stations in which all the needed components are stored. A feasible ALB configuration is ensured considering the precedence graph (Eq. 8 from Scholl, 1995) and the cycle time (Eq. (9)) restrictions. Eq. (8) limits the tasks to stations assignment considering the precedence relations between tasks. Every task i immediate predecessor of task j can be assigned uniquely to those stations not following the one which perform task j. Eqs. (10)–(13) guarantee that all the components stored in a certain location do not exceed its maximum load capacity and physical dimensions. Eq. (10) limits the total weight of all the components stored in a location to the SL load capacity. Eq. (11) ensures that the sum of the component width stored in a SL does not exceed the location width itself, while Eqs. (12) and (13) respectively compare the SL length and height with the ones of every stored component. Component length considers the depth

[1] (The presented procedure for the ergonomic risk assessment of picking activities is based on the REBA method proposed byThe developed procedure exploits the structure and the evaluation criteria of REBA method. Component and SL features provide the method with specific input data of picking activities. The procedure final output is the ergonomic assessment of a component picking from a certain SL according to the risk categories proposed by Hignett and McAtamney (2000).)

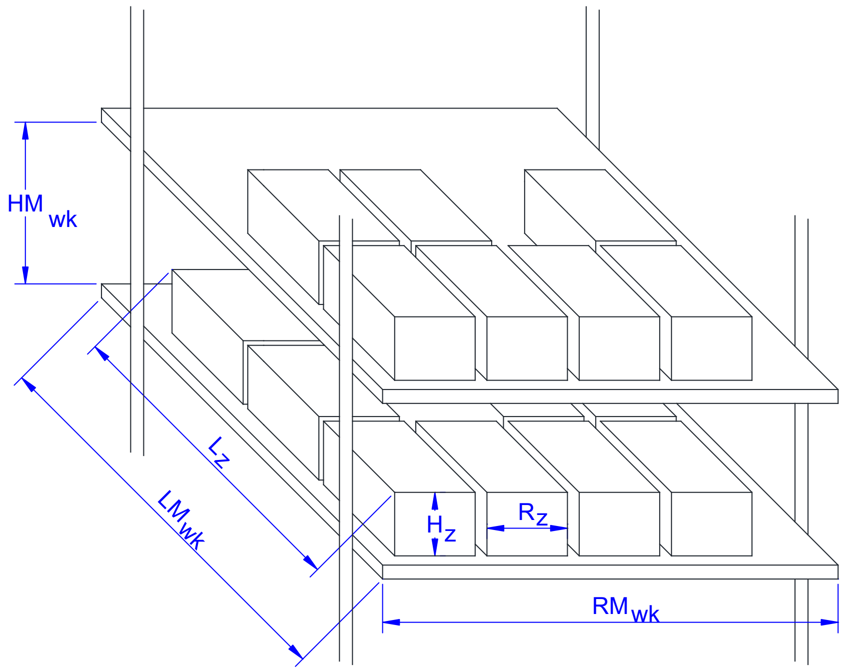

Fig. 6. Geometrical relations between components and storage locations.

of all the aligned container bins determined by the adopted kanban feeding policy. Fig. 6 illustrates the geometric relations behind these constraints.

Eq. (14) represents the congruence conditions for the decision variables. This research innovative content is represented by the constraints of Eqs. (4)–(7) and (10)–(13) which seek to model the influence of component picking activities on the ALBP.

Constraints

Mutual effect of tasks to stations and components to storage locations assignment.

$$\sum_{k=1}^{K} X_{jk} = 1 \quad \forall j \tag{4}$$

$$\sum_{w=1}^{W_k} Y_{zwk} \leqslant 1 \quad \forall z, k \tag{5}$$

$$\sum_{w=1}^{W_k} Y_{zwk} \geqslant A_{jz} \cdot X_{jk} \quad \forall j, z, k \tag{6}$$

$$X_{jk} \geqslant \sum_{w=1}^{W_k} Y_{zwk} \cdot A_{jz} \quad \forall j, z, k \tag{7}$$

Cycle time and precedence graph limitations.

$$\sum_{k=1}^{K} k \cdot X_{jk} \geqslant \sum_{k=1}^{K} k \cdot X_{ik} \quad \forall (j, i) | i \in \xi_j \tag{8}$$

$$\sum_{j=1}^{J} \left(AT_j \cdot X_{jk} + \sum_{z=1}^{Z} A_{jz} \cdot \sum_{w=1}^{W_k} (PT_{zwk} \cdot Y_{zwk}) \right) \leqslant CT \quad \forall k \tag{9}$$

Feasibility of components to storage locations assignment.

$$\sum_{z=1}^{Z} Q_z \cdot Y_{zwk} \leqslant QM_{wk} \quad \forall w, k \tag{10}$$

$$\sum_{z=1}^{Z} R_z \cdot Y_{zwk} \leqslant RM_{wk} \quad \forall w, k \tag{11}$$

$$L_z \cdot Y_{zwk} \leqslant LM_{wk} \quad \forall z, w, k \tag{12}$$

$$H_z \cdot Y_{zwk} \leqslant HM_{wk} \quad \forall z, w, k \tag{13}$$

Variable congruence conditions.

$$X_{jk}, Y_{zwk} \text{binary} \quad \forall j, z, w, k \tag{14}$$

According to Eqs. (4)–(14), the presented MO model for the ALBP includes $J \cdot K + Z \cdot \sum_{k=1}^{K} W_k$ variables, whereas an upper bound to the constraint number is $K + J \cdot (1 + J) + Z \cdot K \cdot (1 + 2J) + 2W \cdot K \cdot (1 + 2Z)$ occurring for the worst theoretical precedence graph distinguished by J tasks.

Furthermore, this paper proposes two different objective functions for the ALBP, namely assembly line takt time (TT) and ergonomic risk (ER) minimization.

Objective functions

1. Minimize the assembly line takt time TT.

The TT objective function (Eq. (15)) aims to minimize the maximum assembly time among the stations, equal to the real cycle time of the assembly line, also known as the bottleneck of the assembly system. Eq. (9) ensures the target cycle time of the assembly line to fulfil the market demand. Given this constraint, the TT objective function optimizes the line efficiency, i.e. the resource utilization / worker workload. In this way, the objective function minimizes the total picking time for each station, optimally locating the different components in the SLs as a consequence of the component attributes and the constraints. Simultaneously, the model optimally assigns the different tasks to the stations, levelling the workload between them. This objective function is defined as the assembly line takt time, which is the minimum time achievable between two sequential assembled products at the line end. The minimization of this objective function represents the well-known version 2 of the simple ALBP (SALBP-2) (Scholl, 1995), whose purpose is to maximize the assembly line throughput (e.g. pieces/hour), equal to $(TT)^{-1}$.

$$\min TT = min\left(\max_k \sum_{j=1}^{J} \left(AT_j \cdot X_{jk} + \sum_{z=1}^{Z} A_{jz} \cdot \sum_{w=1}^{W_k} (PT_{zwk} \cdot Y_{zwk}) \right) \right) \tag{15}$$

2. Minimize the assembly line ergonomic risk ER

The aim of the ER objective function (Eq. (17)) is to minimize the maximum risk of musculoskeletal disorders between the assembly line workers. According to major literature contributions (Bautista et al., 2016), the ER value of each worker is determined as the weighted average of the ergonomic risk of task execution (AE_j) and component picking (PE_{zwk}) activities using their respective durations (AT_j, PT_{zwk}) as weights. Indeed, for each station k, the sum of the execution time of all the assigned tasks, $\sum_{j=1}^{J}(AT_j \cdot X_{jk})$, the picking time of all the required components, $\sum_{j=1}^{J}\sum_{z=1}^{Z}\sum_{w=1}^{W_k} PT_{zwk} \cdot Y_{zwk} \cdot A_{jz}$, and the worker idle time, IT_k, is equal to CT (Eq. (16)). Thus, the objective function allocates the different tasks to the stations and the components to the different SLs jointly minimizing the ergonomic risk of component picking and task execution activities. Aim of this objective function is the ergonomic risk balancing between the workers. The ergonomic risk of worker during idle activities (IE) is included in the objective function to consider the beneficial effect that inactivity has on the risk of musculoskeletal disorders.

$$\sum_{j=1}^{J}\left(AT_j \cdot X_{jk} + \sum_{z=1}^{Z}\sum_{w=1}^{W_k} PT_{zwk} \cdot Y_{zwk} \cdot A_{jz}\right) + IT_k = CT \quad \forall k \tag{16}$$

$$\min ER = min\left(\max_k \sum_{j=1}^{J} \frac{(AT_j \cdot X_{jk}) \cdot (AE_j - IE) + \sum_{z=1}^{Z}\sum_{w=1}^{W_k}(PT_{zwk} \cdot Y_{zwk} \cdot A_{jz}) \cdot (PE_{zwk} - IE)}{CT} + IE\right) \tag{17}$$

The next Section 5 proposes an industrial case study to test and validate the presented MO model for the ALBP aimed at the simultaneous minimization of the assembly line takt time and ergonomic risk considering the characteristics which affect the component picking from SLs at station level.

5. Case study & outcomes

This paper proposes an industrial case study of a real production system for the assembly of professional kitchen appliances. The former paragraph of this Section 5.1 presents all the input data which define the analysed problem, whereas the latter (Section 5.2) illustrates the key results and main outcomes.

5.1. Problem definition

The analysed assembly process is distinguished by 26 tasks which fasten 74 different components overall. The assembly line production rate is 64 pieces/day with a cycle time (CT) of 400 s/piece. The assembly components are refilled 3 times a day according to the previously analysed kanban feeding policy. Four is the number of stations (K) according to the following Eq. (18) (adapted from Scholl, 1995) which estimates the lower bound of the station number (LBK). Thus $K = LBK$.

$$LBK = \left\lceil \frac{\sum_{j=1}^{J}\left(AT_j + \sum_{z=1}^{Z} A_{jz}(\min_{w,k}(PT_{zwk}))\right)}{CT} \right\rceil \tag{18}$$

The layout of the case study assembly system is presented in Fig. 7. Each station is equipped with four different SLs. SL 0 and SL 1 are in front of the worker at workbench and operator shoulder height, respectively. SL 2 is under the workbench, whereas SL 3 is behind the worker accommodated in a large container. The SLs are identical for each assembly station. Furthermore, the geometrical dimensions and load capacity of each SL are listed in Table 7.

Fig. 8 proposes the precedence graph of the assembly tasks, whereas Table 9 presents several relevant information of the assembly process at task level. For each task j are listed the immediate predecessor tasks, the required components, the assembly execution time AT_j and assembly execution ergonomic risk AE_j.

The ergonomic risk is evaluated using the REBA method illustrated in Section 3.4. This method is exploited to assess the posture of the upper limbs, lower limbs and spine during task execution and component picking from each SL identified by Fig. 2. Table 8 reports the score for the posture of trunk, neck and legs as well of upper arm, lower arm and wrist for each SL, along with the corresponding value of the lower and upper limb posture. Furthermore, the components assembled in each task are considered to evaluate the load and coupling scores of the REBA method. Finally, all these information are used to calculate the REBA final score which represents a measure of the ergonomic risk for task execution. Considering the described case study, the ergonomic risk of an idle worker (IE) is estimated to be negligible, i.e. distinguished by a REBA score equal to 1.

An original classification is proposed by the Authors to group the tasks considering their assembly execution time and ergonomic risk (Fig. 9). The so-called "negligible" tasks are the ones distinguished by an assembly execution time shorter than the average time and an assembly execution ergonomic risk lower than medium, according to the classification proposed by the REBA method. "Strenuous" tasks have a high ergonomic risk but a short duration. Thus, their effect on the worker ergonomic risk is limited. On the contrary, "perpetual" tasks are distinguished by low risk musculoskeletal postures maintained for a long time. Finally, the most hazardous tasks, the "harmful" ones, last for a long time with highly risky postures. The analysed case study does not include any "harmful" task due to a proper design of assembly operations and to fulfil occupational safety regulations.

To store each component at assembly station level, a proper container bin is assigned comparing the container geometrical features presented in Table 1 with the component dimensions. Moreover, the component picking time (PT_{zwk}) is evaluated for each potential storage location w (equal for each station k) considering the component z physical characteristics (weight and MAG index), using the functions previously proposed in Table 5 for picking time estimation. Similarly, the component picking ergonomic risk (PE_{zwk}) is assessed using the REBA method considering both each potential SL and the aforementioned component attributes. Appendix A summarizes all these relevant information for each single component.

Finally, the developed MO model for the ALBP is adopted to define a proper balancing of the presented case study assembly line. In this scenario, the MO model involves 1288 decision variables and 20824 constraints. A solving time of about 60 s (with an Intel i7-3770, 3.40 GHz processor and 16 Gb Ram workstation) is required to determine the takt time and ergonomic risk optimal solutions.

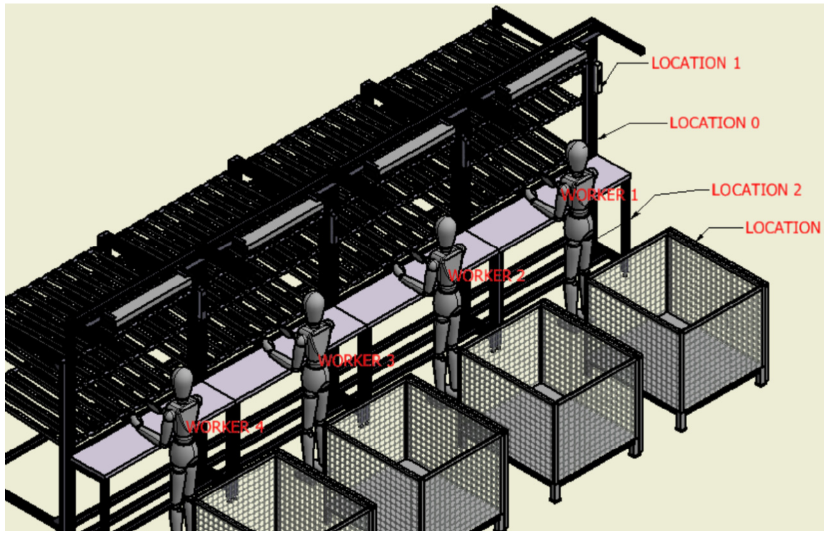

Fig. 7. Layout of the case study assembly system.

Table 7
Case study storage locations characteristics.

Storage location w	Length [mm] LM_{wk}	Height [mm] HM_{wk}	Width [mm] RM_{wk}	Load capacity [kg] QM_{wk}
0	1200	400	1200	120
1	1200	400	1200	120
2	1600	600	1200	150
3	1200	1800	3000	400

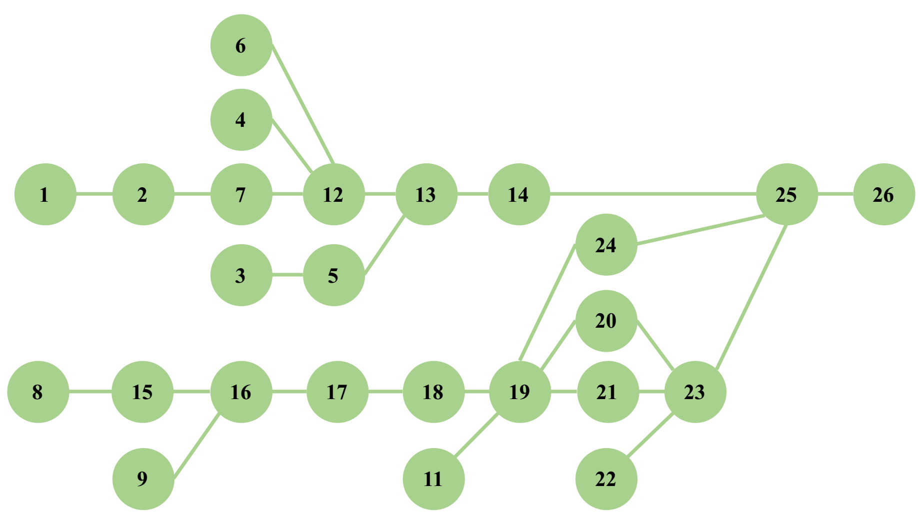

Fig. 8. Case study precedence graph of the assembly tasks.

5.2. Results

This paragraph proposes the results obtained by adopting the MO model for ALBPs proposed in Section 4 to the industrial case study presented in Section 5.1. First, the two objective functions, assembly line takt time (*TT*) and ergonomic risk (*ER*), are separately optimized, defining the so-called single objective optimization problem. As presented in Table 10, *ER* minimization increases *TT* by 20% compared to its optimal value, whereas *TT* optimization worsens *ER* by 60% from low to medium ergonomic risk of musculoskeletal disorders, according to the REBA method classification.

Table 11 represents the assembly line balancing (ALB) configuration for each worker in terms of time load and ergonomic risk determined by the single objective minimization of the two objective functions. *TT* minimization properly balances the time loads between workers. For this ALB configuration, *TT* value is equal to 78% of the cycle time, whereas the ergonomic risk is extremely unbalanced (Table 11). On the contrary, *ER* minimization limits the risk of musculoskeletal disorders to 2.2 REBA score for each worker (low risk of musculoskeletal disorders), but the time load varies from 267 to 377 s between the workers. In this latter ALB configuration, several “perpetual” tasks are assigned to worker #4. These low risky and long-lasting tasks limit his ergonomic risk

Table 8
Evaluation of the REBA scores for the different storage locations and body parts.

Storage location	Trunk	Neck	Legs	*Lower limb posture*	Upper arm	Lower arm	Wrist	*Upper limb posture*
SL 0	3	1	1	***2***	3	1	1	***3***
SL 1	2	2	2	***2***	5	1	1	***6***
SL 2	3	2	3	***5***	4	2	1	***5***
SL 3	5	2	3	***8***	3	1	2	***4***

Table 9
Immediate predecessor tasks, required components, assembly execution time (AT_j) and assembly execution ergonomic risk (AE_j) for each task j of the considered case study.

Task $\boldsymbol{j}$	Immediate predecessor tasks	Required components	Assembly execution time $\boldsymbol{AT_j}$ [sec]	Assembly execution ergonomic risk $\boldsymbol{AE_j}$ [REBA score]
1	–		140	1
2	1	8 24 28 30 33 35 45 65	140	2
3	–	36 62 64	40	4
4	–	9 13 47 60 68	30	4
5	3	29 32	50	1
6	–	7 15 52 58	30	9
7	2	10 16 17 25 26 27 31 57 61 66	50	2
8	–	2 4 12 43 71	17	2
9	–	11 18 19 48 49 50 59	25	1
10	–	5 14 22 23 72	20	2
11	–	1 6 20 21 41 56 63	40	2
12	4, 6, 7	69	40	3
13	5, 12		58	3
14	13	67	40	1
15	8	74	10	6
16	9, 15		12	1
17	10, 16	51	15	6
18	17	3 34 73	60	1
19	11, 18	70	15	5
20	19		110	1
21	19		100	1
22	–	37 38 39	6	2
23	20, 21, 22		6	4
24	19	42 44	6	1
25	14, 23, 24	40 46 53 54 55	20	7
26	25		25	9

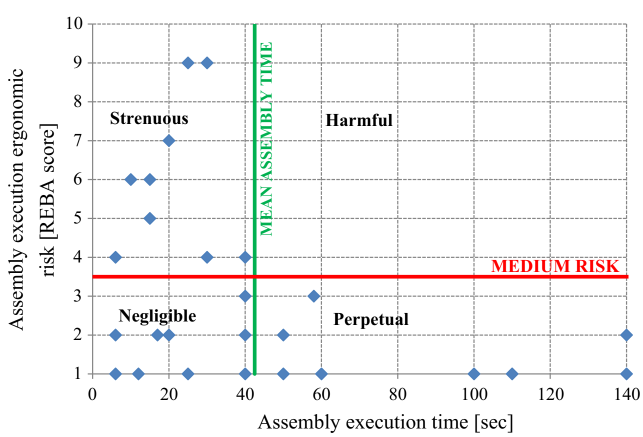

Fig. 9. Assembly task classification of the considered case study according to assembly execution ergonomic risk and assembly execution time.

to 2.26 REBA score, but they increase his time load to 94% of the cycle time.

To determine a trade-off ALB configuration which simultaneously considers both *TT* and *ER*, the MO model presented in Section 4 is exploited. Based on this model, the Pareto frontier (Pareto, 1906) of the TT – ER ALBP is determined by adopting the normalized normal constraint method proposed by Messac, Ismail-Yahaya, and Mattson (2003) (Fig. 10a). The Pareto frontier includes by definition all the optimal solutions of a MO problem. As a consequence, the final solution has to be selected within the set represented by the Pareto frontier using an arbitrary method (Lu, Anderson-Cook, & Robinson, 2012). To this purpose, in order to converge to such a final solution of the analysed ALBP, the Authors exploit the empiric rule proposed by Bortolini, Faccio, Ferrari, Gamberi, and Pilati (2016b, 2016c) and Accorsi, Bortolini, Gamberi, Manzini, and Pilati (in press), resulting in the following Eqs. (19), (20):

$$\min_s (G_s) \qquad (19)$$

Table 10
Objective function values and increments for each single objective optimization problem.

			Single objective optimization problem	
			min (***TT***)	***min*** (***ER***)
Objective function value and increment	***TT***	[sec/piece]	313	377
		Increment%	–	20%
	ER	[REBA score]	3.64	2.27
		Increment%	60%	–

Table 11
Assembly line balancing configuration detailed for each worker determined by *TT* and *ER* single objective minimization.

Worker	Time load [sec]		Ergonomic risk [REBA Score]	
	min (***TT***)	**min** (***ER***)	**min** (***TT***)	**min** (***ER***)
#1	311	377	3.64	2.27
#2	313	332	1.44	2.27
#3	313	267	2.13	2.26
#4	313	274	1.99	2.26

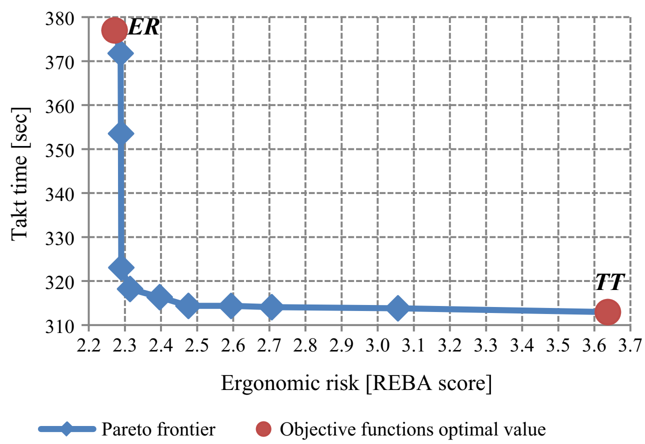

Fig. 10a. Pareto frontier of the *TT* and *ER* MO problem.

$$G_s = \frac{TT_s}{TT^*} \cdot \frac{ER_s}{ER^*} \tag{20}$$

where s is the index of the s-th MO solution lying on the Pareto frontier and TT^*, ER^* are the takt time and ergonomic risk single objective optimal solutions, i.e. their respective optimal values. The solution s that solves Eq. (19) has to be considered the best trade-off solution for the proposed ALBP, thus it defines the ALB configuration to adopt. Fig. 10b depicts *TT* and *ER* objective functions increment compared to their optimum value and the *G* trend over the Pareto frontier, highlighting the final trade-off solution (represented by a green circle).

The final ALBP trade-off solution selected between the Pareto points is distinguished by remarkable performance for both *TT*

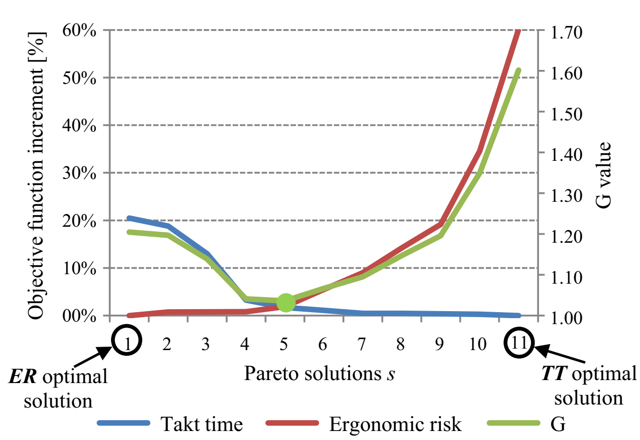

Fig. 10b. TT and ER increments compared to their optimum (red and blue lines) and the G trend (green line) over the Pareto frontier, with the final trade-off solution (green circle). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

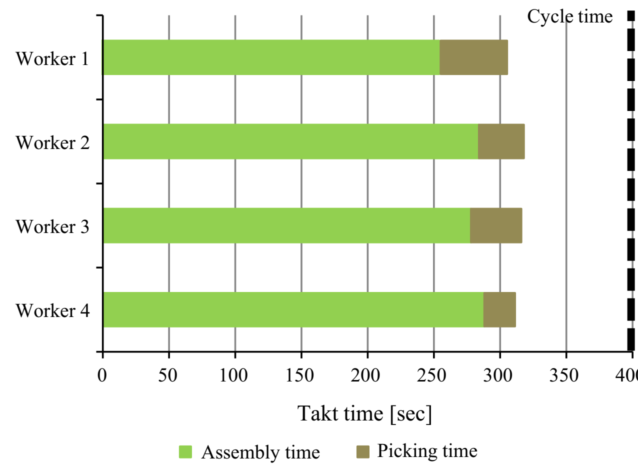

Fig. 11a. Worker time loads of the final trade-off ALBP solution.

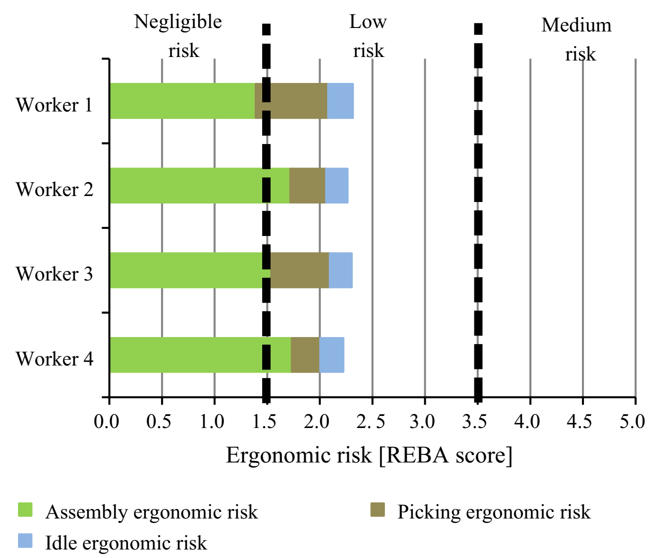

Fig. 11b. Worker ergonomic risk of the final trade-off ALBP solution.

and *ER* objective functions. The assembly line *TT* is 318 s, greater than its minimum by just 1.7%, whereas the *ER* value is 2.31 REBA score (e.g. low risk of musculoskeletal disorders), 1.9% higher than its optimum. The following Figs. 11a and 11b present the distribution of time load and ergonomic risk between the workers proposed by the final trade-off solution. Worker time loads vary from 305 to 318 s, whereas the ergonomic risk is between the 2.22 and 2.31 REBA score, thus distinguished by a low risk of musculoskeletal disorders for each worker. The impact of component picking activities on *TT* and *ER* objective functions is represented by the brown bars in both Figs. 11a and 11b. Component picking effect is equal to maximum 16% of the worker total time load, and to 30% of the ergonomic risk. The component storage disposition in the different station SLs is presented in Fig. 12. The saturation of SL 0 is greater than 95% for each station. SL 1 is fully exploited by the first two stations of the assembly line. SL 2 is entirely used in station 4. SL 3 is reasonably empty for most of the stations. Finally, the decision variable values for the *TT* and *ER* optimal solutions as well for the final trade-off ALB configuration are listed in Appendix B.

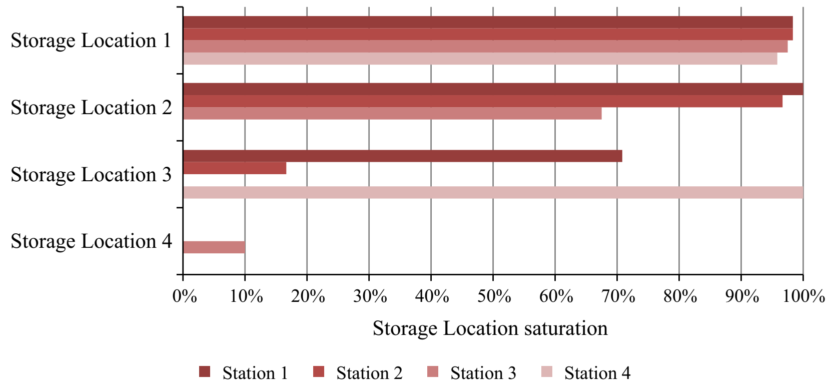

Fig. 12. Storage location saturation of the assembly line stations proposed by the final trade-off ALBP solution.

6. Discussion

The independent optimization of TT and ER offers partial solutions to the ALBP. The minimization of one objective function significantly worsens the other compared to its optimal value. TT optimization properly balances the time loads between workers, whereas their ergonomic risk is extremely unbalanced. A similar pattern is experienced for the ER minimization. This trend is mostly determined by the independence of the assembly task ergonomic risk from its duration. The low risky and long lasting tasks (e.g. "perpetual" ones, according to classification of Fig. 9) have a remarkable impact on the time load of the worker to which they are assigned at almost no ergonomic expense. A major advantage of the developed MO model for the integrated ALBP is represented by the simultaneous optimization of TT and ER. This approach enables to define a final trade-off assembly line configuration distinguished by a negligible worsening of both the objective functions compared to their optimum values. Furthermore, the workers turn out to be extremely balanced from both the time load and the ergonomic risk perspectives.

The production efficiency and ergonomic risk reduction of an assembly line necessitates to minimize the duration and the physical effort of component picking from storage locations. The case study results suggest how the picking activity is a not negligible portion of the operator time and musculoskeletal workload. A MO model which integrates the ALBP with the management of component storage along the assembly line could help, practitioners in particular. The adoption of such a model suggests to balance between the workers the workload of component picking activities. The first workers of the assembly line should perform those tasks which require many small and light components. The locations close to the worker at workbench height should store these components to limit the duration and physical effort of the numerous picking activities. The tasks distinguished by a small number of bulky and heavy components ought to be assigned to the last workers of the line. These workers perform few picking activities from inconvenient locations large enough to store such components.

7. Conclusions

This paper proposes an innovative MO model for the ALBP to assign assembly tasks to stations by distinguishing the assembly activities involved in task execution and component picking. A function is proposed to relate the component picking duration and ergonomic risk with the component storage location at assembly station level and the component attributes, namely dimensions, weight and handiness. The aim of the developed MO model is to simultaneously minimize the assembly line takt time and ergonomic risk, both determined by the task execution and component picking activities. Furthermore, the proposed model for the ALBP not only defines the optimal task assignment to stations, but it also determines the optimal storage location of each component between the available locations at the different assembly stations. The radical innovation of this research is represented by the integration of traditional ALBPs with the component attributes and logistics at assembly station level. Indeed, the tasks to assembly stations assignment significantly affects the allocation of components to storage locations, and vice versa.

The proposed model effectiveness and relevant practical implications are presented through the balancing of a kitchen appliance assembly line of an industrial case study. Ergonomic risk minimization increases the assembly line takt time by 20% compared to its optimal value, whereas takt time optimization worsens the ergonomic risk by 60%. To determine a final ALB trade-off configuration, the Pareto frontier is determined for the analysed ALBP. This represents the MO problem optimal solutions, thus the final ALB configuration is selected within the Pareto frontier using an arbitrary method proposed by the recent literature. The final ALB configuration is distinguished by remarkable performance for both the takt time and ergonomic risk objective functions, which are less than 2% worse that their optimal value. Furthermore, the time load and ergonomic risk are extremely balanced between the workers. Worker time saturation is between 76% and 80% of the cycle time whereas the ergonomic risk varies between 2.2 and 2.3 REBA score, i.e. low risk of musculoskeletal disorders. These distinctive outcomes are enabled by a proper component storage disposition in the different assembly station storage locations defined by the developed MO model for ALBP. The most accessible SLs, e.g. the ones in front of the worker, are fully exploited for component storage to benefit of short-lasting and low risky picking activities. Thus, the saturation of SL 0 and SL 1 is greater than 95% for most of the assembly stations.

Further research should exploit the proposed MO model for assembly line time and ergonomic balancing for assembly systems distinguished by difference features. For instance, relevant research directions should include alternative feeding strategies beyond kanban (e.g. kitting), simultaneous assembly of different products on the same line (e.g. mixed model assembly lines) and the influence of product dimensions on the use of other potential SLs across the assembly station, besides those exploited in this manuscript. Furthermore, an integrated procedure is sought to jointly optimize the assembly station design, the component feeding strategy, their storage location at assembly station level and the task assignment simultaneously considering all the afore-described features. Finally, future contributions should target the

MOCAP technologies commercially available to digitalize the static postures and the dynamic motions of workers during assembly activities for the automatic assessment of the assembly operations from time, space and ergonomic perspectives as well the identification of improvements and corrective actions for the entire assembly process.

Appendix A.

Component attributes, characterises of the selected container bin, picking time and ergonomic risk for each potential storage location and component.

Component z	Component attributes		Container bin characteristics				Picking time PT_{zwk} [sec]				Picking ergonomic risk PE_{zwk} [REBA score]			
	Weight [g]	*MAG* index [MAG]	Length [mm]	Height [mm]	Width [mm]	Weight [kg]	SL 0	SL 1	SL 2	SL 3	SL 0	SL 1	SL 2	SL 3
1	150.0	2.55	200	145	600	4.05	1.5	2.6	3.8	5.3	3	5	7	10
2	120.0	2.21	140	79	870	2.94	1.9	3.3	4.7	6.6	3	5	7	10
3	110.0	1.65	200	145	900	3.78	1.4	2.4	3.4	4.8	2	4	6	9
4	40.0	0.98	90	70	290	0.94	1.3	2.2	3.1	4.4	2	4	6	9
5	160.0	2.21	140	79	870	3.74	1.9	3.3	4.7	6.6	3	5	7	10
6	210.0	3.88	300	120	900	6.20	1.9	3.3	4.7	6.6	3	5	7	10
7	1200.0	12.11	450	300	1260	20.78	4.1	7.1	10.2	14.3	4	7	9	10
8	600.0	1.99	300	120	450	13.00	1.5	2.7	3.8	5.3	2	4	6	9
9	160.0	1.91	200	145	600	4.25	1.5	2.7	3.8	5.3	2	4	6	9
10	8.0	0.46	90	70	290	0.30	1.1	1.9	2.7	3.8	2	4	6	9
11	1.8	0.10	90	70	145	0.11	1.1	1.8	2.6	3.7	3	5	7	10
12	80.0	0.10	90	70	145	1.67	1.1	1.8	2.6	3.7	3	5	7	10
13	8600.0	8.31	300	200	900	24.74	3.3	5.7	8.2	11.5	5	8	9	11
14	200.0	1.54	140	79	1015	8.63	1.9	3.3	4.7	6.6	3	5	7	10
15	5.0	0.08	90	70	145	0.27	1.1	1.9	2.7	3.8	2	4	6	9
16	0.8	0.10	90	70	145	0.09	1.1	1.8	2.6	3.7	3	5	7	10
17	2.0	0.10	90	70	145	0.11	1.1	1.8	2.6	3.7	3	5	7	10
18	8.0	0.10	90	70	145	0.23	1.1	1.8	2.6	3.7	3	5	7	10
19	14.0	0.10	90	70	145	0.35	1.1	1.8	2.6	3.7	3	5	7	10
20	160.0	2.05	200	145	300	3.73	1.9	3.3	4.7	6.6	3	5	7	10
21	6.0	0.95	140	79	435	0.39	1.1	1.9	2.7	3.7	3	5	7	10
22	1.8	0.10	90	70	145	0.11	1.1	1.8	2.6	3.7	3	5	7	10
23	11.0	0.10	90	70	145	0.29	1.1	1.8	2.6	3.7	3	5	7	10
24	3.0	0.10	90	70	145	0.13	1.1	1.8	2.6	3.7	3	5	7	10
25	0.6	0.10	90	70	145	0.08	1.1	1.8	2.6	3.7	3	5	7	10
26	0.7	0.10	90	70	145	0.08	1.1	1.8	2.6	3.7	3	5	7	10
27	19.8	0.10	90	70	145	0.47	1.1	1.8	2.6	3.7	3	5	7	10
28	5.0	0.10	90	70	145	0.17	1.1	1.8	2.6	3.7	3	5	7	10
29	10.0	0.25	90	70	145	0.27	1.1	1.9	2.7	3.8	2	4	6	9
30	68.0	1.24	90	70	435	1.57	1.3	2.2	3.1	4.4	2	4	6	9
31	4.0	0.33	90	70	145	0.15	1.1	1.9	2.7	3.8	2	4	6	9
32	180.0	5.10	200	145	600	4.65	1.9	3.3	4.7	6.6	3	5	7	10
33	200.0	0.59	140	79	290	4.18	1.5	2.7	3.8	5.3	2	4	6	9
34	80.0	0.87	140	130	200	1.87	1.3	2.2	3.1	4.4	2	4	6	9
35	100.0	2.19	200	145	600	3.05	1.1	1.9	2.7	3.7	3	5	7	10
36	50.0	0.25	90	70	435	4.21	1.1	1.9	2.7	3.8	2	4	6	9
37	60.0	0.65	140	79	145	1.29	1.3	2.2	3.1	4.4	2	4	6	9
38	110.0	2.67	200	145	900	3.78	1.5	2.7	3.8	5.3	2	4	6	9
39	400.0	7.22	450	300	1260	16.78	2.3	4.0	5.7	8.0	3	5	7	10
40	60.0	1.45	90	70	580	1.48	1.3	2.2	3.1	4.4	2	4	6	9
41	100.0	2.55	200	145	600	3.05	1.9	3.3	4.7	6.6	3	5	7	10
42	140.0	1.20	200	145	600	3.85	1.4	2.4	3.4	4.8	2	4	6	9
43	20.0	1.03	90	70	435	0.61	1.3	2.2	3.1	4.4	2	4	6	9
44	4.0	0.10	90	70	145	0.23	1.1	1.8	2.6	3.7	3	5	7	10
45	1.5	0.10	90	70	145	0.16	1.1	1.8	2.6	3.7	3	5	7	10
46	35.0	0.54	140	130	200	0.97	1.1	1.9	2.7	3.8	2	4	6	9
47	14.0	0.10	90	70	145	0.91	1.1	1.8	2.6	3.7	3	5	7	10
48	0.6	0.10	90	70	145	0.09	1.1	1.8	2.6	3.7	3	5	7	10

(*continued on next page*)

Appendix A. (*continued*)

Component z	Component attributes		Container bin characteristics				Picking time PT_{zwk} [sec]				Picking ergonomic risk PE_{zwk} [REBA score]			
	Weight [g]	*MAG* index [MAG]	Length [mm]	Height [mm]	Width [mm]	Weight [kg]	SL 0	SL 1	SL 2	SL 3	SL 0	SL 1	SL 2	SL 3
49	1.3	0.10	90	70	145	0.10	1.1	1.8	2.6	3.7	3	5	7	10
50	0.8	0.10	90	70	145	0.09	1.1	1.8	2.6	3.7	3	5	7	10
51	120.0	3.18	300	120	900	4.40	1.9	3.3	4.7	6.6	3	5	7	10
52	1.0	0.10	90	70	145	0.11	1.1	1.8	2.6	3.7	3	5	7	10
53	600.0	5.42	450	300	1260	20.78	1.5	2.7	3.8	5.3	2	4	6	9
54	800.0	4.64	300	300	1350	21.60	1.5	2.7	3.8	5.3	2	4	6	9
55	300.0	1.07	200	145	300	6.53	1.4	2.4	3.4	4.8	2	4	6	9
56	70.0	1.54	200	145	300	1.93	1.1	1.9	2.7	3.7	3	5	7	10
57	2.3	0.10	90	70	145	0.16	1.1	1.8	2.6	3.7	3	5	7	10
58	6.0	0.10	90	70	145	0.31	1.1	1.8	2.6	3.7	3	5	7	10
59	0.4	0.10	90	70	145	0.08	1.1	1.8	2.6	3.7	3	5	7	10
60	0.4	0.10	90	70	145	0.10	1.1	1.8	2.6	3.7	3	5	7	10
61	0.1	0.10	90	70	145	0.07	1.1	1.8	2.6	3.7	3	5	7	10
62	3.3	0.10	90	70	145	0.33	1.1	1.8	2.6	3.7	3	5	7	10
63	3.0	0.10	90	70	145	0.13	1.1	1.8	2.6	3.7	3	5	7	10
64	2.5	0.10	90	70	145	0.27	1.1	1.8	2.6	3.7	3	5	7	10
65	1.0	0.10	90	70	145	0.09	1.1	1.8	2.6	3.7	3	5	7	10
66	1.1	0.10	90	70	145	0.12	1.1	1.8	2.6	3.7	3	5	7	10
67	1.8	0.10	90	70	145	0.21	1.1	1.8	2.6	3.7	3	5	7	10
68	3.2	0.10	90	70	145	0.26	1.1	1.8	2.6	3.7	3	5	7	10
69	3.7	0.10	90	70	145	0.29	1.1	1.8	2.6	3.7	3	5	7	10
70	7.9	0.10	90	70	145	0.54	1.1	1.8	2.6	3.7	3	5	7	10
71	1.5	0.10	90	70	145	0.19	1.1	1.8	2.6	3.7	3	5	7	10
72	2.6	0.10	90	70	145	0.38	1.1	1.8	2.6	3.7	3	5	7	10
73	2.0	0.10	90	70	145	0.15	1.1	1.8	2.6	3.7	3	5	7	10
74	3.6	0.10	90	70	145	0.29	1.1	1.8	2.6	3.7	3	5	7	10

Appendix B.

Assigned station for each task (i.e. decision variable X_{jk} values) for *TT* and *ER* optimal solutions as well for the final trade-off solution of the considered ALBP.

Task j	Assigned station k		
	TT optimal solution	*ER* optimal solution	Final trade-off solution
1	1	1	1
2	3	2	2
3	1	3	2
4	2	2	3
5	3	3	2
6	4	1	1
7	4	2	3
8	1	1	2
9	2	3	1
10	1	3	1
11	1	1	1
12	4	3	3
13	4	3	3
14	4	3	3
15	2	1	2
16	2	3	2
17	2	3	2
18	2	4	3
19	2	4	4

Appendix B. (*continued*)

Task j	Assigned station k		
	TT optimal solution	*ER* optimal solution	Final trade-off solution
20	2	4	4
21	3	4	4
22	1	4	4
23	4	4	4
24	3	4	4
25	4	4	4
26	4	4	4

Assigned station and storage location for each component (i.e. decision variable Y_{zwk} values) for *TT* and *ER* optimal solutions as well for the final trade-off solution of the considered ALBP.

Component z	*TT* optimal solution		*ER* optimal solution		Final trade-off solution	
	Assigned station k	Assigned storage location w	Assigned station k	Assigned storage location w	Assigned station k	Assigned storage location w
1	1	1	1	1	1	2
2	1	0	1	0	2	0
3	2	1	4	0	3	1
4	1	0	1	0	2	0
5	1	1	3	0	1	0
6	1	2	1	1	1	1
7	4	2	1	2	1	2
8	3	1	2	2	2	1
9	2	1	2	1	3	1
10	4	0	2	1	3	0
11	2	0	3	0	1	1
12	1	0	1	0	2	1
13	2	3	2	3	3	3
14	1	0	3	0	1	0
15	4	0	1	1	1	1
16	4	0	2	0	3	0
17	4	0	2	0	3	1
18	2	0	3	1	1	1
19	2	0	3	0	1	0
20	1	1	1	1	1	1
21	1	2	1	0	1	1
22	1	1	3	0	1	0
23	1	0	3	0	1	0
24	3	0	2	0	2	0
25	4	0	2	0	3	0
26	4	0	2	1	3	0
27	4	1	2	1	3	0
28	3	0	2	0	2	0
29	3	0	3	1	2	0
30	3	0	2	0	2	0
31	4	0	2	1	3	0
32	3	0	3	1	2	1
33	3	0	2	1	2	0
34	2	1	4	0	3	1
35	3	1	2	1	2	2
36	1	0	3	1	2	0
37	1	1	4	0	4	0
38	1	1	4	0	4	0
39	1	2	4	2	4	2
40	4	0	4	0	4	0
41	1	1	1	0	1	1
42	3	0	4	1	4	0
43	1	0	1	0	2	0

(*continued on next page*)

Appendix B. (*continued*)

Component z	*TT* optimal solution		*ER* optimal solution		Final trade-off solution	
	Assigned station k	Assigned storage location w	Assigned station k	Assigned storage location w	Assigned station k	Assigned storage location w
44	3	0	4	0	4	0
45	3	0	2	1	2	0
46	4	1	4	0	4	0
47	2	0	2	0	3	0
48	2	0	3	0	1	0
49	2	0	3	0	1	0
50	2	0	3	0	1	0
51	2	1	3	1	2	1
52	4	0	1	0	1	0
53	4	2	4	2	4	2
54	4	2	4	2	4	2
55	4	1	4	1	4	0
56	1	2	1	1	1	2
57	4	0	2	0	3	0
58	4	1	1	0	1	0
59	2	0	3	1	1	0
60	2	0	2	0	3	0
61	4	0	2	0	3	1
62	1	0	3	1	2	1
63	1	0	1	0	1	0
64	1	0	3	0	2	0
65	3	0	2	1	2	0
66	4	0	2	0	3	0
67	4	1	3	0	3	0
68	2	0	2	0	3	1
69	4	0	3	0	3	0
70	2	0	4	0	4	0
71	1	0	1	0	2	1
72	1	0	3	1	1	1
73	2	0	4	0	3	0
74	2	0	1	0	2	1

References

Accorsi, R., Bortolini, M., Gamberi, M., Manzini, R., & Pilati, F. (in press). Multi-objective warehouse building design to optimize the cycle time, total cost, and carbon footprint. *The International Journal of Advanced Manufacturing Technology, 92*(1–4), 839–854.

Alnahhal, M., & Noche, B. (2015). Dynamic material flow control in mixed model assembly lines. *Computers & Industrial Engineering, 85*, 110–119.

Baudin, M. (2002). *Lean assembly: The nuts and bolts of making assembly operations flow*. New York: CRC Press.

Bautista, J., & Pereira, J. (2011). Procedures for the time and space constrained assembly line balancing problem. *European Journal of Operational Research, 212*(3), 473–481.

Bautista, J., Batalla, C., & Alfaro, R. (2012). Incorporating ergonomics factors into the TSALBP. In *IFIP international conference on advances in production management systems* (pp. 413–420). Berlin Heidelberg: Springer.

Bautista, J., Batalla-García, C., & Alfaro-Pozo, R. (2016). Models for assembly line balancing by temporal, spatial and ergonomic risk attributes. *European Journal of Operational Research, 251*(3), 814–829.

Bedaux, C. (1928). *The bedaux method of wage payment*. Hoffmann Manufacturing Company.

Boothroyd, G., Dewhurst, P., & Knight, W. (2011). *Product design for manufacture and assembly* (3rd ed.). Boca Raton, FL: CRC Press; Taylor & Francis Group.

Bortolini, M., Faccio, M., Gamberi, M., & Pilati, F. (2016a). Including material exposure and part attributes in the manual assembly line balancing problem. *IFAC-PapersOnLine, 49*(12), 926–931.

Bortolini, M., Faccio, M., Ferrari, E., Gamberi, M., & Pilati, F. (2016b). Fresh food sustainable distribution: Cost, delivery time and carbon footprint three-objective optimization. *Journal of Food Engineering, 174*, 56–67.

Bortolini, M., Faccio, M., Ferrari, E., Gamberi, M., & Pilati, F. (2016c). Time and energy optimal unit-load assignment for automatic S/R warehouses. *International Journal of Production Economics, 190*, 133–145.

Boysen, N., Fliedner, M., & Scholl, A. (2007). A classification of assembly line balancing problems. *European Journal of Operational Research, 183*(2), 674–693.

Cheshmehgaz, H. R., Haron, H., Kazemipour, F., & Desa, M. I. (2012). Accumulated risk of body postures in assembly line balancing problem and modeling through a multi-criteria fuzzy-genetic algorithm. *Computers & Industrial Engineering, 63*(2), 503–512.

Chica, M., Cordon, O., Damas, S., & Bautista, J. (2011). A multiobjective memetic ant colony optimization algorithm for the 1/3 variant of the time and space assembly line balancing problem. In *IEEE workshop on computational intelligence in production and logistics systems (CIPLS), 2011* (pp. 1–7). IEEE.

Chica, M., Bautista, J., Cordón, Ó., & Damas, S. (2016). A multiobjective model and evolutionary algorithms for robust time and space assembly line balancing under uncertain demand. *Omega, 58*, 55–68.

Chutima, P., & Chimklai, P. (2012). Multi-objective two-sided mixed-model assembly line balancing using particle swarm optimisation with negative knowledge. *Computers & Industrial Engineering, 62*(1), 39–55.

Faccio, M., Gamberi, M., Pilati, F., & Bortolini, M. (2015). Packaging strategy definition for sales kits within an assembly system. *International Journal of Production Research, 53*(11), 3288–3305.

Faccio, M., Gamberi, M., Bortolini, M., & Pilati, F. (in press). Macro and micro logistic aspects in defining the parts-feeding policy in mixed-model assembly systems. *International Journal of Services and Operations Management* [in press].

Finnsgård, C., Wänström, C., Medbo, L., & Neumann, W. P. (2011). Impact of materials exposure on assembly workstation performance. *International Journal of Production Research, 49*(24), 7253–7274.

Finnsgård, C., & Wänström, C. (2013). Factors impacting manual picking on assembly lines: An experiment in the automotive industry. *International Journal of Production Research, 51*(6), 1789–1798.

Hanson, R., Medbo, L., & Medbo, P. (2012). Assembly station design: A quantitative comparison of the effects of kitting and continuous supply. *Journal of Manufacturing Technology Management, 23*(3), 315–327.

Hignett, S., & McAtamney, L. (2000). Rapid entire body assessment (REBA). *Applied Ergonomics, 31*(2), 201–205.

Hu, S. J., Ko, J., Weyand, L., Elmaraghy, H. A., Lien, T. K., Koren, Y., & Ellipsis Shpitalni, M. (2011). Assembly system design and operations for product variety. *CIRP Annals - Manufacturing Technology, 60*(2), 715–733.

Jainury, S. M., Ramli, R., Ab Rahman, M. N., & Omar, A. (2014). Integrated set parts supply system in a mixed-model assembly line. *Computers & Industrial Engineering, 75*, 266–273.

Kara, Y., Atasagun, Y., Gökçen, H., Hezer, S., & Demirel, N. (2014). An integrated model to incorporate ergonomics and resource restrictions into assembly line balancing. *International Journal of Computer Integrated Manufacturing, 27*(11), 997–1007.
Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics, 8*(4), 199–201.
Kieffer, C. (2016). *Musculoskeletal disorders: What recognition as occupational diseases? A study on 10 European countries*. Paris: EUROGIP. ISBN- 979-10-91290-79-1.
Kucukkoc, I., & Yaman, R. (2013). A new hybrid genetic algorithm to solve more realistic mixed-model assembly line balancing problem. *International Journal of Logistics Systems and Management, 14*(4), 405–425.
Lu, L., Anderson-Cook, C. M., & Robinson, T. J. (2012). A case study to demonstrate a Pareto Frontier for selecting a best response surface design while simultaneously optimizing multiple criteria. *Applied Stochastic Models in Business and Industry, 28*(3), 206–221.
Maynard, H., & Stegemerten, G. (1948). *Methods time measurements*. New York: McGRAW-Hill.
Maynard, H. B. (1972). *MOST work measurement systems*. New York: HB Maynard and Company Inc..
McAtamney, L., & Corlett, E. N. (1993). RULA: A survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics, 24*(2), 91–99.
Messac, A., Ismail-Yahaya, A., & Mattson, C. A. (2003). The normalized normal constraint method for generating the Pareto frontier. *Structural and Multidisciplinary Optimization, 25*(2), 86–98.
Niosh (1981). *Work practices guide for manual lifting*. Cincinnati: DHHS (NIOSH).
Occhipinti, E. (1998). OCRA: A concise index for the assessment of exposure to repetitive movements of the upper limbs. *Ergonomics, 41*(9), 1290–1311.
OECD (2015). *OECD employment outlook 2015*. Paris: OECD Publishing.
Otto, A., & Scholl, A. (2011). Incorporating ergonomic risks into assembly line balancing. *European Journal of Operational Research, 212*(2), 277–286.
Paoli, P., & Merllié, D. (2001). *Third european survey on working conditions 2000*. Luxembourg: Office for Official Publications of the European Communities. ISBN 92-897-0130-7.
Pareschi, A. (1994). *Impianti industriali*. Bologna: Società Editrice Esculapio.
Pareto, V. (1906). *Manuale di economia politica con una introduzione alla scienza sociale*. Milan, Italy: Societa Editrice Libraria.
Salveson, M. E. (1955). The assembly line balancing problem. *Journal of Industrial Engineering, 6*(3), 18–25.
Savino, M., Mazza, A., & Battini, D. (2016). New easy to use postural assessment method through visual management. *International Journal of Industrial Ergonomics, 53*, 48–58.
Scholl, A. (1995). *Balancing and sequencing of assembly lines*. Heidelberg: Physica-Verlag.
Sivasankaran, P., & Shahabudeen, P. (2014). Literature review of assembly line balancing problems. *The International Journal of Advanced Manufacturing Technology, 73*(9–12), 1665–1694.
Wänström, C., & Medbo, L. (2008). The impact of materials feeding design on assembly process performance. *Journal of Manufacturing Technology Management, 20*(1), 30–51.
Xu, Z., Ko, J., Cochran, D. J., & Jung, M. C. (2012). Design of assembly lines with the concurrent consideration of productivity and upper extremity musculoskeletal disorders using linear models. *Computers & Industrial Engineering, 62*(2), 431–441.