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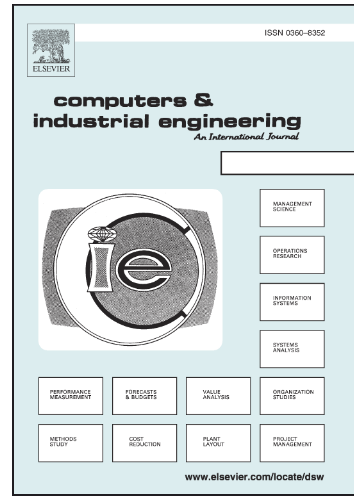

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Integrating ergonomics and lean manufacturing principles in a hybrid assembly line

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Abstract

Lean manufacturing is a production method that was established in the wake of the Japanese Toyota Production System and rapidly established in the worldwide manufacturing industry. Lean characteristics combine just-in-time practices, work-in-progress and waste reduction, improvement strategies, defect-free production, and standardization. The primary goal of lean thinking is to improve profits and create value by minimizing waste. This study introduces a novel mathematical model to design lean processes in hybrid assembly lines. The aim was to provide an effective, efficient assembly line design tool that meets the lean principles and ergonomic requirements of safe assembly work. Given the production requirements, product characteristics and assembly tasks, the model defines the assembly process for hybrid assembly lines with both manual workers and automated assembly machines. Each assembly line solution ensures an acceptable risk level of repetitive movements, as required by current law.

This model helps managers and practitioners to design hybrid assembly lines with both manual workers and automated assembly machines. The model was tested in a case study of an assembly line for hard shell tool cases. Results show that worker ergonomics is a key parameter of the assembly process design, as other lean manufacturing parameters, e.g. takt time, cycle time and work in progress.

Keywords:

Lean manufacturing, occupational safety, ergonomics, automation, human factors, hybrid assembly line.

1. Introduction

Lean thinking is a production strategy that aims to increase profit, with limited resources. Just-in-time (JIT) practices, waste reduction, improvement strategies, defect-free production and work standardization are the principal characteristics of lean thinking. The primary goal of lean production is to reduce costs and increase productivity by eliminating waste. Anything other than the minimum amount of equipment, materials, parts, space and employee time necessary to produce the required products is waste (Suzaki, 1987). Seven types of waste negatively affect the productivity of manufacturing companies: correction, overproduction, motion, material movement, waiting, inventory and processing. The presence of all seven types of waste negatively impacts the product lead-time, cost and quality (Walder et al., 2007). Several industries and manufacturing processes, from the automotive industry to the service industry, integrate their production strategies with lean thinking principles, aiming to improve productivity and quality through cost reduction.

Previous studies have widely investigated the impact of human factors and worker behaviours on company performance and expected outcomes (Wygant et al., 1993; Resnick and Zanotti, 1997; Shikdar and Sawaqed, 2004; Dul et al., 2004; Othman et al., 2012; Xu et al., 2012). Based on such principles, the applied science of ergonomics analyses the importance of workstation and work process design and the effects on worker safety and health. Past and recent studies have widely discussed how ergonomics can optimize human performance and overall work system performance (Dul and Neumann, 2009). The design of ergonomic workplaces and jobs reduces injury and absenteeism rates, while improving productivity, quality and reliability (Botti et al., 2014). Previous studies have shown that musculoskeletal disorders (MSDs) lead to significant loss of productivity due to higher absenteeism and injury rates (Cheshmehgaz et al., 2012).

Work-related MSDs are common occupational diseases among assembly workers due to repetitive motions or heavy workloads (Xu et al., 2012). Botti et al. (2015) proposed a mathematical model to design ergonomic job rotation policies in assembly lines, that ensures optimal person-job fit. From an ergonomic perspective, the mathematical model includes the characteristics of workers and tasks to accomplish, aiming to improve the productivity of the entire work system.

Ergonomics and production requirements are key elements of the lean planning process. The integration of ergonomic principles in the lean process plays a leading role in the successful implementation of the lean strategy. Past studies have widely investigated the impact of lean thinking on worker health and safety (Smith, 2003; De Treville and Antonakis, 2006; Kester, 2013; Yusoff et al., 2013). Several studies have investigated the potential correlation between specific lean practices (e.g., waste reduction and continuous flow) and ergonomics, occupational health and related risk factors (Adler et al., 1997; Jackson and Mullarkey; 2000; Conti et al., 2006; Sprigg and Jackson, 2006). Furhtermore, high-strain jobs have a high risk of musculoskeletal disorders and psychological load, leading to company costs and losses (Nunes and Machado, 2007).

A parallel research path aims to identify how manufacturing industries can improve their lean production strategies through industrial robot automation (Bowler and Kurfess, 2010; Hedelind and Jackson, 2011; Barbosa et al., 2014). The reasons to automate the manufacturing processes include increased quality and efficiency demands, as well as the presence of hazardous working conditions and the high cost of specialized manual workers. Using technology to automate difficult or repetitive tasks positively impacts safety and ergonomic issues, as well as other labour challenges experienced by many organizations, e.g. aging workforce and the related expected increase of injuries in the labour force (Kozak, 2015). Automated machines are part of the assembly process in different industries. A recent study of semi-automatic lines in the meat processing industry aimed to improve the health and safety of meat processing workers through ergonomics and automation (Botti et al., 2015). The study introduced a layout proposal for a typical manual process, replacing laborious manual activities with automated machinery. Despite the illusory economic disadvantage due to high investment costs, the results have shown that automated machinery may provide short- and long-term benefits to workers, employers and customers.

Although automation has been widely adopted in manufacturing, numerous companies still rely on manual workers to perform assembly operations. The current practice shows that the decision to automate rather than include manual workstations is primarily guided by economic considerations and production requirements. Robot technology is widely used in the manufacturing industry when products are well-defined and properly designed. Specifically, high production volumes allow a reasonable payback time for the considerable investment in automatic machines (Lien and Rasch, 2001).

From a lean perspective, the decision to automate parts of the assembly process is based on specific goals: to increase production volume, decrease the through-put time, decrease the lead-time, reduce the value of WIP and improve the assembly quality (Neumann et al., 2002). The indirect costs of planning, automation changes and maintenance tilt the balance in favour of manual processes (Bley et al., 2004).

Previous studies have supported the need for joint optimization of human factors and technical aspects in production system design, but no mathematical model has supported the integration of ergonomics principles during the design of assembly systems (Ólafsdóttir and Rafnsson, 1998; Coury et al., 2000; Neumann et al., 2002). Recent research has analysed the impact of workplace design on productivity levels, integrating lean concepts with ergonomics principles (Walder et al., 2007; Vieira et al., 2012; Xu et al., 2012; Yusoff et al., 2013; Al Zuheri et al., 2014). These studies do not include the impact of different assembly alternatives (i.e., manual or automatic workstations) during the assembly process design.

This paper introduces an innovative mathematical model to define ergonomic lean processes in manufacturing assembly lines. The aim was to design the optimal layout of the assembly processes that meet the lean goals of improving production efficiency and the ergonomic principles for manual material handling. Given the production requirements, product characteristics and assembly tasks, the model defines the assembly process for hybrid assembly lines with both manual workers and automated assembly machines. Finally, the effectiveness of the mathematical model was tested in a case study based on an assembly process for hard shell tool cases.

The remainder of this study is organized as follows. Section 2 reviews previous studies investigating the correlation between lean manufacturing and ergonomics. Section 3 defines the lean objectives and the integer linear programming (ILP) model for the ergonomic design of assembly lines with both manual and automatic assembly workstations. See Appendix A.1 for a full list of the model notations. Section 4 demonstrates the application of the ILP model in a case study based on an assembly process for hard shell tool cases. Finally, Sections 5 and 6 discuss the results and conclusions.

2. Literature review

Lean production methods spread globally in the 1980s and 1990s, in the wake of the Japanese Toyota Production System (Silver, 2003). The positive effects of lean thinking on business performances have been demonstrated by the widespread diffusion of lean production methods over the past 20 years. Lean manufacturing companies aim to improve their productivity and the efficient use of resources through waste removal and cost reduction. The lean definition for waste includes work in progress (WIP), defects and non-value added time, such as worker time spent waiting for products and unnecessary movements. Cost reduction strategies are directed toward specific efforts that reduce the resources spent on poor quality products, reducing the WIP value and decreasing the transportation costs. Lean thinking also aims the realization of flexible processes and the reduction of overburden and stress, which generate waste (Corominas et al., 2004; Schafer et al., 2008). Several studies have investigated variations in the quality of working life due to the implementation of lean manufacturing (Schouteten and Benders, 2004; Shoaf et al., 2004; Saurin and Ferreira, 2009; Koukoulaki, 2014). The results have drawn both criticism and eulogistic praise of lean manufacturing strategies. Worker interviews and questionnaires and case study analysis of the effects of lean manufacturing on worker safety and health have reported increased health, job satisfaction and job motivation. Consequently, workers perceive better working conditions and avoid excessive fatigue and accidental injuries (Smith, 2003; Vieira et al., 2012; Aqlan et al., 2014). A parallel research path has demonstrated the disadvantages of lean production and the negative effects on employee autonomy, work demands and psychological strain (Jackson and Martin, 1996; Bao et al., 1997; Ólafsdóttir and Rafnsson, 1998; Leroyer et al., 2006; Lloyd and James, 2008) .

In particular, the standardization of work processes in lean production methods may hinder empowerment and job control (Klein, 1991; Sprigg and Jackson, 2006). However, numerous studies have attributed the increased work pace and lack of recovery time in lean companies to JIT practices and work standardization (Saurin and Ferreira, 2009). In particular, the rigid application of lean production methods is associated with increased musculoskeletal risk factors and stress in manual workers (Berggren et al., 1991; Brenner et al., 2004; Lloyd and James, 2008; Koukoulaki, 2014). The cause of such a phenomenon is that lean processes frequently result in highly repetitive operations, stressful postures and high forces, while eliminating critical rest periods for employees (Kester, 2013). Injured workers are not able to work, and replacement workers are not as efficient at performing the tasks. Therefore, increased injury rates hinder the desired results for lean processes. In the long term, the economic savings from quality, productivity and efficiency improvements pay for the higher cost of workers' compensation claims for MSDs.

Human factors and ergonomics are key components of the lean strategy, in addition to the lean principles of waste reduction and value creation. Thus, successful lean processes integrate ergonomics in the early stages of the assembly process design.

The integration of technology to automate difficult or repetitive tasks positively impacts safety and ergonomic issues. However, several companies have reported high levels of dissatisfaction with automation investments in the past, due to the inflexibility of these facilities in terms of reflecting changing market conditions (Bley et al., 2004). The shorter product life cycle and high product complexity further explain the trend of assembly automation reduction. Automation in lean production systems requires high flexibility and the ability to increase the throughput, despite dynamic changes, such as demand or supply disruptions, with no additional resources (Moghaddam and Nof, 2015). When flexibility is necessary and companies are required to decrease the lot size, good solutions are missing (Krüger et al., 2009). Further limitations of the current automated systems include the high programming efforts and limited ability to assemble not standardized products. Krüger et al. (2009) have investigated the requirements for a successful cooperation of human and machines in assembly lines. Their research suggests a sequential division of tasks among workers and machines to obtain the best capabilities of robotic and human capabilities. Conventionally, machines perform simple tasks upstream in the assembly line. The complex and frequently varied tasks that give the assembled products their individual features are performed downstream by human operators.

The following Section 3 introduces the innovative mathematical model for the design of ergonomic lean processes in hybrid assembly lines. Given the production requirements, product characteristics and assembly tasks, the model defines the optimal assembly sequences for manual and automatic workstations. The aim is to improve ergonomics for manual workers and cost reduction for the whole assembly process, following the principles of lean manufacturing.

3. Methods

This section introduces the lean production system modelling for the design of ergonomic lean processes in hybrid multi-model assembly lines. Two objective functions drive the optimization model and define optimal assembly processes for each product family. The first objective addresses the lean principles of just-in-time production and WIP reduction. The second objective aims to reduce the overall cost of the hybrid assembly system.

3.1. Assembly process modelling

Hybrid assembly lines involve close cooperation between humans and automated machinery. The effective cooperation is possible when the production requirements meet the ergonomics principle for worker health and safety. The proposed ergonomic lean approach is based on the human-paced work principle. Automated machines process enough products to keep up with the pace of the successive manual workstations. Thus, the final stages of the assembly process pull the production flow, reflecting a just-in-time perspective. The result is a lean assembly process, in which manual workers set the machine assembly pace.

Buffer inventory is necessary to ensure that parts are available for downstream workstations. These buffers prevent the delay of upstream machines and the consequent reduction of throughput. Furthermore, additional buffers preceding late workstations collect processed semi-products waiting for the late process (Figure 1). In particular, an additional buffer is necessary at manual workstations to prevent semi-product shortages due to the delay of manual workers.

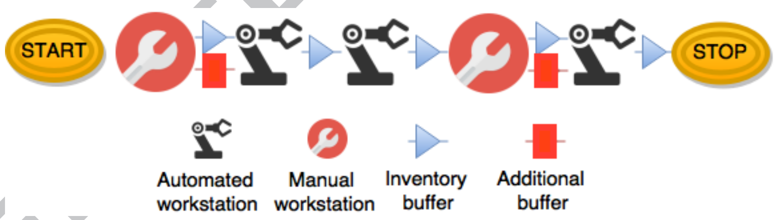

Fig. 1. Example of hybrid assembly line

Figure 1 shows inventory buffer and additional buffer for a hybrid assembly line. The blue triangle indicates the presence of inventory buffer, while the red rectangle reflects the additional buffer. Because manual workstations pull automated workstations in the proposed lean assembly process, no additional buffer is required between an automated machine and the following workstation, whether it is manual or automated. However, an additional buffer is required after each manual workstation. The presence of the buffer increases the amount of inventory and WIP. High inventory levels lead to higher inventory storage costs, as well as longer throughput times for products to move through the system. Consequently, lean principles aim to reduce WIP and the amount of components and assemblies. Figure 2 shows the sequential processing alternatives between manual and automated workstations.

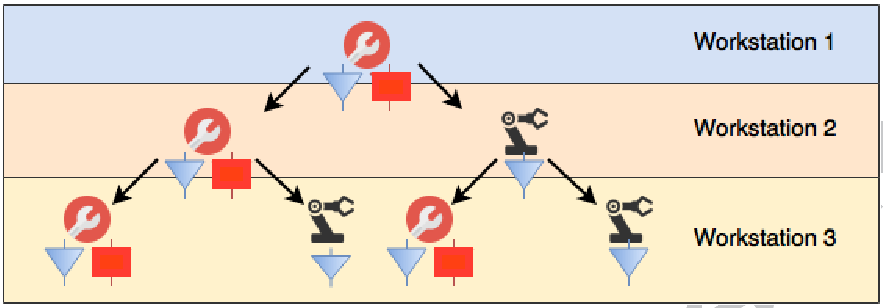

Fig. 2. Sequential processing alternatives in hybrid assembly lines.

The additional buffer is required after each manual workstation and before the automated machines followed by a manual workstation (Figure 2). The buffer size is the actual number of workpieces stored in the buffer. Specifically, it depends on the desired safety time, f, to prevent the production interruption in case of semi-finished product shortage, and the mean lateness, e, of the manual workstations. Specifically, the computation of the mean lateness is based on historical stochastic data. Equation (1) defines the buffer inventory size to protect throughput from any interruptions, while Equation (2) defines the additional buffer size.

$$j_{pt} = \frac{f}{d_{pt}} \qquad (1).$$

$$s_{pt} = \frac{e}{d_{pt}} \qquad (2).$$

Given the cycle time (d_{pt}) to perform manual task t for product p, j_{pt} is the number of p products in the buffer inventory to ensure that parts are available for the downstream workstations (Equation 1). Similarly, s_{pt} is the number of p processed products in the additional buffer waiting for the late manual process.

Automation requires high investment costs in machinery and skilled labour. Companies have reported that the planning and operation expenses exceed the cost reductions promised by high automation in production. Furthermore, indirect costs, such as defects cost, planning and retrieving the know-how for automated machinery reprogramming, reduce the satisfaction with investments in automation (Bley et al., 2004). Automation is an interesting option when labour costs and deduction costs for facilities are significant. Equation (3) introduces the total cost of the hybrid assembly process due to automated machinery, $C_{machinery}$ (Equation 4), and the cost of the hybrid assembly process due to manual labour, C_{labour} (Equation 5).

$$C_{total} = C_{machinery} + C_{labour} \quad (3).$$

$$C_{machinery} = \sum_{t=1}^{T}(x_t \cdot i_{max\ t}) + \sum_{t=1}^{T}\sum_{p=1}^{P}(r_t \cdot i_{pt}) + \sum_{t=1}^{T}\left[q_t \cdot \sum_{p=1}^{P}(g_p \cdot c_{pt})\right] + \sum_{t=1}^{T}\left[o_t \cdot \sum_{p=1}^{P}(g_p \cdot v_{pt})\right] \quad (4).$$

$$C_{labour} = \sum_{t=1}^{T}(y_t \cdot l_{pt}) + \sum_{t=1}^{T}\left[o'_{\ t} \cdot \sum_{p=1}^{P}(g_p \cdot v_{pt})\right] \quad (5).$$

$C_{machinery}$ is the sum of four different costs: the investment cost for the machinery purchase, the reprogramming cost for the batch switch, the cost of the energy and the non-quality cost for automated production defects. Specifically, x_t is the investment cost of the automated machinery to perform task t; r_t is the machinery reprogramming cost for the product batch switch; q_t is the energy consumption of the automatic machine for t; g_p is the daily product p batch size; c_{pt} is the automatic workstation cycle time for product p for task t; o_t is the defective product percentage of the automatic machine for task t, and v_{pt} is the value of product p after task t. Equation (6) shows the formulation of i_{pt} .

$$i_{pt} = \left\lceil \frac{k_p}{c_{pt}} \right\rceil \quad (6).$$

Given k_p as the takt time of product p, i_{pt} is the number of required automatic machines working simultaneously for task t to ensure the production of product p (Equation 6). Finally, $i_{max\ t}$ is the maximum number of automatic machines working simultaneously to perform task t.

Similarly, C_{labour} is the sum of two different costs: the cost of manual work and the non-quality cost of manual production defect. In addition, y_t is the manual worker hourly cost to perform task t, and it includes the cost of worker safety, such as the protections, training and PPE related to task t.

o'_t is the defective products percentage due to the manual production of task t. Equation (7) shows the formulation for l_{pt}.

$$l_{pt} = \left\lceil \frac{k_p}{d_{pt}} \right\rceil \quad (7).$$

Given d_{pt} as the cycle time to perform manual task t for product p, and k_p as the takt time of product p, l_{pt} is the number of manual workers required for task t to ensure the production of product p (Equation 7).

The sum of $C_{machinery}$ and C_{labour} is the total cost of the hybrid assembly process (Equation 3).

3.2. Operation assumptions

The mathematical model for the design of assembly sequences of manual and automated workstations in hybrid multi-modal assembly lines is subject to the following assumptions:

- Each task t is performed either by automated machinery or by manual workers for each product type p. Workers do not operate at automatic workstations and vice versa;
- Each task t is univocally performed in a single workstation;
- Processing times are deterministic;
- Each product that does not have task t in his assembly process cycle goes to the next workstation;
- The additional buffer is arranged at each manual workstation, as before the automatic machine following a manual workstation, in order to avoid the machine pacing phenomenon;
- The maximum capacity of the buffer is infinite;
- The manual workers monitor the automatic machines in hidden time;
- The automatic machine for task t is able to process each product type p;
- Each task t is performed in the cycle of at least one product type p;
- The same manual workers are employed to produce the whole product p family;

- Workers performing the same task t for a given product p are assumed to be exposed to same ergonomic risk level;
- The cycle time d_{pt} to perform task t for product p at the manual workstation is assumed to be the same for each worker;
- Workers operating at workstations with multiple manual workers do not inhibit the work of other operators at the same workstation;
- The identification of defective products is performed after the assembly process.

Such conditions define the operation assumptions used within the following mathematical model.

3.3. The mathematical model

The ILP model seeks the optimal assembly sequences of manual and automatic workstations for hybrid multi-model assembly lines. Given the characteristics of the assembly process and the automated machines working parameters, the model assigns manual workers or automated machinery to each workstation. Each assembly sequence includes the ergonomic risk assessment using the OCRA index (ISO 11228-3, 2007) to meet the requirements of the Italian occupational health and safety law for manual material handling (Ministero del Lavoro e delle Politiche Sociali, 2008). Specifically, the OCRA method is a well-known risk assessment methodology for the evaluation of the ergonomic risk of manual material handling of low loads at high frequency. The OCRA index defines a ergonomic risk level for manual workers, comparing the actual number of technical actions performed by the worker to a required number of technical actions that the worker may perform in safety condition.

The model inputs address the characteristics of the products, manual processes, automated machines, as well as the production requirements. Table 1 provides the notations for the model formulation.

Table 1
Indices and parameters for the ILP model.

Indices	
p	Product index, $p = 1 \ldots P$

t	Task index, $t = 1 \ldots T$
Parameters	
a_{pt}	1 if task t is standardizable for all the products and the assembly activities are not complex, 0 otherwise [binary]
b	Duration of the shift [h]
c_{pt}	Cycle time to perform task t for product p with automated machinery [s/unit and machine]
d_{pt}	Cycle time to perform task t for product p at the manual workstation [s/unit and worker]
e_{pt}	Mean lateness of the manual workstation for task t and product p [s]
f_{pt}	Safety time for task t and product p [s]
g_p	Daily batch size of product p [units]
h_{pt}	1 if task t is in the assembly process of product p, 0 otherwise [binary]
i_{pt}	Number of automatic machines required for task t to ensure the production of product p [machines]
$i_{max\ t}$	Maximum number of automatic machines working simultaneously to perform task t [machines]
l_{pt}	Number of manual workers required for task t to ensure the production of product p [workers]
k_p	Takt time for the production of product p [s/unit]
o_t	Percentage of defective products due to automated task t [%]
o'_t	Percentage of defective products due to manual task t [%]
q_t	Hourly energy consumption of the automated machinery for task t [€/h]
r_t	Hourly cost of machine reprogramming for task t [€/machine and hour]
v_{pt}	Value of product p after task t [€/unit]
x_t	Hourly cost of automated machinery for the automated task t, safety barriers and transport system of assembled products to the next workstation [€/hour and machine]
y_t	Hourly cost of the manual workers at the manual workstation for task t [€/hour and worker]

The parameters for the ILP model in Table 1 stem from analysis of the production requirements and the characteristics of the manual workers and automated machinery. Table 2 shows the OCRA parameters included in the model of the ergonomic risk assessment (ISO 11228-3, 2007).

Table 2
OCRA parameters for the ILP model, referred to the most stressed upper limb (ISO 11228-3, 2007).

OCRA Parameters	
$n_{TC,pt}$	Number of technical actions for product p and task t
k_f	Constant of frequency of technical actions per minute
$F_{M,pt}$	Force multiplier for product p and task t
$P_{M,pt}$	Posture multiplier for product p and task t
$Re_{M,pt}$	Repetitiveness period multiplier for product p and task t
$A_{M,pt}$	Additional multiplier for product p and task t
Rc_M	Recovery period multiplier
t_M	Duration multiplier

The ILP model decisional variables, W_{pt} and Z_t, define the assignment of either manual workers or automated machines to each workstation. $W_{p,t}$ defines the presence of automated machinery or manual workers for each workstation (Equation 8). Z_t is derived from W_{pt}, and it defines for each task if automated machinery is employed for the assembly process of at least one product type (Equation 9). Analytically,

$$W_{pt} = \begin{cases} 1, \text{if task } t \text{ in the assembly process of product } p \text{ is performed by automated machinery} \\ 0, \text{otherwise} \end{cases} \quad \forall\, p, t \qquad (8), \text{ and}$$

$$Z_t = \begin{cases} 1, \text{ if automated machinery for task } t \text{ is in the assembly process of at least one product type} \\ 0, \text{otherwise} \end{cases} \quad \forall\, t \qquad (9).$$

The model objective functions are as follows (see Equations 9 and 10).

$$\varphi = \sum_{t=1}^{T} \sum_{p=1}^{P} \left\{ \frac{v_{pt}}{d_{pt}} \cdot \left[f_{pt} \cdot h_{pt} + e_{pt} \cdot \left(h_{pt} - W_{pt} \right) \right] \right\} \qquad (10), \text{ and}$$

$$\chi = b \cdot \sum_{t=1}^{T} (Z_t \cdot x_t \cdot i_{max\ t}) + \sum_{t=1}^{T} \sum_{p=1}^{P} \frac{1}{3600} \left(W_{pt} \cdot q_t \cdot c_{p,t} \cdot g_p \right) + b \cdot \sum_{t=1}^{T} \left[r_t \cdot \sum_{p=1}^{P} \left(W_{pt} \cdot i_{p,t} \right) \right] + \sum_{t=1}^{T} \left[o_t \cdot \sum_{p=1}^{P} \left(W_{pt} \cdot v_{p,t} \cdot g_p \right) \right] + b \cdot \sum_{t=1}^{T} \left\{ y_t \cdot \sum_{p=1}^{P} \left[\left(h_{pt} - W_{pt} \right) \cdot l_{p,t} \right] \right\} + \sum_{t=1}^{T} \left\{ o'_{t} \cdot \sum_{p=1}^{P} \left[\left(h_{pt} - W_{pt} \right) \cdot v_{p,t} \cdot g_p \right] \right\} \qquad (11).$$

The first objective function, φ, is from the previous Equations (1) and (2). φ evaluates the daily value of the WIP. Specifically, Equation (10) shows the sum of the values of the inventory buffer and the additional buffer. The inventory buffer is required for each workstation in the assembly process of product p, (h_{pt} not 0). The additional buffer is required for the manual workstations, when $(h_{pt} - W_{pt})$ is not 0.

The second objective function, χ, quantifies the daily cost of the hybrid assembly system. The formulation of χ is from the previous Equations (3), (4) and (5). Specifically, parameters i_{pt} and l_{pt} are from the previous Equations (6) and (7). χ includes the fixed costs of automated machinery for task t (e.g. investment costs, safety barriers and transport system of assembled products between consecutive workstations), variable costs of automated machinery as energy consumption costs for such machinery, the machinery reprogramming cost due to the batch switch, the cost of defects caused by the automated machinery, the labour cost, and the cost of manual assembly defects.

The following equations define the proposed ILP model formulation.

$$min\ \{\varphi, \chi\} \qquad (12).$$

$$W_{pt} \leq h_{pt} \qquad \forall p,t \quad (13).$$

$$W_{pt} \leq a_{pt} \qquad \forall p,t \quad (14).$$

$$\sum_{p=1}^{P} W_{pt} \leq P \cdot Z_t \qquad \forall t \quad (15).$$

$$Z_t \leq \sum_{p=1}^{P} W_{pt} \qquad \forall t \quad (16).$$

$$\sum_{p=1}^{P}\left[\left(h_{pt}-W_{pt}\right)\cdot n_{TC,pt}\cdot g_p\right] \leq 2.2\cdot\sum_{p=1}^{P}\left[\left(h_{pt}-W_{pt}\right)\cdot\left(k_f\cdot F_{M,pt}\cdot P_{M,pt}\cdot R_{eM,pt}\cdot A_{M,pt}\cdot d_{pt}\cdot g_p\cdot 1/60\right)\right]\cdot R_{cM}\cdot t_M \qquad \forall t \quad (17).$$

$$W_{pt}\ binary \qquad \forall p,t \quad (18).$$

$$Z_t\ binary \qquad \forall t \quad (19).$$

Equation (12) minimizes the introduced objective functions, while Equation (13) ensures that the automated machinery is not assigned to workstations that do not belong to the assembly process of product p. Equation (14) shows that the automated machinery may be assigned to the assembly workstations for products with standardizable assembly characteristics. Equations (15) and (16) ensure that for each task, Z_t is not zero if automated machinery is employed for the assembly process of at least one product type. Equation (17) stems from the International Standard ISO 11228-3, and it restricts the OCRA index value to a threshold limit value for each task (ISO 11228-3, 2007). Finally, Equations (18) and (19) provide consistence to the binary variables. The proposed model size is $P \cdot T + T$ binary variables and $2(P \cdot T) + 3T$ constraints.

Section 4 introduces a full application of the proposed model to a case study based on the assembly process of hard shell tool cases. The input data are discussed before presenting and comparing the results and conclusions.

4. Case study

This section applies the proposed mathematical model to a real case study of the design of a hybrid assembly process for the manual assembly line of an Italian hard shell tool cases manufacturer. Six assembly workers manually assemble 4 different product types. Figure 3 shows the reference assembly process and the manual workstations.

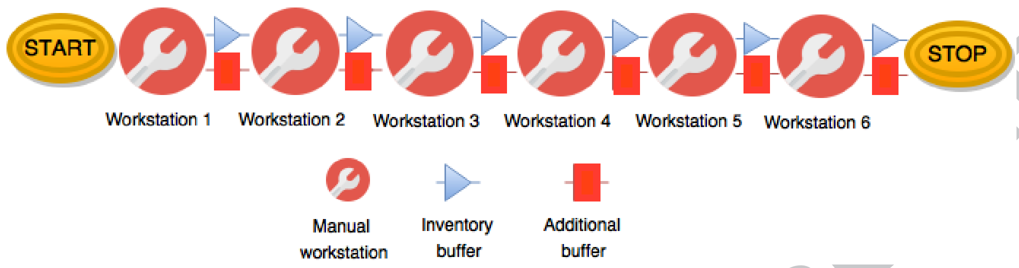

Fig. 3. Layout of the reference assembly process.

The reference process is a manual assembly line with 6 manual workstations and 6 manual workers. A single worker is assigned to each manual workstation. An inventory buffer and additional buffer are allocated after each manual workstation to prevent delays and disruptions due to component shortages (Figure 3). Table 3 shows the tasks performed by each worker at each workstation.

Table 3
Description of the tasks for the reference assembly line.

Task description	***Workstation***	***Task index t***	$h_{p,t}$	$a_{p,t}$
Raw material and components retrieval	1	1	1	1
Lock assembly	2	2	1	1
Top sponge application	3	3	1	1
Valve assembly	4	4	1	1
Bottom sponge application	5	5	1	1
Handles assembly	6	6	1	1

The tasks in Table 3 describe an assembly process for the production of hard shell tool cases at an Italian manufacturing company. The assembly task sequence is the same for each product type (i.e., $h_{p,t}$= 1 for each product type and task). Each task is standardizable and the assembly operations may be performed by automated machinery (i.e., $a_{p,t}$= 1 for each product type and task, Table 3). Sensitive values of the manual assembly process parameters are hidden (e.g., the cycle times, takt times and batch sizes) for confidentiality reasons. The safety time $f_{p,t}$ varies from 1 to 3 hours, while the mean lateness of manual workstations varies from 2 to 12 seconds, depending on the product type and the task. Table 4 shows the other model parameters.

Table 4
Case study parameters.

t	*1*	*2*	*3*	*4*	*5*	*6*
i **[machines]**	1	1	1	1	1	1
$l_{max\ t}$ **[workers]**	1	1	1	1	1	1
o_t **[%]**	2	2	1	2	1	2
o'_t **[%]**	4	5	3	5	3	5
q_t **[€/h]**	2.80	2.40	1.20	1.20	1.20	2.40
r_t **[€/machine and hour]**	100	100	100	100	100	100
x_t **[€/hour and machine]**	56	40.88	32.1	47.44	32.1	40.88
y_t **[€/hour and worker]**	15	15	15	15	15	15

Table 5
OCRA parameters for the ergonomic risk assessment through OCRA method.

OCRA parameters						
t	*1*	*2*	*3*	*4*	*5*	*6*
$n_{TC,pt}$ ***Product 1***	14	8	5	4	3	12
$n_{TC,pt}$ ***Product 2***	15	8	5	5	3	12
$n_{TC,pt}$ ***Product 3***	14	8	5	4	3	12
$n_{TC,pt}$ ***Product 4***	15	10	5	5	3	12
k_f ***Product from 1 to 4***	30	30	30	30	30	30
$F_{M,t}$ ***Product from 1 to 4***	0.65	0.35	1.00	0.85	1.00	0.20
$P_{M,t}$ ***Product from 1 to 4***	0.60	0.60	1.00	0.60	1.00	0.60
$Re_{M,t}$ ***Product from 1 to 4***	1.00	0.70	1.00	0.70	1.00	0.70
$A_{M,t}$ ***Product from 1 to 4***	1.00	0.90	1.00	0.95	1.00	0.80
Rc_M	0.60	0.60	0.60	0.60	0.60	0.60
t_M	1.00	1.00	1.00	1.00	1.00	1.00

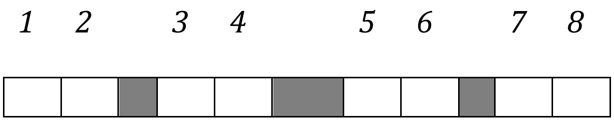

Fig. 4. Distribution of recovery period

Table 5 shows the OCRA parameters for the ergonomic risk assessment using the OCRA method (Occhipinti 1998, ISO 11228-3 2007). The values of the technical actions $n_{TC,t}$ refer to the most stressed arm for each worker. The work shift is 8 hours, and breaks are distributed as shown in Figure 4. A lunch break and two 10-minute breaks are distributed throughout the 8-hour shift. Given the recovery distribution in Figure 4, Rc_M is equal to 0.60 for each worker, corresponding to 4 hours without an adequate recovery period. Job rotations are not allowed during the work shift, and each worker performs the same single task for the entire 8 hours. Therefore, repetitive manual tasks last for a relevant part of the shift, and t_M = 1 for each worker.

The OCRA indices in Table 6 define the workers' exposure to repetitive movements of the upper limbs.

Table 6
OCRA index values for the ergonomic risk assessment of assembly line workers in the reference assembly line.

Worker	*Task*	*OCRA Index*
Worker 1	1	3.4
Worker 2	2	1.3
Worker 3	3	0.7
Worker 4	4	1.5
Worker 5	5	0.6
Worker 6	6	3.7

The OCRA index is computed for each task adopting the multiple-task analysis (ISO 11228-3). Specifically, each task ,*t* , is considered as the sum of multiple repetitive sub-tasks for the assembly of product, *p*, such that $h_{p,t}$=1. The threshold limit value of the OCRA index for hand activities is 2.2. Lower values of the OCRA index define activities that pose an acceptable risk. High OCRA indices (greater than or equal to 3.5) characterize high-risk repetitive tasks (Occhipinti, 1998,ISO 11228-3, 2007). Table 6 shows that high risk repetitive movement of the upper limbs is associated with the task performed at workstation 6 (i.e., the OCRA index for the manual worker at workstation 6 is equal to 3.7).

The introduced data define the model inputs for the considered case study. Forty-eight binary variables are introduced and subjected to 60 feasibility constraints. The model and the input data are coded in AMPL language and processed adopting the Gurobi Optimizer© v.5.5 solver. An Intel® CoreTM i7-4770 CPU @ 3.50GHz and 32.0GB RAM workstation was used. The average solving time was approximately 0.5 seconds. The key outcomes are discussed in the following section.

Section 5 shows the effects of the introduced bi-objective ILP model and describes how it can support researchers and practitioners in the design of efficient assembly lines, meeting both the lean principles and ergonomic requirements for safe assembly work.

5. Results and discussion

This section introduces the results of the application of the bi-objective ILP model to the reference case study. The aim is to define optimal bi-objective layout solutions, ensuring the minimization of the WIP and the cost reduction of the hybrid assembly system. Each bi-objective solution identifies an assembly layout alternative that make each objective function "quasi" optimal. The study adopts the bi-objective optimisation approach proposed by Messac et al. (2003). Equation (10) and Equation (11) are the objective functions of the bi-objective optimisation model.

The normalized Pareto frontier in Figure 5 shows the trends of the two objective functions in the normalized *WIP-Cost* diagram (Messac et al., 2003). The points from W to C are the Pareto points composing the normalized Pareto frontier (Figure 5). Each Pareto point represents an effective non-dominated trade-off assembly layout configuration.

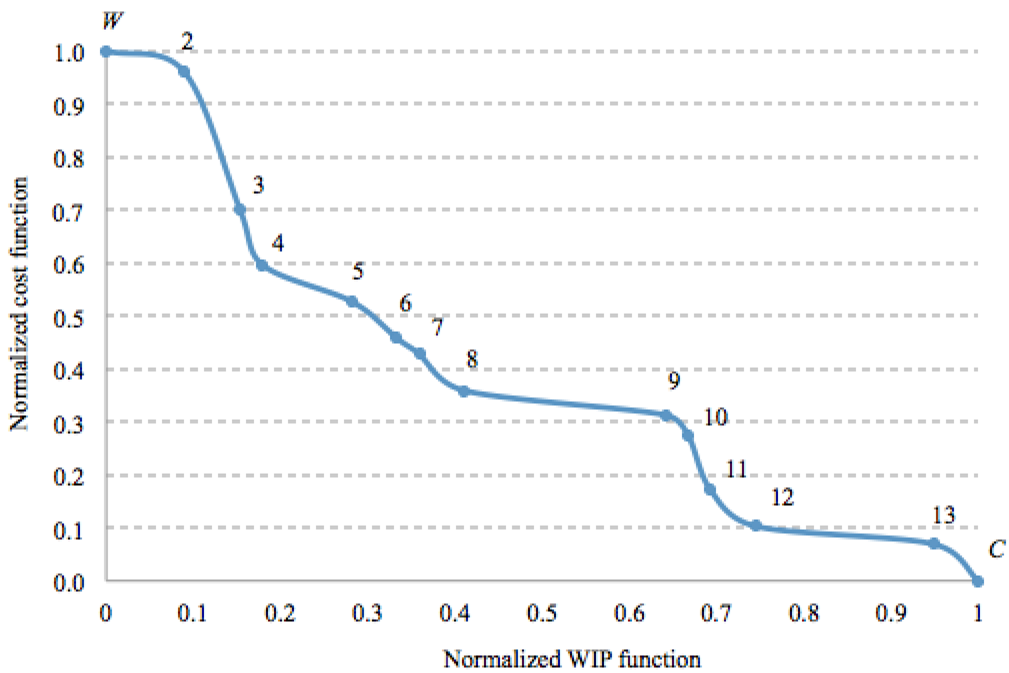

Fig. 5. Normalized WIP-Cost Pareto frontier.

Table 7
Pareto points coordinates.

Pareto Point	$\bar{\varphi}(j)$	$\bar{\chi}(j)$
W	0.00	1.00
2	0.09	0.96
3	0.15	0.70
4	0.18	0.60
5	0.28	0.53
6	0.33	0.46
7	0.36	0.43
8	0.41	0.36
9	0.64	0.31
10	0.67	0.28
11	0.69	0.17
12	0.74	0.10
13	0.95	0.07
C	1.00	0.00

Point W (0;1) is the normalized anchor point for the normalized WIP objective function, $\bar{\varphi}(j)$ (i.e., the assembly layout solution in point W ensures the minimum cost of the WIP). Point C (1;0) is the normalized anchor point for the normalized cost objective function, $\bar{\chi}(j)$ (i.e., the assembly layout solution in point C ensures the minimum cost of the assembly system). Each Pareto point from $j=2$ to $j=13$ identifies a bi-objective solution that make "quasi" optimal each objective function (Figure 5 and Table 7). The choice among the Pareto points is not univocal. It depends on the importance given to the model drivers, $\bar{\varphi}(j)$ and $\bar{\chi}(j)$. Equation (20) introduces a heuristic criterion to evaluate the decision.

$$D(j) = \bar{\varphi}(j) + \bar{\chi}(j) \tag{20}$$

The decision function $D(j)$ matches the trends of both the WIP and the cost functions. An effective trade-off configuration is at its minimum value (Figure 6 and Table 8).

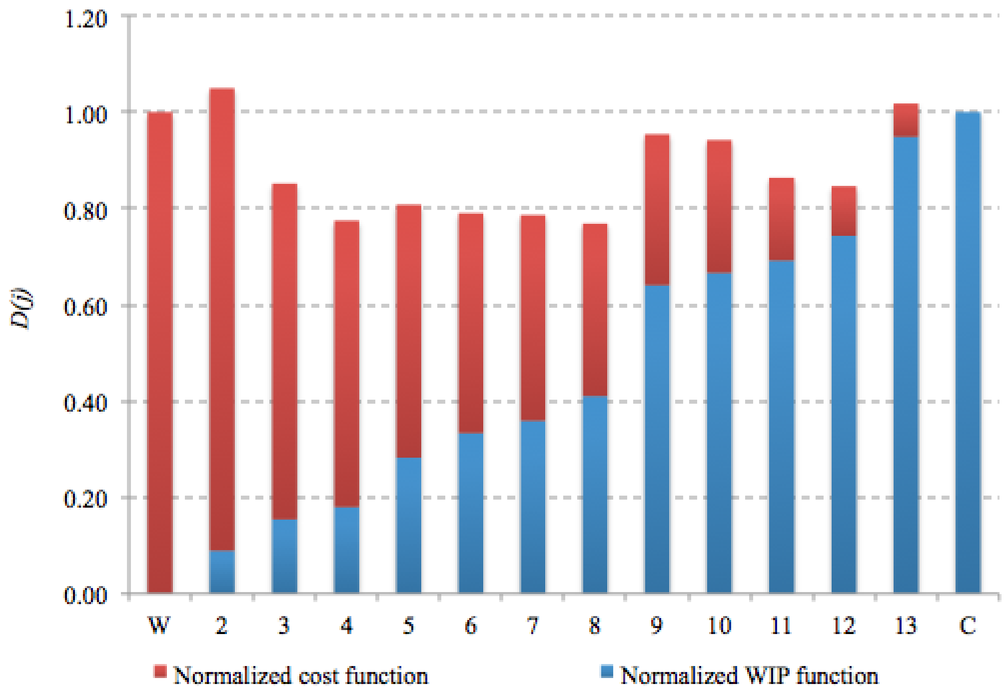

Fig. 6. Decision function chart for the Pareto points.

Table 8
Decision function values for each *j* point.

j	*W*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*C*
D (j)	1.00	1.05	0.85	0.78	0.81	0.79	0.79	0.77	0.95	0.94	0.86	0.85	1.02	1.00

The solution in point *j=8* minimises the decision function *D (j)*. The assembly layout for such a point is a good trade-off between the two normalized anchor points *W* and *C* [i.e., $\bar{\varphi}(j = 8) = 0.41$ and $\bar{\chi}(j = 8) = 0.36$, Table 7]. Given the un-normalized lower bounds for the two objective functions χ and φ, the performance losses are $\Delta\chi(j = 8)$ = 0.06% and $\Delta\varphi(j = 8)$ = 8.49%. Figure 7 shows the assembly layouts for solutions at points *W*, *C* and *j=8*.

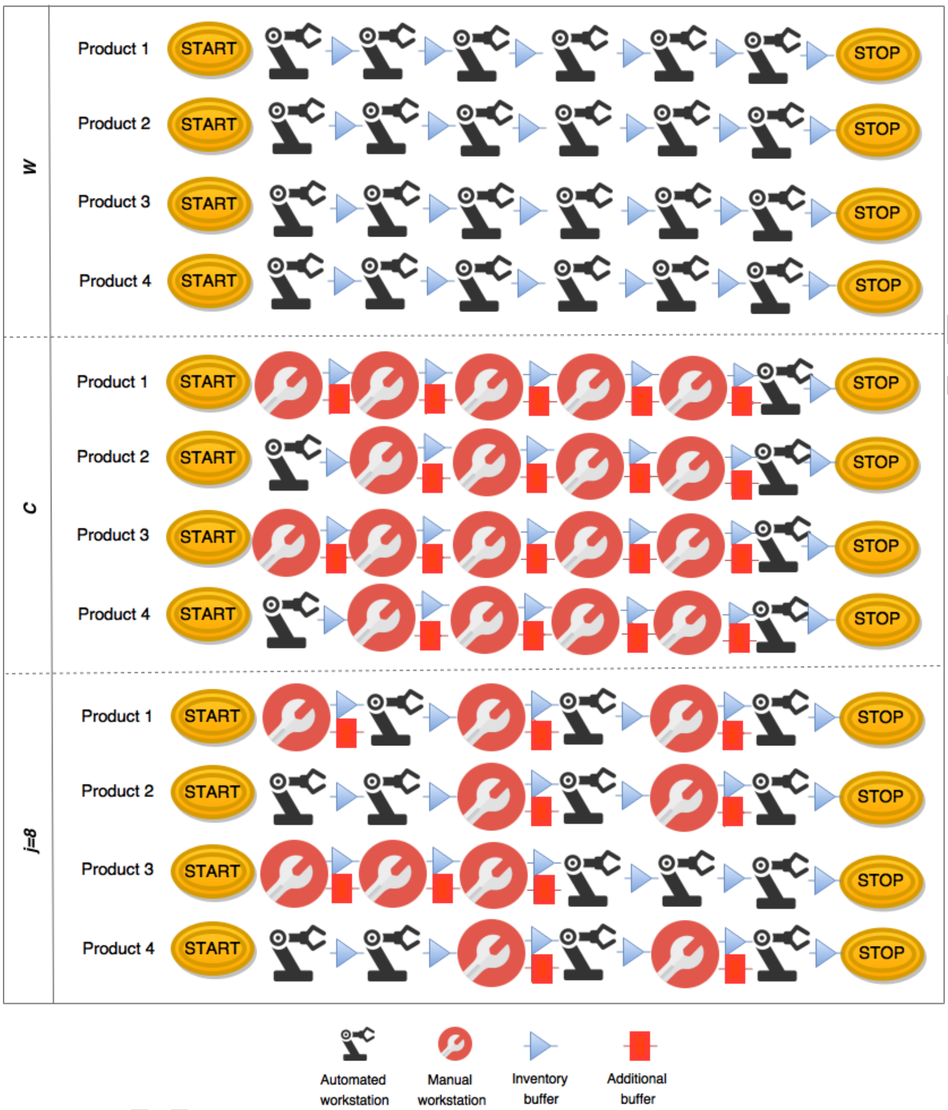

Fig. 7. Layout of the assembly process for solutions in points *W*, *C* and *j=8*.

The assembly layout for the solution at point *W* minimizes the daily cost of the WIP, while the assembly layout for solution at point *C* minimizes the daily cost of the assembly system (Figure 7). The assembly layout at point *j=8* matches the production requirements of the assembly system, representing a good trade-off between the two introduced objective functions. The three assembly layouts in Figure 7 ensure that task *t=6* is performed by automated machinery (i.e., the OCRA index for worker 6 in the reference case study is higher than the threshold limit value).

Table 9
OCRA index values for the ergonomic risk assessment of assembly line workers in ponit *C* and point *j=8*.

Worker	*Task*	*OCRA Index in C*	*OCRA Index in j=8*
Worker 1	1	2.1	2.1

Worker 2	2	1.3	2.1
Worker 3	3	0.7	0.7
Worker 4	4	1.5	0
Worker 5	5	0.6	0.4
Worker 6	6	0	0

The assembly layouts at point *j=8* and point C suggest the adoption of automated machinery for products *p=2* and *p=4 in task t=1*. Consequently, the exposure to the ergonomic risk of worker 1 reduces and the OCRA index value for task *t=1* decreases as well (see Table 6 and Table 9). Each model solution represents an optimal design alternative for the design of hybrid assembly lines, based on the preferred objective. The final choice to automate a workstation or to adopt manual workers is up to practitioners.

6. Conclusions

Lean manufacturing is a production strategy that is used to increase profit by eliminating waste. After the success of the Japanese Toyota Production System in the 1980s, lean manufacturing was rapidly established in the worldwide manufacturing industry. Despite the promising results in the economic performances of some companies, recent studies have shown a potential correlation between specific lean practices and workers' ergonomics, occupational health and related risk factors. However, automation plays a strategic role in increasing productivity and reducing the production time in manufacturing companies. Further reasons to automate the manufacturing processes include the presence of hazardous working conditions and the high cost of specialized manual workers. The current market requires companies to find a balance between the advantages of automated production and the dynamic demand for customized products. When automation cannot provide great flexibility, production system design requires the joint optimization of human and technical aspects.

This paper addresses the design of hybrid assembly lines, fulfilling the principles of lean manufacturing and the ergonomic requirements for safe assembly work. A bi-objective integer linear programming mathematical model drives the choice between manual and automatic workstations. The primary assumption is the design of hybrid lean processes that avoid the machine pacing of workers and the related harmful effects. Given the production requirements and characteristics of the work system, the result is a set of worker-paced hybrid assembly line solutions. The model defines the sequences of manual and automatic workstations, in which the machine pace is set by the manual workstations. Furthermore, each assembly line solution ensures an acceptable risk level of repetitive movements, as required by current law. The case study introduces the application of the proposed mathematical model to an assembly line. The aim is to investigate the impact of ergonomics on the lean manufacturing process. Results show that worker ergonomics is a key parameter of the assembly process design, as other lean manufacturing parameters, e.g. takt time, cycle time and work in progress. The model includes the OCRA risk assessment, as required by the Italian regulations on occupational safety. Specifically, the mathematical model restricts the OCRA index value to a threshold limit value for each task (ISO 11228-3, 2007). The choice of a different ergonomic risk assessment method might produce different results and have a substantial impact on the design of hybrid assembly lines. Future developments of this work include the adoption of a different ergonomic risk assessment method and the analysis of the impact on the solutions of model. Finally, the proposed mathematical model will be tested on complex assembly lines with no sequential workstations.

Appendix A.

A.1. Notation

The following notation is utilized in the proposed mathematical model.

A.1.1 Indices

p	Product index, $p = 1 \ldots P$
t	Task index, $t = 1 \ldots T$

A.1.2 Parameters

a_{pt}	1 if task t is standardizable for all the products and the assembly activities are not complex, 0 otherwise [binary]
b	Duration of the shift [h]
c_{pt}	Cycle time to perform task t for product p with automated machinery [s/unit and machine]
d_{pt}	Cycle time to perform task t for product p at the manual workstation [s/unit and worker]
e_{pt}	Mean lateness of the manual workstation for task t and product p [s]
f_{pt}	Safety time for task t and product p [s]
g_p	Daily batch size of product p [units]
h_{pt}	1 if task t is in the assembly process of product p, 0 otherwise [binary]
i_{pt}	Number of automatic machines required for task t to ensure the production of product p [machines]
$i_{max\,t}$	Maximum number of automatic machines working simultaneously to perform task t [machines]
j_{pt}	Number of p products in the buffer inventory [units]
k_p	Takt time for the production of product p [s/unit]
l_{pt}	Number of manual workers required for task t to ensure the production of product p [workers]
o_t	Percentage of defective products due to automated task t [%]
o'_t	Percentage of defective products due to manual task t [%]
q_t	Hourly energy consumption of the automated machinery for task t [€/h]

r_t	Hourly cost of machine reprogramming for task t [€/machine and hour]
s_{pt}	Number of p processed products in the additional buffer [units]
v_{pt}	Value of product p after task t [€/unit]
x_t	Hourly cost of automated machinery for the automated task t, safety barriers and transport system of assembled products to the next workstation [€/hour and machine]
y_t	Hourly cost of the manual workers at the manual workstation for task t [€/hour and worker]
OCRA parameters	
$n_{TC,pt}$	Number of technical actions of the task t
k_f	Constant of frequency of technical actions per minute
$F_{M,t}$	Force multiplier for task t
$P_{M,t}$	Posture multiplier for task t
$Re_{M,t}$	Repetitiveness period multiplier for task t
$A_{M,t}$	Additional multiplier for task t
$Rc_{M,t}$	Recovery period multiplier
$t_{M,t}$	Duration multiplier

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Integrating ergonomics and lean manufacturing principles in an hybrid assembly line

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Integrating ergonomics and lean manufacturing principles in a hybrid assembly line

Highlights

- Bi-objective mathematical model for the design of lean processes in assembly lines.
- Lean principles and ergonomic requirements for workers safety are included.
- The model is applied to a case study from a tool case manufacturing company.
- Results show different alternatives for assembly lines meeting the two objectives.