The Impact of Ergonomics on the Design of Hybrid Multi-model Production Lines in Lean Manufacturing

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Abstract. Lean manufacturing is a production method aiming to reduce costs and increase productivity by eliminating waste. Previous studies investigating the variations in the quality of working life due to the implementation of lean manufacturing have shown both negative and positive effects on workers health and perceptions of workplace safety and job satisfaction. This study investigates the impact of ergonomics on the design of manufacturing processes following the principles of lean production. A mathematical model is introduced to address the design of hybrid multi-model production lines with both manual and automatic workstations. The model includes the ergonomic risk assessment ensuring an acceptable exposure of the workers to the risk of developing musculoskeletal disorders in hand intensive tasks. The OCRA Index and the Strain Index job analysis methods are included. The aim is to analyze the variations in the solutions of the model, due to the different ergonomic risk assessment method adopted.

Keywords: Hybrid multi-model production line design · Ergonomic risk assessment · Lean manufacturing · Occupational safety

1 Introduction

Lean manufacturing is a production method that was established in the wake of the Japanese Toyota Production System. The primary goal of lean manufacturing is to reduce costs and increase productivity by eliminating waste. Specifically, waste is anything other than the minimum amount of equipment, materials, parts, space and employee time necessary to produce the required products. Previous studies investigating the variations in the quality of working life due to the implementation of lean manufacturing have shown both negative and positive effects on workers health and perceptions of workplace safety and job satisfaction. Several researches draw eulogistic praise of lean manufacturing strategies, reporting increased health, job satisfaction and job motivation. The results of such studies show that workers perceive better working conditions and avoid excessive fatigue and accidental injuries after the adoption of lean production principles in their workplaces [1–3]. Conversely, a parallel research path

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stresses the disadvantages of lean manufacturing and the negative effects on employee autonomy, work demands and psychological strain. Recent studies claim that lean principles as Just-in-time (JIT) and work standardization increase work pace and lack of recovery [4]. The rigid application of lean manufacturing in industry is associated with increased musculoskeletal risk factors, musculoskeletal disorders and stress [5–8]. Work-related Musculoskeletal Disorders (WMSDs) refer to repetitive strain injuries or cumulative trauma disorders affecting the back, lower limbs, and especially upper limbs and neck [9].

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 and recent studies have widely discussed how ergonomics can optimize human performance and overall work system performance [10]. Previous researches have shown the impact of human factors and worker behaviors on company performance and expected outcomes [11–16]. Further researches have focused on the impact of lean thinking on worker health and safety, investigating [1,17–23]. Results of these studies have shown controversial opinions on the effects of lean manufacturing methods on workers performances. Several studies have reported that the rigid application of lean manufacturing principles is associated with increased musculoskeletal risk factors and stress in manual workers [5–8].

Several methods and procedures are available to assess the risk of repetitive movements and exertions. Such risk assessment methods analyze main and additional risk factors of repetitive work. The first are repetitiveness, force, awkward postures and movements, and lack of proper recovery periods. The latter are mechanical factors (e.g., vibrations), environmental factors (e.g., exposure to high and low temperatures), and organizational factors (e.g., machine-paced work) [24].

Previous studies have compared different risk assessment methods to define how various methods differ in the analysis of the same workstation [25–28]. Jones and Kumar [25] have compared the results of 5 ergonomic risk assessment methods (RULA, REBA, ACGIH TLV, SI and OCRA Index) for the analysis of a repetitive sawmill task. Similarly, Roman-Liu has compared 10 easy-to-use methods for assessing musculoskeletal load and risk for developing WMSDs [27]. The results of the study from Paulsen et al. have shown that both the SI and the OCRA checklist assessments possess adequate inter-rater reliability for the purposes of occupational health research and practice [28].

The following Sect. 2 introduces the bi-objective integer linear mathematical model to define ergonomic lean processes in production lines. The aim was to design the optimal layout of the production processes that meet the lean goals of improving production efficiency and the ergonomic principles for manual material handling. The model defines the production process for hybrid production lines with both manual workers and automated machinery. The ergonomic risk assessment ensures an acceptable exposure of the workers to the risk of developing musculoskeletal disorders in hand intensive tasks. Specifically, the Occupational Repetitive Action (OCRA) Index [29] and the Revised Strain Index (RSI) [30] ergonomic risk assessment methods are included.

2 Methods

This section introduces the bi-objective integer linear mathematical model for the design of hybrid production lines in industry. The proposed mathematical model is based on the self-paced work principle. The aim is to prevent the machine-paced work and the related negative effects on workers' health and safety [31,32].

The proposed mathematical model includes an ergonomic lean approach based on the self-paced work principle. Final stages of the lean manufacturing processes pull the production flow, reflecting a just-in-time perspective. 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. Additional buffers are necessary at manual workstations to prevent semi-product shortages due to the delay of manual workers, and the consequent machine-paced phenomenon. No additional buffer is required between an automated machine and the following workstation, whether it is manual or automated. However, the use of inventory and additional buffers increases the amount of inventory and WIP. Given the cycle time (c_{wi}) to perform manual work activity w for item i, the desired safety time s, and the mean lateness l, the following Eq. (1) defines the inventory buffer size (b_{wi}), while Eq. (2) analyses the additional buffer size (a_{wi}).

$$b_{wi} = \frac{s_{wi}}{c_{wi}} \tag{1}$$

$$a_{wi} = \frac{l_{wi}}{c_{wi}} \tag{2}$$

Specifically, b_{wi} defines the number of items in the inventory buffer, while a_{wi} defines the number of items in the additional buffer. The use of inventory and additional buffers contrasts with the lean principle of minimum WIP.

The overall cost of a hybrid production line is due to automated machinery (Eq. 3) and to manual workers (Eq. 4).

$$C_{automation} = \sum_{w=1}^{W} \left(r_w \cdot r'_{max\,w}\right) + \sum_{w=1}^{W} \sum_{i=1}^{I} \left(e_w \cdot r'_{wi}\right) + \sum_{w=1}^{W} \left[g_w \cdot \sum_{i=1}^{I} (d_i \cdot t_{wi})\right] + \sum_{w=1}^{W} \left[n_w \cdot \sum_{i=1}^{I} (d_i \cdot v_{wi})\right] \tag{3}$$

$$C_{manual\,work} = \sum_{w=1}^{W} \left(m_w \cdot m'_{wi}\right) + \sum_{w=1}^{W} \left[n'_w \cdot \sum_{i=1}^{I} (d_i \cdot v_{wi})\right] \tag{4}$$

The following Table 1 shows the parameters adopted in Eqs. (3), (4) and in the mathematical model.

Table 1. Indices and parameters of the mathematical model.

Description	
Indices	
i	Item index, i = 1…I
w	Work task index, w = 1…W
Parameters	
x_{wi}	1 if work task *w* is standardizable for all the products and the job activities are not complex, 0 otherwise [binary]
h	Duration of the shift [h]
t_{wi}	Cycle time to perform work task *w* for item *i* with automated machinery [s/unit and machine]
c_{wi}	Cycle time to perform work task *w* for item *i* at the manual workstation [s/unit and worker]
l_{wi}	Mean lateness of the manual workstation for work task *w* and item *i* [s]
s_{wi}	Safety time for work task *w* and item *i* [s]
d_i	Daily batch size of item *i* [units]
y_{wi}	1 if work task *w* is in the production process of item *i*, 0 otherwise [binary]
r'_{wi}	Number of automatic machines required for work task *w* to ensure the production of item *i* [machines]
$r'_{max\,wi}$	Maximum number of automatic machines working simultaneously to perform work task *w* [machines]
b_{wi}	Number of items *i* in the buffer inventory [units]
k_i	Takt time for the production of item *i* [s/unit]
m'_{wi}	Number of automatic machines required for work task *w* to ensure the production of item *i* [workers]
n_w	Percentage of defective products due to automated work task *w* [%]
n'_w	Percentage of defective products due to manual work task *w* [%]
g_w	Hourly energy consumption of the automated machinery for work task *w* [€/h]
e_w	Hourly cost of machine setup for work task *w* [€/machine and hour]
a_{wi}	Number of *i* processed items in the additional buffer [units]
v_{wi}	Value of item *i* after work task *w* [€/unit]
r_w	Hourly cost of automated machinery for the automated work task *w* [€/hour and machine]
m_w	Hourly cost of the manual workers at the manual workstation for work task *w* [€/hour and worker]
OCRA parameters	
$n_{TC,wi}$	Number of technical actions for product p and work task *w* and item *i*
k_f	Constant of frequency of technical actions per minute
$F_{M,wi}$	Force multiplier for work task *w* and item *i*
$P_{M,wi}$	Posture multiplier for work task *w* and item *i*
$Re_{M,wi}$	Repetitiveness period multiplier for work task *w* and item *i*
$A_{M,wi}$	Additional multiplier for work task *w* and item *i*
Rc_M	Recovery period multiplier
t_M	Duration multiplier

(*continued*)

Table 1. (*continued*)

Description	
RSI parameters	
IM_{wi}	Intensity of exertion multiplier, for work task w and item i
EM_{wi}	Efforts per minute multiplier, for work task w and item i
DM_{wi}	Duration per exertion multiplier, for work task w and item i
PM_{wi}	Hand/wrist posture multiplier, for work task w and item i

2.1 The Mathematical Model

The aim of the proposed integer linear programming mathematical model is to address employers and practitioners during the design of hybrid production lines. Given the characteristics of the manufacturing process and the automated machines working parameters, the model assigns manual workers or automated machinery to each workstation. The indices and parameters of the model are in previous Table 1.

The mathematical model is subject to a set of operation assumptions as: each task is performed either by automated machinery or by manual workers, processing times are deterministic, and workers performing the same task for a given item are assumed to be exposed to same ergonomic risk level.

Two decision variables, A_{wi} and B_w, define the optimal alternation of automated and manual workstations. A_{wi} defines the presence of manual workers or automated machinery for each work task w and item i (Eq. 5). B_w is derived from A_{wi} and it defines if automated machinery is adopted for at least one item type, for each work task t (Eq. 6).

$$A_{wi} = \begin{cases} 1, \textit{if work task w in the assembly process of item i is performed by automated machinery} \\ 0, \textit{otherwise} \end{cases} \quad \forall i, w \tag{5}$$

$$B_w = \begin{cases} 1, \textit{if automated machinery for work task w is in the assembly process of at least one item type} \\ 0, \textit{otherwise} \end{cases} \quad \forall w \tag{6}$$

The objective functions in Eqs. (7) and (8) drive the optimization model, defining optimal production processes with both automatic and manual workstations.

$$\phi = \sum\nolimits_{w=1}^{W} \sum\nolimits_{i=1}^{I} \left\{ \frac{v_{wi}}{c_{wi}} \cdot [s_{wi} \cdot y_{wi} + l_{wi} \cdot (y_{wi} - A_{wi})] \right\} \tag{7}$$

$$\psi = b \cdot \sum_{w=1}^{W} \left(B_w \cdot r_w \cdot r'_{max\,w}\right) + \sum_{w=1}^{W} \sum_{i=1}^{I} \frac{1}{3600} \cdot \left(A_{wi} \cdot g_w \cdot t_{wi} \cdot d_i\right)$$
$$+ b \cdot \sum_{w=1}^{W} \left[e_w \cdot \sum_{i=1}^{I} \left(A_{wi} \cdot r'_{wi}\right)\right] + \sum_{w=1}^{W} \left[n_w \cdot \sum_{i=1}^{I} \left(A_{wi} \cdot d_i \cdot v_{wi}\right)\right]$$
$$+ b \cdot \sum_{w=1}^{W} \left\{m_w \cdot \sum_{i=1}^{I} \left[\left(y_{wi} - A_{wi}\right) \cdot m'_{wi}\right]\right\} + \sum_{w=1}^{W} \left\{n'_w \cdot \sum_{i=1}^{I} \left[\left(y_{wi} - A_{wi}\right) \cdot d_i \cdot v_{wi}\right]\right\} \quad (8)$$

The first objective function, ϕ, is from the previous Eqs. (1) and (2), and it evaluates the daily value of the WIP. Specifically, the daily value of the WIP is the sum of the values of the inventory buffer and the additional buffer. The second objective function, ψ, is derived from previous Eqs. (3) and (4), and it computes the daily cost of the hybrid production system. The following Equations from (9)–(16) define the constraints of the mathematical model.

$$min \{\phi, \psi\} \quad (9)$$

$$A_{wi} \leq y_{wi} \quad \forall i, w \quad (10)$$

$$A_{wi} \leq x_{wi} \quad \forall i, w \quad (11)$$

$$\sum_{i=1}^{I} A_{wi} \leq I \cdot B_w \quad \forall w \quad (12)$$

$$B_w \leq \sum_{i=1}^{I} A_{wi} \quad \forall w \quad (13)$$

$$\frac{\sum_{i=1}^{I} \left[\left(y_{wi} - A_{wi}\right) \cdot n_{TC,wi} \cdot d_i\right]}{\sum_{i=1}^{I} \left[\left(y_{wi} - A_{wi}\right) \cdot \left(k_f \cdot F_{M,wi} \cdot P_{M,wi} \cdot R_{eM,wi} \cdot A_{M,wi} \cdot c_{wi} \cdot d_i \cdot 1/60\right)\right] \cdot R_{cM} \cdot t_M} \leq 2.2 \quad \forall w \quad (14a)$$

$$6.06 + 0.93 \cdot \left(\frac{1}{3600} \cdot \left(y_{wi} - A_{wi}\right) \cdot c_{wi} \cdot d_i\right) \leq \frac{10}{0.090 \cdot IM_{wi} \cdot EM_{wi} \cdot DM_{wi} \cdot PM_{wi}} \quad \forall i, w \quad (14b)$$

$$A_{wi}\, binary \quad \forall i, w \quad (15)$$

$$B_w\, binary \quad \forall w \quad (16)$$

Equation (9) minimizes the objective functions, while Eq. (10) ensures that automated machinery is not assigned to workstations that are not required to process item i. Equation (11) assigns automated machinery to the manufacturing processes of items with standardizable production characteristics. Equations (12) and (13) ensure that B_w is equal to 1 if automated machinery is adopted in the production process of at least one item i. Equations (14a) and (14b) restrict the ergonomic risk indices to their threshold limit value. Specifically, Eq. (14a) stems from the International Standard ISO 11228-3, and it restricts the OCRA index value to the threshold limit value of 2.2 for each work task [33]. Equation (14b) shows the linearized formulation for the RSI. Such constraint restricts the RSI value to the threshold limit value of 10 for each work task and item (Garg et al. 2016). Finally, Eqs. (15) and (16) provide consistence to the binary variables.

The model size is $(I \cdot W) + W$ binary variables and $2 \cdot (I \cdot W) + 3 \cdot W$ constraints in case of the OCRA index risk assessment method, and $(I \cdot W) + W$ binary variables and $3 \cdot (I \cdot W) + 2 \cdot W$ constraints in case of the RSI method.

The following Sect. 4 shows the application of the model to four different case studies. The aim is to show the impact of each risk assessment method on the results of the model.

3 Case Studies

This Section introduces the application of the proposed integer linear programming model to four manual processes in different industries. Specifically, the first case study is from a production line for hard-shell tool cases. The second case study is based on the manual process for the industrial production of typical Italian flat unleavened bread. The third case study analyses the manufacturing process for the production of mechanical parts. Finally, the fourth case study is from the meat-processing industry and it is focused on manual ham-deboning lines. The aim is to define the optimal sequence of automated and manual workstations based on the two lean manufacturing principles in Eqs. (7) and (8), i.e. the minimum WIP and the minimum cost of the system. The following Table 2 gathers the mean values of the parameters for the ergonomic risk assessment in each case study.

Values in Table 2 refer to activities performed by manual workers in four different industries. Four different raters assessed the workstations of each case study using both the OCRA index and the RSI methods, resulting in 21 pairs of ergonomic risk assessments. The parameters for the OCRA index computation refer to the most stressed arm, for each manual worker. Sensitive values of the manual assembly process parameters are hidden (e.g., punctual values of ergonomic risk indices, frequency of movements and cycle times) for confidentiality reasons.

The introduced data define the model inputs for the considered case studies. The model and the input data were coded in AMPL language and processed adopting the Gurobi Optimizer© v.5.5 solver. An Intel® CoreTM i7-4770 CPU @ 3.50 GHz and 32.0 GB RAM workstation was used. The average solving time was approximately 0.5 s. The key outcomes are discussed in the following Sect. 4.

4 Results and Discussion

The following Tables 3 and 4 show the results of the application of the bi-objective integer linear programming model to the reference case studies including the two-different ergonomic risk assessment methods. When the preferred objective is the minimization of the WIP, the model assigns automated machinery to each workstation.

Table 2. Distributions for the ergonomic risk assessment through OCRA index and RSI methods.

	Case study 1	Case study 2	Case study 3	Case study 4
Industry	Manufacturing	Food processing	Metalwork	Meat processing
Number of tasks	6	5	4	6
OCRA parameters				
F_M (mean)	0.64	0.89	0.96	0.65
P_M (mean)	0.82	1.00	0.68	0.60
Re_M (mean)	0.88	0.88	0.93	0.80
A_M (mean)	0.95	1.00	0.80	0.80
Rc_M	0.60	0.70	0.70	1.00
OCRA index (mean)	2.51	1.32	1.43	2.23
SD OCRA index	2.01	0.70	1.01	1.51
Total number of high-risk tasks [tasks]	2	1	1	2
RSI parameters				
IM (mean)	2.70	1.51	1.15	2.05
EM (mean)	3.32	4.98	3.77	4.20
DM (mean)	2.11	1.47	2.19	1.67
HM (mean)	0.58	0.51	0.59	0.87
PM (mean)	1.14	1.00	1.00	1.08
RSI (mean)	12.35	5.48	4.23	12.41
SD RSI	8.12	2.73	0.42	5.05
Total number of high-risk tasks [tasks]	4	1	0	4

Table 3. Distributions for the ergonomic risk assessment through OCRA index

	Case study 1	Case study 2	Case study 3	Case study 4
Objective: Minimum WIP				
Percentage of automatic workstations [%]	100%	100%	100%	100%
Objective: Minimum cost of the system				
Percentage of automatic workstations [%]	33%	20%	25%	33%
OCRA index (mean)	0.89	0.82	0.72	0.89
SD OCRA index	0.85	0.51	0.61	0.81
RSI (mean)	5.39	3.47	3.31	7.28
SD RSI	5.61	2.15	2.21	7.21
Maximum OCRA index	2.06	1.38	1.48	2.06
Maximum RSI	13.01	5.32	4.71	16.54

Table 4. Distributions for the ergonomic risk assessment through RSI methods.

	Case study 1	Case study 2	Case study 3	Case study 4
Objective: Minimum WIP				
Percentage of automatic workstations [%]	100%	100%	100%	100%
Objective: Minimum cost of the system				
Percentage of automatic workstations [%]	67%	20%	0%	67%
OCRA index (mean)	0.27	0.82	1.43	0.65
SD OCRA index	0.41	0.51	1.01	0.83
RSI (mean)	1.32	3.47	4.23	1.98
SD RSI	2.11	2.15	0.42	3.09
Maximum OCRA index	0.80	1.38	2.83	2.06
Maximum RSI	4.73	5.32	4.71	6.53

Conversely, when the preferred objective is the minimization of the cost of the system, the model assigns manual workers to each workstation that does not expose the worker to the risk of repetitive work.

Different solutions are possible, depending on the adopted risk assessment method. The following Tables 5, 6, 7 and 8 show the comparison of the results of the ergonomic risk assessments through OCRA index and RSI, for each case study. In case of high ergonomic risk index, the model assigns automated machinery to the workstation that expose the worker to high ergonomic risk. The grey cells in each table refer to the workstations with automatic machinery. Green cells refer to manual workstations that do not expose the workers to the risk of repetitive movements. Red cells refer to manual workstation in which the ergonomic risk index is higher than the threshold limit value. Specifically, the threshold limit value for the OCRA index is 2.2 [29], while the threshold limit value for the RSI is equal to 10 (Garg, Moore and Kapellusch 2016). Higher values of such indices identify the exposure of the workers to high-risk

Table 5. Comparison of the different ergonomic risk assessment methods for Case Study 1.

Risk constraint	**OCRA index**		**RSI**	
Risk index	RSI	OCRA index	RSI	OCRA index
Task 1				
Task 2				
Task 3				
Task 4				
Task 5				
Task 6				

Table 6. Comparison of the different ergonomic risk assessment methods for Case Study 2.

Risk constraint	**OCRA index**		**RSI**	
Risk index	RSI	OCRA index	RSI	OCRA index
Task 1				
Task 2				
Task 3				
Task 4				
Task 5				

Table 7. Comparison of the different ergonomic risk assessment methods for Case Study 3.

Risk constraint	**OCRA index**		**RSI**	
Risk index	RSI	OCRA index	RSI	OCRA index
Task 1				
Task 2				
Task 3				
Task 4				

Table 8. Comparison of the different ergonomic risk assessment methods for Case Study 4.

Risk constraint	**OCRA index**		**RSI**	
Risk index	RSI	OCRA index	RSI	OCRA index
Task 1				
Task 2				
Task 3				
Task 4				
Task 5				
Task 6				

repetitive tasks. The green rows in Tables 5, 6, 7 and 8 show that both the two ergonomic risk assessment indices for workers in such workstations are lower than their reference threshold limit value. The manual task in workstation 1 for Case Study 3, and two manual tasks in Case Study 4 are characterized by a high value for the OCRA index, while the RSI for the same tasks is lower than 10 (see the red cell in Tables 7 and 8).

Conversely, two tasks in Case Study 1 are characterized by high values for the RSI (see the red cells in Table 5), while the OCRA index for the same tasks is lower than threshold limit value. The reason of such discrepancies may be in the different parameters investigated by the two ergonomic risk assessment methods.

Specifically, the RSI does not contemplate the presence of additional risk factors in Case Studies 3 and 4, as the use of gloves interfering with handling ability or the exposure of the workers to cold environments. Furthermore, the posture multiplier included in the ergonomic risk assessment with RSI analyses the amount of flexion or extension of the wrist when applying force. Posture factors as the position of the elbow or the pinch for workers in Case Studies 3 and 4 are not considered. The OCRA index includes the assessment of such risk factors. Consequently, the adoption of the OCRA index is more appropriate when such additional risk factors are present.

The RSI includes the duration multiplier for the analysis of the average time that an exertion is applied. Such parameter has a sensitive impact on the overall calculation of the RSI, i.e. when the duration of exertions is high, the adoption of the RSI is more appropriate.

5 Conclusions

This research has shown a bi-objective mathematical model for the design of hybrid manual processes with both manual workers and automated machinery, including the ergonomic risk assessment with two different methods. The application of the mathematical model to four case studies has shown that the adoption of different ergonomic risk assessment methods has impact on the solutions of the model. Specifically, the OCRA index and the RSI include different parameters for the analysis of the ergonomic risk of repetitive work. As an example, the RSI does not include the analysis of additional risk factors as the exposure to cold temperatures, or the analysis of the posture of shoulder, elbow and pinch. However, raters stated that the ergonomic risk assessment through OCRA index is more complex than the RSI and longer training is required. Finally, the generalization of these results may be limited to the moderate duration of the tasks and limited frequency of the exertions, as described in the reference case studies.

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