Productivity and ergonomic risk in human based production system: a job-rotation scheduling model

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PRODUCTIVITY AND ERGONOMIC RISK IN HUMAN BASED PRODUCTION SYSTEM: A JOB-ROTATION SCHEDULING MODEL

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Abstract

The competitiveness of modern manufacturing systems is based on a high production rate and a high level of flexibility. Despite the high level of automation achieved in production systems, flexibility is often provided by human dexterity and the cognitive capabilities of the workforce, as in assembly lines. In the case of repetitive manual tasks, workers are exposed to the risk of musculoskeletal disorders (MSDs). In these contexts, a high production rate leads to high physical workload, and job rotation is adopted in order to reduce the ergonomic risk. Traditionally, ergonomics and human performance issues have been investigated separately. However, in the design and scheduling of human-based manufacturing systems, a reliable description of human components is required in order to jointly evaluate production system performance and assess workers' risk of MSDs

In this paper, the authors propose a model which aims to find optimal job rotation schedules in work environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model is a mixed integer programming model allowing for the maximization of production rate jointly reducing and balancing human workloads and ergonomic risk within acceptable limits. Risk and its acceptability are evaluated using the OCRA (OCcupational Repetitive Actions) method (ISO 11228-3:2007), widely recognized as an effective tool for the risk assessment of Upper Limb Work related MSDs (UL-WMSDs). Moreover, the different workers' performance due to their respective training levels and skills is considered in the problem formulation.

The model is applied to an industrial case study. Results show the model's capacity to identify optimal job rotation schedules jointly achieving productivity and ergonomic risk goals. Performances of the solutions obtained improve as workforce flexibility increases.

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1. Introduction

In globalized turbulent markets, capital-intensive industries are often subjected to the risk of unprofitable underutilization of their production capacity. Production and process flexibility are still recognized as being the most effective answers to both dynamic and uncertain market demand and pressing international competition (Francas *et al*., 2011). However, in many cases the paradigm of a fully automated factory has failed, since automation does not always provide reliable flexible solutions at a reasonable cost. As an example, in the automotive industry the final assembly stage, providing the highest degree of customization and including the largest number of (complex) tasks, is often the least automated (Kruger *et al*., 2009; Michalos *et al*., 2010). In these work contexts, a high level of flexibility , and thus competitiveness, are obtained by increasing the contribution of the human component, since the dexterity and cognition of workers in both manual and cognitive tasks are major flexibility enablers. As a consequence, in many production environments, human labour continues to play an important role and lean forms of automation are ever more adopted as they are reliable and economically effective. In this scenario, increasing attention, both from a scientific and industrial point of view, is being paid to repetitive manual tasks performed in assembly lines, where most frequently workers are subjected to work-related musculoskeletal disorders (WMSDs) and where an increase in production rate leads directly to an increase in physical workloads (Colombini *et al.*, 2002).

WMSDs and loss of efficiency are typical issues tackled by human based production systems (Lötters *et al.*, 2005; Thun *et al.*, 2011). In Europe, WMSDs are the most common occupational injuries (almost 40% of all work-related injuries) and their cost is estimated at between 0.5% and 2.0% of the EU Gross National Product (EASHW, 2010). Moreover, in many EU Countries demographic developments have led to an aging of the workforce (Mummolo, 2014; CEDEFOP, 2010). The related deterioration of physical and cognitive performances of workforce negatively affects the flexibility of human-based production systems, as in case of manual and semi-automated assembly lines. The need to “develop forward planning tools for employment and skills needs” has become urgent (EC, 2012). There is a need to incorporate the human component into traditional scheduling theory, and to assess the risk of MSDs in the most reliable way possible. With specific regard to the risk of upper limb MSDs (UL-WMSD) due to the presence of multiple repetitive tasks, as in assembly lines, the OCRA method is widely acknowledged (Colombini *et al.*, 2002). Although several methods for determining risk factors for UL-WMSDs have been developed (Chiasson *et al.*, 2012; Schaub *et al.*, 2012), the OCRA method has been standardized by ISO (with ISO 11228-3 technical standard) and by CEN (with EN 1005-5, referring, in particular, to the safe design of machinery, under the scope of the EU “Machinery Directive”).

Human labour has often been considered as the only cost effective alternative to expensive automated solutions, as well as an easily interchangeable highly flexible resource, able to adapt production capacity and to quickly change product features. Despite this, previously the influence of human behaviour on production system performance has been underestimated. Ergonomic studies and human reliability measures have been widely investigated for production and safety related issues separately (Xu *et al*., 2012). Models are still far from being considered experienced and reliable, since an appropriate and complete description of human behaviour is a complex task which has not yet been fully addressed. Complexity dimensions rely on individual, technological, organizational, and social factors. Learning, forgetting, recovery, and tiredness phenomena cause dynamic variability of human performance (e.g. task duration, human reliability in inspection tasks) (Jaber *et al.*, 2013). Furthermore, at a given time during a work shift, human performance is uncertain and varies stochastically due to systemic and random factors (Digiesi *et al.*, 2006, 2009).

In order to smooth workload and the related ergonomic risk among employees, to cross-train them at a low cost, and to increase productivity, job rotation is the most widespread labour flexibility instrument in the case of repetitive assembly tasks (Paul *et al*., 1999).

In this paper, the authors propose an OCRA-based mixed integer nonlinear programming (MINLP) model aiming at finding optimal job rotation schedules in work-environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model aims at maximizing the production rate of the system jointly reducing and balancing human workloads within acceptable limits.

The paper is organized as follows: in section two a review of scientific literature on models for job rotation scheduling in high repetitive manual tasks is introduced; in the third section the OCRA index for UL-WMSDS risk evaluation in multitask jobs is illustrated; in the fourth section, the job rotation scheduling problem is formalized; in the fifth section, a case study from the automotive industry is presented and discussed; finally, conclusions and possible extension of the work are found in the last section.

2. Ergonomic Job Rotation Scheduling

Traditionally, assembly task assignment and ergonomic evaluations are carried out independently (Xu *et al*., 2012). Few researches jointly consider physical demands and completion time of tasks in assignment problems, and solve them using heuristic methods (Carnahan *et al.*, 2000a, 2000b; Choi, 2009; Otto and Scholl, 2011). The integration of ergonomic aspects, as well as worker's skills, within traditional production oriented management tools will be crucial for future research (Battaia and Dolgui, 2013).

Repetitive manual work exposes operators to the risk of incurring WMSDs, especially when this work contains, for example, a high percentage of awkward postures or requires the application of force. Job rotation is considered as an appropriate organizational strategy to reduce physical workload (Paul *et al*. 1999, Boenzi *et al*., 2013a, 2013b) in human-based production systems (e.g. assembly lines), to prevent musculoskeletal disorders, to increase job satisfaction and thus productivity. Moreover, multi-skilled employees able to perform several tasks in different workstations during the same work shift are required in new hybrid assembly systems, as well as in traditional ones in order to deal with product variability, uncertain demand, and workers' substitution. Due to heterogeneity in the composition of the labour force, assignment restrictions should also be taken into account.

Carnahan *et al.* (2000b) were the first in the modelling and solving of ergonomic job rotation scheduling problems to prevent back injuries among operators by using integer programming and genetic algorithm. Tharmmaphornphilas and Norman (2007) propose a heuristic method for developing job rotation schedules to reduce the likelihood of lower back injury due to lifting. Seçkiner and Kurt (2006) define a solution procedure for the problem based on a simulated annealing algorithm aiming at minimizing the workload of operators. Azizi *et al.* (2009) developed a mathematical programming model to balance the effects of rotation intervals on workers' behaviour. Costa and Miralles (2009) consider workers' heterogeneity and maximize the number of different tasks carried out by each worker, while maintaining productivity at reasonable levels; this approach has been extended recently using a Mixed Integer Linear Programming approach (Moreira and Costa, 2013). Finally, Otto and Scholl (2013) develop a smoothing heuristic integrated into a tabu search approach.

By following the OCRA ergonomic assessment method, Asensio-Cuesta *et al.* (2011) propose a genetic algorithm to balance the level of risk to workers caused by high repetitive manual tasks and to obtain job rotation schedules preventing WMSDs. This genetic algorithm, called "Ergonomic and Competent Rotation" (ECRot), allows the inclusion of workers' competences in the model, in order to assign them different tasks during the work-shift.

Models available in scientific literature provide a solution to the ergonomic problem by considering productivity rate as a constraint. In this paper, the authors build a model able to solve both ergonomic and productivity problems. Through a dual approach, appropriate job rotation schedules are developed, making it possible to both increase production rate and to reduce the risk of MSDs for the most exposed workers. Features of the proposed model are the joint evaluation of both the overall attained production levels and of the OCRA indexes for workers, also taking into account the possibility of differences among classes of workers (in particular, in terms of task completion time) and individual risk limits. Finally, despite dynamic human performance variability in task execution (see Digiesi *et al*., 2006, 2009), in this paper a deterministic approach is adopted neglecting time dependent phenomena such as learning, forgetting, tiredness, and recovery. In fact, in the industrial context, the stochastic problem can be transformed into a deterministic one for relatively simple tasks, such as tasks characterized by short completion time (Becker and Scholl, 2006; Otto and Scholl, 2013). Furthermore, following traditional scheduling theory, task completion time is used as a human performance measure, rather than other tangible factors such as human error rate or human reliability.

3. UL-WMSDS risk evaluation in multitask jobs: the OCRA index

The OCRA is a method described in ISO 11228-3 standard that can be used to evaluate the possibility of risk of upper limb work-related musculoskeletal disorders (UL-WMSDs) for workers employed in low load – high frequency manual tasks.

These tasks often entail many adverse factors (high frequency of actions, awkward postures and movement of the upper limbs, excessive use of force, lack of recovery periods, duration, etc.), which are jointly analysed in the method. The result is a synthetic index (the OCRA index) which is representative of the attained level of risk. The ISO standard classifies the risk level in 5 categories by the association between the OCRA index (independent variable) and the prevalence of exposed workers affected by UL-WMSDs (Table 1). In particular, a multi-zone approach is used by ISO to classify the risk: the green zone (i.e. below the threshold value of 2,2) when the risk of disease or injury is negligible and no action is required; the yellow zone (i.e. below the threshold value of 3,5) when a risk of disease or injury cannot be neglected and organizational measures should be taken; the red zone (i.e. beyond the threshold value of 3,5) when there is a considerable risk of disease or injury and a redesign of tasks and workplaces is required.

Table 1: OCRA risk level evaluation (ISO, 2007)

OCRA index	Risk Level
0 – 2,2	Acceptable
2,3 – 3,5	Uncertain
3,6 – 4,5	Low
4,6 – 9	Medium
Over 9	High

In the case of a *single task* performed in the work shift, the OCRA index is expressed as the ratio of the number of technical actions (derived from tasks featuring repetitive movements) effectively performed during the work shift (Actual Technical Actions, ATA) to the number of recommended technical actions (Reference Technical Actions, RTA):

$$OCRA = \frac{n_{ATA}}{n_{RTA}} = \frac{f \cdot t}{RF \cdot t}, \qquad (1)$$

with t the duration of the task and f the average frequency of actions in the task. The average frequency is defined as the ratio of the total number of technical actions performed during a typical working cycle (e.g. the assembly of an object) to the cycle time, determined with technical considerations. The number of RTA is evaluated as the product of the duration of the task (t) times a reference frequency of technical actions during a work cycle (RF). The reference frequency is calculated taking into account the different features of the task and of the organization of the work shift. The factors considered evaluate the “lack of Recovery” due to period distribution (R_{cM}), the duration of the repetitive task during a shift (t_M), the Repetitiveness of the movements (R_{eM},), the use of Force (F_M), the type of Posture (P_M), and Additional factors (A_M) such as the use of tools causing vibrations, localized compression, cold environment, cold surface, hot surface, etc.. It is worth highlighting that, according to the technical standard, for the determination of factors F_M, P_M and A_M (≤ 1), it is necessary to know the fraction of the cycle time during which these risk enablers are present. These factors can assume discrete values, decreasing as the fraction of time increases. Since differences exist among workers (for example an awkward posture could be maintained longer), also these factors can vary. Therefore, these factors should be evaluated for each category of workers grouped, for example, on the basis of their overall speed in completing a cycle. The OCRA index is then representative of the ergonomic risk to which the category of worker performing a given task is exposed.

In the case of a *multitask job*, with q the total number of different tasks to be performed in a work shift, the OCRA index can be evaluated for each worker as (ISO, 2007):

$$OCRA = \sum_{p=1}^{q} f_p t_p \Bigg/ \left(k_f R_{cM} t_M \sum_{p=1}^{q} F_{Mp} P_{Mp} R_{eMp} A_{Mp} t_p \right) \qquad (2)$$

where:

f_p (average) frequency of actions per minute [min^{-1}] of task p;

t_p net duration of task p in the shift [min];

k_f constant of frequency of technical actions per minute (30 [min^{-1}]);

R_{cM} lack of recovery multiplier;

t_M duration multiplier;

F_{Mp} force multiplier;

P_{Mp} posture multiplier;

R_{eMp} repetitiveness multiplier;

A_{Mp} additional factors multiplier;

f_p is the average frequency of actions performed to accomplish task p; therefore it can vary for each repetitive task p (1,..., q), depending both on technical constraints (how the workplace and its tools are devised) and production constraints (task time and production rate);

t_p depends on organizational and production factors which determine the task assignment of each worker in the shift;

R_{cM} can vary for each work shift according to the rest schedule, determined by organizational choices (i.e. break schedules);

t_M is dependent on the net duration of each work shift;

k_f is a constant value for each work shift;

the different multipliers (F_{Mp}, P_{Mp}, R_{eMp}, and A_{Mp}) characterize each repetitive task p on the basis of ergonomic considerations and additional factors.

4. Productivity and ergonomic risk balancing

Different solutions can be adopted to reduce the risk of WMSDs in the case of high repetitive manual tasks. Organizational solutions suggested by the standard ISO 11228 include both the reduction of the number of cycles and the redistribution of breaks within the shift. In fact, reducing the number of cycles means reducing the frequency of actions per minute. However, this solution also means increasing the cycle time, and thereby reducing the production rate. Boenzi *et al*. (2013b) developed a two step approach which aimed to find one or more job rotation and break schedule, which have the overall effect of reducing and balancing the human workload among employees, maintaining a constant level of production without taking into account differences in skill levels which employees have.

Given a daily work shift (i.e. number, duration and distribution of working time slots and planned pauses), the authors aim to demonstrate how it is possible to increase the production rate by developing appropriate job rotation schedules within the work shift and, at the same time, to reduce the risk of musculoskeletal injury for the most exposed workers.

4.1 Problem Formulation

Let us consider a work shift, consisting of r working time slots. Two consecutive working time slots are separated by a break. The assigned duration of the work shift w_s [min] (excluding the planned pauses) is equal to the sum of the r working time slot durations w_h [min] (h = 1, …, r).

Each manual task p (p = 1, …, q) is performed only at the assigned workstation. Moreover, all tasks are parallel and independent (i.e. parallel lines).

We now consider m categories of operators. The operator l (l =1,…,m) is potentially able to perform every specific task p. In the following, we will assume that the number of technical actions necessary to realize each unit of type p is fixed, whereas the requested time can vary depending on the worker. Task completion time per unit (t_{lp} [min/u]) is a widely used measure of performance of the worker (l) in the manual repetitive task (p).

Therefore, in the most general case, each worker l could be characterized by his own specific task completion time for the assigned task p (t_{lp}). The completion time t_{lp} can be expressed as a function of the workers capability and skill:

$$t_{lp} = \alpha_{lp} t_p \qquad (3)$$

where t_p is the "nominal" task completion time and α_{lp} is the skill factor coefficient ($\alpha_{lp} \geq 1$) of the worker l for the given task p. Only in case where worker l is the most suitable for task p, his performance represents the "nominal" performance at the workstation and his skill factor assumes unitary value ($\alpha_{lp}=1$). As a consequence, the production level required from workstation p during the working time slot h is a time dependent constraint, which may not always be fulfilled.

Taking into account ergonomic issues, for a given task completion time t_{lp} the OCRA index value related to worker l increases with his production output in any of the time slots of the work shift. In fact the number of Actual Technical Actions (ATA) during time slot h can be expressed as:

$$n_{ATA,lph} = z_{lph} n_p \qquad (4)$$

where z_{lph} [u] is the production output, and n_p [u^{-1}] the given number of technical actions per unit produced, while the number of Reference Technical Actions (RTA) may be formulated as:

$$n_{RTA,lph} = e d_{lph} w_h \qquad (5)$$

with:

$$e = k_f R_{cM} t_M \qquad (6)$$

and

$$d_{lph} = (F_M P_M R_{eM} A_M)_{lph} \, . \qquad (7)$$

While e value is constant for a given work shift net duration and break scheduling, d_{lph} is a decreasing function of both the production z_{lph} and of the observed cycle completion time t_{lp}. Therefore, for a given worker, increasing the production level means increasing the numerator and non-linearly decreasing the denominator of the formula because the fraction of time characterized by the presence of risk enabling factors increases.

Comparing workers' abilities for a given product output, the lower the worker's skill level, the longer the task completion time, and the higher the related OCRA index value.

4.2 Maximizing production

The model proposed is a mixed integer nonlinear programming model. Given the task completion times of all tasks and categories of operators, the desirable production output, and the ergonomic risk constraints, the model identifies one or more optimal job rotation schedules which maximize the output of the production system. At the same time the solution guarantees a reduced musculoskeletal risk for the most exposed categories of employees, and a balanced workload.

Introducing ~~a~~ the binary variable y_{lph} that assumes unitary value whenever worker l is assigned to task p in the working time period h, and zero otherwise, the objective function (O.F.) to be maximized is the overall production level:

$$O.F. = \underset{\{y_{lph};z_{lph}\}}{MAX} \sum_{l=1}^{m}\sum_{p=1}^{q}\sum_{h=1}^{r} y_{lph} z_{lph};$$
$$y_{lph} \in \{0;1\} \quad \forall l,p,h \qquad (8)$$

Constraints include:

a. Assignment constraints

Each worker (l) can perform only one task (p) in each working time period (h):

$$\sum_{p=1}^{q} y_{lph} = 1 \quad \forall l,h$$
$$\sum_{l=1}^{m} y_{lph} = 1 \quad \forall p,h \qquad (9)$$

b. Technological constraints

In each time period (h) the maximum (integer) number of output units from a workstation (p) depends on the skill level of the worker (l) assigned to the workstation. The maximum value is obtained by dividing the time period duration (w_h) by the task completion time *(βt_{lp})*. The additional factor β (>1) is introduced in order to model the uncertainty of t_{lp} due to the stochastic variability of human performance; it takes into account possible over-timing with respect to the observed value of the task completion time (t_{lp}).

$$1 \le z_{lph} \le w_h / (\beta t_{lp}) \qquad \forall l, p, h$$

$$z_{lph} \in N \qquad \forall l, p, h \qquad (10)$$

c. Production constraints

For each work shift an admissible range of output units is settled:

$$z_p^{\min} \le z_p \le z_p^{MAX} \qquad \forall p \qquad (11)$$

where

$$z_p = \sum_{l=1}^{m} \sum_{h=1}^{r} z_{lph} \qquad \forall p \quad (12)$$

d. Ergonomic risk constraints

A maximum admissible risk index value for each operator *l* is considered ($OCRA_l^{MAX}$):

$$OCRA_l \le OCRA_l^{MAX} \qquad \forall l \qquad (13)$$

where

$$OCRA_l = \sum_{p=1}^{q} \sum_{h=1}^{r} y_{lph} z_{lph} n_p \Bigg/ \left(e \sum_{p=1}^{q} \sum_{h=1}^{r} y_{lph} d_{lph} w_h \right) \qquad (14)$$

e. Risk balancing constraint

An upper limit for the OCRA index values variability (CV_{OCRA}^{MAX}) is considered in order to balance the ergonomic risk among the workers:

$$CV_{OCRA} \le CV_{OCRA}^{MAX} \qquad (15)$$

where CV_{OCRA} is the coefficient of variation defined as the ratio of the standard deviation to the mean of the OCRA index values of the operators in the work shift:

$$CV_{OCRA} = \frac{\sigma_{OCRA}}{\mu_{OCRA}} \qquad (16)$$

with:

$$\sigma_{OCRA} = \sqrt{\frac{1}{m} \sum_{l=1}^{m} \left(OCRA_l - \mu_{OCRA} \right)^2} \text{ and } \mu_{OCRA} = \frac{1}{m} \sum_{l=1}^{m} OCRA_l \,. \qquad (17)$$

4.3 Minimizing the ergonomic risk

The problem can be easily re-formulated when the aim is to decrease the ergonomic risk. For a given level of production the objective is thus the minimization of the mean value of the OCRA index of the whole workforce.

$$O.F. = \min_{\{y_{lph};z_{lph}\}} \mu_{OCRA};$$

$$y_{lph} \in \{0;1\} \quad \forall l,p,h \qquad (18)$$

At the same time the balancing of the workload and of the corresponding risk among operators is guaranteed by the constraint (15). Constraints (9)-(13) complete the model.

5. CASE STUDY

In this section, a case study from the automotive industry is presented and the related human workload balancing problem in case of repetitive manual tasks is solved in order to test the capability of the model. The study refers to the production system of an international manufacturer of car seats for commercial vehicles. The system consists of dedicated manual assembly work stations (WSs), mainly in parallel. In each assembly station, the worker executes both activities requiring low physical force (e.g. fixing seat skeletons or semi finished seats or their parts into dedicated mechanical equipment) as well as movements which require exerting hand and finger force for the manual leather-dressing of seats.

Description

The car seat assembly line is operated in eight hours shifts. In each work shift four breaks are planned, so that the work shift is divided into five working time slots (r=5) (see Figure 1). The net duration of one work shift is 405 [min].

	06:00 - 14:00								
h	1		2		3		4		5
w_h [min]	80	15	80	15	95	30	80	15	70

Figure 1: Production time slots and breaks during the work shift

The reported case study refers to three parallel and independent manual assembly stations (p=1, 2, 3). In WS1 the complete setting up of a double-seat assembly is carried out. Its metallic structure is blocked on custom mechanical equipment which permits easy positional adjustments of the complex (2-axis rotation). The main assembling phases consist in lining the sitting part and the back of the seat and mounting all the required parts (seatbelts, plastic carters, etc.), utilizing electric and electronic screwdrivers and a special steam-ejecting nozzle to stretch out and refinish leather coats.

In WS2, seat backrest assembly is carried out. The three components: backrest metallic skeleton, filling and leather coat are accurately positioned onto a press device which packs the layers in various time-steps. At the end of each step, the operator must refinish the packing operation and finally stretch out leather wrinkles on the seats backrest surface with a steam nozzle.

In WS3 the final assembly of complete single-seats takes place. The operator fixes the seat in a vertical position on a rotating mechanical device and mounts all the completing parts (plastic carters, armrests, belt lock, etc.) utilizing electric and electronic screwdrivers.

The assembly stations are operated by three workers (l=1, 2, 3) each of them able to perform the three different repetitive tasks of the assembly stations. The workers can execute each task with different performances according to their skill level. Three different skill levels have been assumed: high (1,00), medium (1,15), and low (1,25). As previously stated, task completion time (t_{lp}) of worker l performing task p increases proportionally to α_{lp} (see rel. 3), with respect to an observed nominal task time (t_p) of the most skilled operator. The skill factor values (α_{lp}) and the nominal task time (t_p) are reported in table 2.

Table 2: Nominal production time t_p [s] and worker skill factors α_{lp}

α_{lp}	$p=1$	$p=2$	$p=3$
$l=1$	1,00	1,15	1,00
$l=2$	1,00	1,00	1,00
$l=3$	1,25	1,15	1,00
t_p [s]	1080	170	210

The maximum output of the assembly stations (due to technical constraints) can be obtained assigning to each workstation the most skilled worker/s. With such an assignment, the nominal (or attained) production in each time slot and in the overall work shift is shown in Table 3.

Table 3: Nominal production rate per time slot and work shift

p	l	z_{lph} [u]					z_p [u]
		$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	
1	1	4	4	5	4	3	20
2	2	26	26	30	26	22	130
3	3	21	21	26	21	19	108

The ranges of the desirable output per work shift are the following (production constraints):

$16\ [u] \le z_1 \le 20\ [u]$, $100\ [u] \le z_2 \le 130\ [u]$, $100\ [u] \le z_3 \le 108\ [u]$.

The actual production schedule, which does not include job rotation, is shown in table 4.

Table 4: Actual production schedule

p	l	z_{lph} [u]					z_p [u]
		$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	
1	1	4	4	4	4	3	19
2	2	21	21	23	21	17	103
3	3	20	20	24	20	18	102

Under the made assumptions, in the actual scenario the production capacity is not fulfilled. Moreover, the OCRA index values (see table 5) reveal that the ergonomic risk is unbalanced among the different categories of worker, each of them being included in a different class of risk (RL_1=L - Low, RL_2= U - Uncertain, RL_3=A - Acceptable).

Table 5: Ergonomic risk estimation (OCRA index and Risk Level – RL) of the actual vs nominal production rate

l	Nominal		Actual	
	$OCRA_l$	RL_l	$OCRA_l$	RL_l
1	4,9	L	3,8	L
2	4,1	L	2,7	U
3	2,8	U	2,1	A
μ_{OCRA} [u]	3,95		2,87	
σ_{OCRA} [u]	1,04		0,86	
CV_{OCRA}	0,26		0,30	

If the system is forced to produce at a rate close to the nominal one, the increase in the risk level would not be acceptable for any of the worker categories (RL_1=L, RL_2=L, RL_3=U).

Results and discussion

In the industrial context it can be useful to investigate the capability of the model in searching for suitable job rotation schedules to maximize the total production, at the same time balancing and limiting the ergonomic risk.

The model has been applied in three different scenarios illustrated below. For the first and the second scenario, the maximization problem has been formulated assuming the following upper limit values of the OCRA indexes and of the coefficient of variation CV: ($OCRA_1^{MAX}$=3,5, $OCRA_2^{MAX}$=3,5, $OCRA_3^{MAX}$=2,2) and CV^{MAX}=0,25.

1) JRMPS - Job Rotation Maximum Production with Skills

In this scenario the different skills and training levels of the workforce are considered. This can be the case, for example, with long-time running production platforms, with a mixed aged work force, assuming that age diversity leads to different cycle times, or in the case of complex sequences of manual tasks, for which different training and ability levels substantially differentiate the workers. In table 6 one of the optimal solutions of the scheduling problem (8) is shown with the corresponding production output. The overall production performance is increased by 5,4% if compared with the actual scenario (see table 9). At the same time the mean value of the OCRA index is slightly increased (+2,4%) while the single worker OCRA index values show lower risk levels (RL_1=U, RL_2=U, RL_3=A). It is worth noting that due to the constraints (15) a good balance of ergonomic risk is achieved (CV_{OCRA} is reduced by 28,0%, see table 10).

2) JRMP - Job Rotation Maximum Production

In order to evaluate the influence of the workers' flexibility on the maximum achievable production rate, in this scenario the operators are considered fully interchangeable, thus expanding the numbers of the admissible job rotation schedules in the solution domain. The workers are therefore assumed as equally skilled (α_{lp}=1, l=1, 2, 3 and p=1, 2, 3).

Such a scenario can be hypothesized in newly established enterprises or with very frequent turn-over, where workers' age and training can be considered more uniform and older workers' expertise is not a major concern for the nature of the performed tasks or, equivalently, when the manual task is very simple and does not require the development of particular abilities. As an example, in table 7 the job rotation and production schedule of a solution in the set of optimal solutions of (8) is illustrated. In this scenario, the perfect inter-changeability of the operators leads to six possible permutations of an optimal schedule. In this scenario the best system performances are observed: the technological constraints are saturated; the nominal production rate is reached in each time slot; the ergonomic risk level for each operator decreases if compared with the actual schedule (RL_1=U, RL_2=U, RL_3=A); finally, a great workload balance is obtained (Δ_{CV} = -47,3%). In order to pursue this optimal solution it is therefore necessary to employ flexible workers equally trained in performing all tasks.

3) JRmR - Job Rotation minimum Risk

In order to fully investigate the potentiality of the model, in this scenario the problem is now formulated with the goal of minimizing the mean value of the risk (18) satisfying the production and risk balancing constraints (15). The risk balancing upper limit considered has now therefore been reduced to CV_{OCRA}^{MAX} =0.1 and the workers are assumed to be equally skilled. The scenario could be referred to as a labour-intensive work environment with a high management commitment to health and safety issues. Even in this case, the model is able to find optimal solutions (table 8). Although the problem is solved with a different goal, the model is able to find a solution characterized by not only the lowest risk level (RL_1= RL_2= RL_3=A) and the highest degree of balance (Δ_{CV} = -88,0%), but which also ensures an increased production level compared to the actual scenario (Δz = +12,5%) and a negligible decrement (-2,7%) compared to the JRMP scenario solution. These results show the capability of the model in identifying the opportunities of job rotation guaranteed by the greater flexibility of the operators.

Table 6: Job rotation and production schedule obtained in the JRMPS scenario

p	l	z_{lph} $[u]$					z_p* $[u]$
		h=1	h=2	h=3	h=4	h=5	
1	1	-	4	5	-	-	20
	2	4	-	-	4	3	
	3	-	-	-	-	-	
2	1	22	-	-	22	-	111
	2	-	26		-	-	
	3	-	-	23	-	18	
3	1	-	-	-	-	19	105
	2	-	-	26	-	-	
	3	20	20	-	20	-	

Table 7: Job rotation and production schedule in the JRMP scenario

p	l	z_{lph} $[u]$					z_p* $[u]$
		h=1	h=2	h=3	h=4	h=5	
1	1	-	-	5	4	3	20
	2	4	4	-	-	-	
	3	-	-	-	-	-	
2	1	-	-	-	-	-	130
	2	-	-	30	26	-	
	3	26	26	-	-	22	
3	1	21	21	-	-	-	108
	2	-	-	-	-	19	
	3	-	-	26	21	-	

Table 8: Job rotation and production schedule in the JRmR scenario

p	*l*	z_{lph} *[u]*					z_p* *[u]*
		h=1	*h=2*	*h=3*	*h=4*	*h=5*	
1	1	-	-	-	4	4	17
	2	-	-	-	-	-	
	3	3	3	3	-	-	
2	1	-	-	-	-	-	127
	2	26	26	27	-	-	
	3	-	-	-	26	22	
3	1	21	21	26	-	-	108
	2	-	-	-	21	19	
	3	-	-	-	-	-	

Table 9: Production output estimation for different scheduling solutions

p	*Actual*	*JRMPS*		*JRMP*		*JRmR*	
	z_p *[u]*	z_p *[u]*	*Δz%*	z_p *[u]*	*Δz%*	z_p *[u]*	*Δz%*
1	19	20	*5,3%*	20	*5,3%*	17	*-10,5%*
2	103	111	*7,8%*	130	*26,2%*	127	*23,3%*
3	102	105	*2,9%*	108	*5,9%*	108	*5,9%*
z_{TOT}	224	236	*5,4%*	258	*15,2%*	252	*12,5%*

Table 10: Ergonomic risk comparison (OCRA index and risk level – RL) for different scheduling solutions

l	*Actual*		*JRMPS*		*JRMP*		*JRmR*	
	$OCRA_l$	RL_l	$OCRA_l$	RL_l	$OCRA_l$	RL_l	$OCRA_l$	RL_l
1	3,8	L	3,3	U	2,8	U	2,1	A
2	2,7	U	3,3	U	3,0	U	2,2	A
3	2,1	A	2,2	A	2,2	A	2,1	A
				Δ%		*Δ%*		*Δ%*
μ_{OCRA} *[u]*	2,87		2,93	*2,3%*	2,65	*-7,6%*	2,12	*-26,2%*
σ_{OCRA} *[u]*	0,86		0,64	*-26,3%*	0,42	*-51,2%*	0,08	*-91,1%*
CV_{OCRA}	0,30		0,22	*-28,0%*	0,16	*-47,3%*	0,04	*-88,0%*

6. CONCLUSIONS

In this paper, a dual approach to the ergonomic job rotation scheduling problem is proposed in work environments characterized by high repetitive - low load manual tasks with high frequency of repetition. Workload risk and its acceptability are evaluated by means of the OCRA method. The mixed integer nonlinear programming model takes into account the specific performance of the workers due to training levels and skills. The problem formulation and its solutions show great flexibility in choosing which one of the two inter-connected aspects should deserve major attention, e.g. finding production maximization solutions under ergonomic constraints or, vice-versa, average risk level minimization solutions, under production constraints. The production-oriented formulation of the problem maximizes the production rate while assigning most suitable operators to workstations in each working time slot of the shift. Results show how it is possible to increase productivity as well as to reduce and balance ergonomic risk through an appropriate rotation of workers. Conversely, the dual formulation of the problem makes it possible to significantly reduce the ergonomic risk maintaining the production level under given production constraints.

Results suggest that the effectiveness of the optimal solutions can be significantly increased when flexible workers are employed, thus demonstrating the importance of worker training for both productivity and ergonomic purposes.

Future work will include dynamic variability of human performance during the work shift, due to phenomena such as learning, forgetting, tiredness, and recovery. The integration of ergonomic issues in classical line balancing procedures is expected to be a new, wide field of interest especially in the view of an aging workforce .

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Abstract

The competitiveness of modern manufacturing systems is based on a high production rate and a high level of flexibility. Despite the high level of automation achieved in production systems, flexibility is often provided by human dexterity and the cognitive capabilities of the workforce, as in assembly lines. In the case of repetitive manual tasks, workers are exposed to the risk of musculoskeletal disorders (MSDs). In these contexts, a high production rate leads to high physical workload, and job rotation is adopted in order to reduce the ergonomic risk. Traditionally, ergonomics and human performance issues have been investigated separately. However, in the design and scheduling of human-based manufacturing systems, a reliable description of human components is required in order to jointly evaluate production system performance and assess workers' risk of MSDs.

In this paper, the authors propose a model which aims to find optimal job rotation schedules in work environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model is a mixed integer programming model allowing for the maximization of production rate jointly reducing and balancing human workloads and ergonomic risk within acceptable limits. Risk and its acceptability are evaluated using the OCRA (OCcupational Repetitive Actions) method (ISO 11228-3:2007), widely recognized as an effective tool for the risk assessment of Upper Limb Work related MSDs (UL-WMSDs). Moreover, the different workers' performance due to their respective training levels and skills is considered in the problem formulation.

The model is applied to an industrial case study. Results show the model's capacity to identify optimal job rotation schedules jointly achieving productivity and ergonomic risk goals. Performances of the solutions obtained improve as workforce flexibility increases.

Keywords

Job Rotation; Human Workload Balancing; UL-WMSDs; OCRA; Mathematical Programming; Automotive

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1. Introduction

In globalized turbulent markets, capital-intensive industries are often subjected to the risk of unprofitable underutilization of their production capacity. Production and process flexibility are still recognized as being the most effective answers to both dynamic and uncertain market demand and pressing international competition (Francas *et al.*, 2011). However, in many cases the paradigm of a fully automated factory has failed, since automation does not always provide reliable flexible solutions at a reasonable cost. As an example, in the automotive industry the final assembly stage, providing the highest degree of customization and including the largest number of (complex) tasks, is often the least automated (Kruger *et al.*, 2009; Michalos *et al.*, 2010). In these work contexts, a high level of flexibility , and thus competitiveness, are obtained by increasing the contribution of the human component, since the dexterity and cognition of workers in both manual and cognitive tasks are major flexibility enablers. As a consequence, in many production environments, human labour continues to play an important role and lean forms of automation are ever more adopted as they are reliable and economically effective. In this scenario, increasing attention, both from a scientific and industrial point of view, is being paid to repetitive manual tasks performed in assembly lines, where most frequently workers are subjected to work-related musculoskeletal disorders (WMSDs) and where an increase in production rate leads directly to an increase in physical workloads (Colombini *et al.*, 2002).

WMSDs and loss of efficiency are typical issues tackled by human based production systems (Lötters *et al.*, 2005; Thun *et al.*, 2011). In Europe, WMSDs are the most common occupational injuries (almost 40% of all work-related injuries) and their cost is estimated at between 0.5% and 2.0% of the EU Gross National Product (EASHW, 2010). Moreover, in many EU Countries demographic developments have led to an aging of the workforce (Mummolo, 2014; CEDEFOP, 2010). The related deterioration of physical and cognitive performances of workforce negatively affects the flexibility of human-based production systems, as in case of manual and semi-automated assembly lines. The need to "develop forward planning tools for employment and skills needs" has become urgent (EC, 2012). There is a need to incorporate the human component into traditional scheduling theory, and to assess the risk of MSDs in the most reliable way possible. With specific regard to the risk of upper limb MSDs (UL-WMSD) due to the presence of multiple repetitive tasks, as in assembly lines, the OCRA method is widely acknowledged (Colombini *et al.*, 2002). Although several methods for determining risk factors for UL-WMSDs have been developed (Chiasson *et al.*, 2012; Schaub *et al.*, 2012), the OCRA method has been standardized by ISO (with ISO 11228-3 technical standard) and by CEN (with EN 1005-5, referring, in particular, to the safe design of machinery, under the scope of the EU "Machinery Directive").

Human labour has often been considered as the only cost effective alternative to expensive automated solutions, as well as an easily interchangeable highly flexible resource, able to adapt production capacity and to quickly change product features. Despite this, previously the influence of human behaviour on production system performance has been underestimated. Ergonomic studies and human reliability measures have been widely investigated for production and safety related issues separately (Xu *et al.*, 2012). Models are still far from being considered experienced and reliable, since an appropriate and complete description of human behaviour is a complex task which has not yet been fully addressed. Complexity dimensions rely on individual, technological, organizational, and social factors. Learning, forgetting, recovery, and tiredness phenomena cause dynamic variability of human performance (e.g. task duration, human reliability in inspection tasks) (Jaber *et al.*, 2013). Furthermore, at a given time during a work shift, human performance is uncertain and varies stochastically due to systemic and random factors (Digiesi *et al.*, 2006, 2009).
In order to smooth workload and the related ergonomic risk among employees, to cross-train them at a low cost, and to increase productivity, job rotation is the most widespread labour flexibility instrument in the case of repetitive assembly tasks (Paul *et al.*, 1999).
In this paper, the authors propose an OCRA-based mixed integer nonlinear programming (MINLP) model aiming at finding optimal job rotation schedules in work-environments characterized by low load manual tasks with a high frequency of repetition (e.g. assembly lines). The model aims at maximizing the production rate of the system jointly reducing and balancing human workloads within acceptable limits.
The paper is organized as follows: in section two a review of scientific literature on models for job rotation scheduling in high repetitive manual tasks is introduced; in the third section the OCRA index for UL-WMSDS risk evaluation in multitask jobs is illustrated; in the fourth section, the job rotation scheduling problem is formalized; in the fifth section, a case study from the automotive industry is presented and discussed; finally, conclusions and possible extension of the work are found in the last section.

2. Ergonomic Job Rotation Scheduling

Traditionally, assembly task assignment and ergonomic evaluations are carried out independently (Xu *et al.*, 2012). Few researches jointly consider physical demands and completion time of tasks in assignment problems, and solve them using heuristic methods (Carnahan *et al.*, 2000a, 2000b; Choi, 2009; Otto and Scholl, 2011). The integration of ergonomic aspects, as well as worker's skills, within traditional production oriented management tools will be crucial for future research (Battaia and Dolgui, 2013).

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Repetitive manual work exposes operators to the risk of incurring WMSDs, especially when this work contains, for example, a high percentage of awkward postures or requires the application of force. Job rotation is considered as an appropriate organizational strategy to reduce physical workload (Paul *et al.* 1999, Boenzi *et al.*, 2013a, 2013b) in human-based production systems (e.g. assembly lines), to prevent musculoskeletal disorders, to increase job satisfaction and thus productivity. Moreover, multi-skilled employees able to perform several tasks in different workstations during the same work shift are required in new hybrid assembly systems, as well as in traditional ones in order to deal with product variability, uncertain demand, and workers' substitution. Due to heterogeneity in the composition of the labour force, assignment restrictions should also be taken into account.

Carnahan *et al.* (2000b) were the first in the modelling and solving of ergonomic job rotation scheduling problems to prevent back injuries among operators by using integer programming and genetic algorithm. Tharmmaphornphilas and Norman (2007) propose a heuristic method for developing job rotation schedules to reduce the likelihood of lower back injury due to lifting. Seçkiner and Kurt (2006) define a solution procedure for the problem based on a simulated annealing algorithm aiming at minimizing the workload of operators. Azizi *et al.* (2009) developed a mathematical programming model to balance the effects of rotation intervals on workers' behaviour. Costa and Miralles (2009) consider workers' heterogeneity and maximize the number of different tasks carried out by each worker, while maintaining productivity at reasonable levels; this approach has been extended recently using a Mixed Integer Linear Programming approach (Moreira and Costa, 2013). Finally, Otto and Scholl (2013) develop a smoothing heuristic integrated into a tabu search approach.

By following the OCRA ergonomic assessment method, Asensio-Cuesta *et al.* (2011) propose a genetic algorithm to balance the level of risk to workers caused by high repetitive manual tasks and to obtain job rotation schedules preventing WMSDs. This genetic algorithm, called "Ergonomic and Competent Rotation" (ECRot), allows the inclusion of workers' competences in the model, in order to assign them different tasks during the work-shift.

Models available in scientific literature provide a solution to the ergonomic problem by considering productivity rate as a constraint. In this paper, the authors build a model able to solve both ergonomic and productivity problems. Through a dual approach, appropriate job rotation schedules are developed, making it possible to both increase production rate and to reduce the risk of MSDs for the most exposed workers. Features of the proposed model are the joint evaluation of both the overall attained production levels and of the OCRA indexes for workers, also taking into account the possibility of differences among classes of workers (in particular, in terms of task completion

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time) and individual risk limits. Finally, despite dynamic human performance variability in task execution (see Digiesi *et al.*, 2006, 2009), in this paper a deterministic approach is adopted neglecting time dependent phenomena such as learning, forgetting, tiredness, and recovery. In fact, in the industrial context, the stochastic problem can be transformed into a deterministic one for relatively simple tasks, such as tasks characterized by short completion time (Becker and Scholl, 2006; Otto and Scholl, 2013). Furthermore, following traditional scheduling theory, task completion time is used as a human performance measure, rather than other tangible factors such as human error rate or human reliability.

3. UL-WMSDS risk evaluation in multitask jobs: the OCRA index

The OCRA is a method described in ISO 11228-3 standard that can be used to evaluate the possibility of risk of upper limb work-related musculoskeletal disorders (UL-WMSDs) for workers employed in low load – high frequency manual tasks.

These tasks often entail many adverse factors (high frequency of actions, awkward postures and movement of the upper limbs, excessive use of force, lack of recovery periods, duration, etc.), which are jointly analysed in the method. The result is a synthetic index (the OCRA index) which is representative of the attained level of risk. The ISO standard classifies the risk level in 5 categories by the association between the OCRA index (independent variable) and the prevalence of exposed workers affected by UL-WMSDs (Table 1). In particular, a multi-zone approach is used by ISO to classify the risk: the green zone (i.e. below the threshold value of 2,2) when the risk of disease or injury is negligible and no action is required; the yellow zone (i.e. below the threshold value of 3,5) when a risk of disease or injury cannot be neglected and organizational measures should be taken; the red zone (i.e. beyond the threshold value of 3,5) when there is a considerable risk of disease or injury and a redesign of tasks and workplaces is required.

Table 1: OCRA risk level evaluation (ISO, 2007)

OCRA index	Risk Level
0 – 2,2	Acceptable
2,3 – 3,5	Uncertain
3,6 – 4,5	Low
4,6 – 9	Medium
Over 9	High

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In the case of a *single task* performed in the work shift, the OCRA index is expressed as the ratio of the number of technical actions (derived from tasks featuring repetitive movements) effectively performed during the work shift (Actual Technical Actions, ATA) to the number of recommended technical actions (Reference Technical Actions, RTA):

$$OCRA = \frac{n_{ATA}}{n_{RTA}} = \frac{f \cdot t}{RF \cdot t}, \qquad (1)$$

with t the duration of the task and f the average frequency of actions in the task. The average frequency is defined as the ratio of the total number of technical actions performed during a typical working cycle (e.g. the assembly of an object) to the cycle time, determined with technical considerations. The number of RTA is evaluated as the product of the duration of the task (t) times a reference frequency of technical actions during a work cycle (RF). The reference frequency is calculated taking into account the different features of the task and of the organization of the work shift. The factors considered evaluate the "lack of Recovery" due to period distribution (R_{cM}), the duration of the repetitive task during a shift (t_M), the Repetitiveness of the movements (R_{eM},), the use of Force (F_M), the type of Posture (P_M), and Additional factors (A_M) such as the use of tools causing vibrations, localized compression, cold environment, cold surface, hot surface, etc.. It is worth highlighting that, according to the technical standard, for the determination of factors F_M, P_M and A_M (≤1), it is necessary to know the fraction of the cycle time during which these risk enablers are present. These factors can assume discrete values, decreasing as the fraction of time increases. Since differences exist among workers (for example an awkward posture could be maintained longer), also these factors can vary. Therefore, these factors should be evaluated for each category of workers grouped, for example, on the basis of their overall speed in completing a cycle. The OCRA index is then representative of the ergonomic risk to which the category of worker performing a given task is exposed.

In the case of a *multitask job*, with q the total number of different tasks to be performed in a work shift, the OCRA index can be evaluated for each worker as (ISO, 2007):

$$OCRA = \sum_{p=1}^{q} f_p t_p \Bigg/ \left(k_f R_{cM} t_M \sum_{p=1}^{q} F_{Mp} P_{Mp} R_{eMp} A_{Mp} t_p \right) \qquad (2)$$

where:

f_p (average) frequency of actions per minute [min^{-1}] of task p;

t_p net duration of task p in the shift [min];

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k_f constant of frequency of technical actions per minute (30 [min^{-1}]);

R_{cM} lack of recovery multiplier;

t_M duration multiplier;

F_{Mp} force multiplier;

P_{Mp} posture multiplier;

R_{eMp} repetitiveness multiplier;

A_{Mp} additional factors multiplier;

f_p is the average frequency of actions performed to accomplish task p; therefore it can vary for each repetitive task p (1,..., q), depending both on technical constraints (how the workplace and its tools are devised) and production constraints (task time and production rate);

t_p depends on organizational and production factors which determine the task assignment of each worker in the shift;

R_{cM} can vary for each work shift according to the rest schedule, determined by organizational choices (i.e. break schedules);

t_M is dependent on the net duration of each work shift;

k_f is a constant value for each work shift;

the different multipliers (F_{Mp}, P_{Mp}, R_{eMp}, and A_{Mp}) characterize each repetitive task p on the basis of ergonomic considerations and additional factors.

4. Productivity and ergonomic risk balancing

Different solutions can be adopted to reduce the risk of WMSDs in the case of high repetitive manual tasks. Organizational solutions suggested by the standard ISO 11228 include both the reduction of the number of cycles and the redistribution of breaks within the shift. In fact, reducing the number of cycles means reducing the frequency of actions per minute. However, this solution also means increasing the cycle time, and thereby reducing the production rate. Boenzi *et al.* (2013b) developed a two step approach which aimed to find one or more job rotation and break schedule, which have the overall effect of reducing and balancing the human workload among employees, maintaining a constant level of production without taking into account differences in skill levels which employees have.

Given a daily work shift (i.e. number, duration and distribution of working time slots and planned pauses), the authors aim to demonstrate how it is possible to increase the production rate by developing appropriate job rotation schedules within the work shift and, at the same time, to reduce the risk of musculoskeletal injury for the most exposed workers.

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4.1 Problem Formulation

Let us consider a work shift, consisting of r working time slots. Two consecutive working time slots are separated by a break. The assigned duration of the work shift w_s [min] (excluding the planned pauses) is equal to the sum of the r working time slot durations w_h [min] ($h = 1, \ldots, r$).

Each manual task p ($p = 1, \ldots, q$) is performed only at the assigned workstation. Moreover, all tasks are parallel and independent (i.e. parallel lines).

We now consider m categories of operators. The operator l ($l = 1,\ldots,m$) is potentially able to perform every specific task p. In the following, we will assume that the number of technical actions necessary to realize each unit of type p is fixed, whereas the requested time can vary depending on the worker. Task completion time per unit (t_{lp} [min/u]) is a widely used measure of performance of the worker (l) in the manual repetitive task (p).

Therefore, in the most general case, each worker l could be characterized by his own specific task completion time for the assigned task p (t_{lp}). The completion time t_{lp} can be expressed as a function of the workers capability and skill:

$$t_{lp} = \alpha_{lp} t_p \qquad (3)$$

where t_p is the "nominal" task completion time and α_{lp} is the skill factor coefficient ($\alpha_{lp} \geq 1$) of the worker l for the given task p. Only in case where worker l is the most suitable for task p, his performance represents the "nominal" performance at the workstation and his skill factor assumes unitary value ($\alpha_{lp} = 1$). As a consequence, the production level required from workstation p during the working time slot h is a time dependent constraint, which may not always be fulfilled.

Taking into account ergonomic issues, for a given task completion time t_{lp} the OCRA index value related to worker l increases with his production output in any of the time slots of the work shift. In fact the number of Actual Technical Actions (ATA) during time slot h can be expressed as:

$$n_{ATA,lph} = z_{lph} n_p \qquad (4)$$

where z_{lph} [u] is the production output, and n_p [u^{-1}] the given number of technical actions per unit produced, while the number of Reference Technical Actions (RTA) may be formulated as:

$$n_{RTA,lph} = e d_{lph} w_h \qquad (5)$$

with:

$$e = k_f R_{cM} t_M \qquad (6)$$

and

$$d_{lph} = (F_M P_M R_{eM} A_M)_{lph} \qquad (7)$$

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While e value is constant for a given work shift net duration and break scheduling, d_{lph} is a decreasing function of both the production z_{lph} and of the observed cycle completion time t_{lp}. Therefore, for a given worker, increasing the production level means increasing the numerator and non-linearly decreasing the denominator of the formula because the fraction of time characterized by the presence of risk enabling factors increases.

Comparing workers' abilities for a given product output, the lower the worker's skill level, the longer the task completion time, and the higher the related OCRA index value.

4.2 Maximizing production

The model proposed is a mixed integer nonlinear programming model. Given the task completion times of all tasks and categories of operators, the desirable production output, and the ergonomic risk constraints, the model identifies one or more optimal job rotation schedules which maximize the output of the production system. At the same time the solution guarantees a reduced musculoskeletal risk for the most exposed categories of employees, and a balanced workload.

Introducing a the binary variable y_{lph} that assumes unitary value whenever worker l is assigned to task p in the working time period h, and zero otherwise, the objective function (O.F.) to be maximized is the overall production level:

$$O.F. = \underset{\{y_{lph};z_{lph}\}}{MAX} \sum_{l=1}^{m}\sum_{p=1}^{q}\sum_{h=1}^{r} y_{lph} z_{lph};$$
$$y_{lph} \in \{0;1\} \quad \forall l,p,h \qquad (8)$$

Constraints include:

a. Assignment constraints

Each worker (l) can perform only one task (p) in each working time period (h):

$$\sum_{p=1}^{q} y_{lph} = 1 \quad \forall l,h$$
$$\sum_{l=1}^{m} y_{lph} = 1 \quad \forall p,h \qquad (9)$$

b. Technological constraints

In each time period (h) the maximum (integer) number of output units from a workstation (p) depends on the skill level of the worker (l) assigned to the workstation. The maximum value is obtained by dividing the time period duration (w_h) by the task completion time (βt_{lp}). The additional factor β (>1) is introduced in order to model the uncertainty of t_{lp} due to the stochastic variability of human performance; it takes into account possible over-timing with respect to the observed value of the task completion time (t_{lp}).

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$$1 \le z_{lph} \le w_h / (\beta t_{lp}) \qquad \forall l,p,h$$
$$z_{lph} \in N \qquad \forall l,p,h \qquad (10)$$

c. Production constraints

For each work shift an admissible range of output units is settled:

$$z_p^{\min} \le z_p \le z_p^{MAX} \qquad \forall p \qquad (11)$$

where

$$z_p = \sum_{l=1}^{m} \sum_{h=1}^{r} z_{lph} \qquad \forall p \quad (12)$$

d. Ergonomic risk constraints

A maximum admissible risk index value for each operator l is considered ($OCRA_l^{MAX}$):

$$OCRA_l \le OCRA_l^{MAX} \qquad \forall l \qquad (13)$$

where

$$OCRA_l = \sum_{p=1}^{q} \sum_{h=1}^{r} y_{lph} z_{lph} n_p \Bigg/ \left(e \sum_{p=1}^{q} \sum_{h=1}^{r} y_{lph} d_{lph} w_h \right) \qquad (14)$$

e. Risk balancing constraint

An upper limit for the OCRA index values variability (CV_{OCRA}^{MAX}) is considered in order to balance the ergonomic risk among the workers:

$$CV_{OCRA} \le CV_{OCRA}^{MAX} \qquad (15)$$

where CV_{OCRA} is the coefficient of variation defined as the ratio of the standard deviation to the mean of the OCRA index values of the operators in the work shift:

$$CV_{OCRA} = \frac{\sigma_{OCRA}}{\mu_{OCRA}} \qquad (16)$$

with:

$$\sigma_{OCRA} = \sqrt{\frac{1}{m} \sum_{l=1}^{m} \left(OCRA_l - \mu_{OCRA} \right)^2} \text{ and } \mu_{OCRA} = \frac{1}{m} \sum_{l=1}^{m} OCRA_l . \qquad (17)$$

4.3 Minimizing the ergonomic risk

The problem can be easily re-formulated when the aim is to decrease the ergonomic risk. For a given level of production the objective is thus the minimization of the mean value of the OCRA index of the whole workforce.

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giorgio mossa 10/10/y 20:19 Eliminato: $CV_{OCRA} = \frac{\sigma_{OCRA}}{\mu_{OCRA}}$
giorgio mossa 10/10/y 20:19 Formattato ... [170]
giorgio mossa 10/10/y 20:19 Eliminato: $\sigma_{OCRA} = \sqrt{\frac{1}{m} \sum_{l=1}^{m} (OCRA_l -$
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$$O.F. = \min_{\{y_{lph};z_{lph}\}} \mu_{OCRA};$$

$$y_{lph} \in \{0;1\} \quad \forall l,p,h \qquad (18)$$

At the same time the balancing of the workload and of the corresponding risk among operators is guaranteed by the constraint (15). Constraints (9)-(13) complete the model.

5. CASE STUDY

In this section, a case study from the automotive industry is presented and the related human workload balancing problem in case of repetitive manual tasks is solved in order to test the capability of the model. The study refers to the production system of an international manufacturer of car seats for commercial vehicles. The system consists of dedicated manual assembly work stations (WSs), mainly in parallel. In each assembly station, the worker executes both activities requiring low physical force (e.g. fixing seat skeletons or semi finished seats or their parts into dedicated mechanical equipment) as well as movements which require exerting hand and finger force for the manual leather-dressing of seats.

Description

The car seat assembly line is operated in eight hours shifts. In each work shift four breaks are planned, so that the work shift is divided into five working time slots (η=5) (see Figure 1). The net duration of one work shift is 405 [min].

	06:00 - 14:00								
h	1		2		3		4		5
w_h [min]	80	15	80	15	95	30	80	15	70

Figure 1: Production time slots and breaks during the work shift

The reported case study refers to three parallel and independent manual assembly stations (p=1, 2, 3). In WS1 the complete setting up of a double-seat assembly is carried out. Its metallic structure is blocked on custom mechanical equipment which permits easy positional adjustments of the complex (2-axis rotation). The main assembling phases consist in lining the sitting part and the back of the seat and mounting all the required parts (seatbelts, plastic carters, etc.), utilizing electric and electronic screwdrivers and a special steam-ejecting nozzle to stretch out and refinish leather coats.

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Eliminato: $O.F. = \min_{\{y_{lph};z_{lph}\}} \mu_{OCRA};$ $y_{lph} \in \{0;1\} \quad \forall l,p,h$

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Formattato: Inglese (Regno Unito)

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Eliminato: The system consists of ... [182]

In WS2, seat backrest assembly is carried out. The three components: backrest metallic skeleton, filling and leather coat are accurately positioned onto a press device which packs the layers in various time-steps. At the end of each step, the operator must refinish the packing operation and finally stretch out leather wrinkles on the seats backrest surface with a steam nozzle.

In WS3 the final assembly of complete single-seats takes place. The operator fixes the seat in a vertical position on a rotating mechanical device and mounts all the completing parts (plastic carters, armrests, belt lock, etc.) utilizing electric and electronic screwdrivers.

The assembly stations are operated by three workers (l=1, 2, 3) each of them able to perform the three different repetitive tasks of the assembly stations. The workers can execute each task with different performances according to their skill level. Three different skill levels have been assumed: high (1,00), medium (1,15), and low (1,25). As previously stated, task completion time (t_{lp}) of worker l performing task p increases proportionally to α_{lp} (see rel. 3), with respect to an observed nominal task time (t_p) of the most skilled operator. The skill factor values (α_{lp}) and the nominal task time (t_p) are reported in table 2.

Table 2: Nominal production time t_p [s] and worker skill factors α_{lp}

α_{lp}	$p=1$	$p=2$	$p=3$
$l=1$	1,00	1,15	1,00
$l=2$	1,00	1,00	1,00
$l=3$	1,25	1,15	1,00
t_p [s]	1100	170	220

The maximum output of the assembly stations (due to technical constraints) can be obtained assigning to each workstation the most skilled worker/s. With such an assignment, the nominal (or attained) production in each time slot and in the overall work shift is shown in Table 3.

Table 3: Nominal production rate per time slot and work shift

p	l	z_{lph} $[u]$					z_p $[u]$
		$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	
1	1	4	4	5	4	3	20
2	2	26	26	30	26	22	130
3	3	21	21	26	21	19	108

The ranges of the desirable output per work shift are the following (production constraints):

$16\ [u] \le z_1 \le 20\ [u]$, $100\ [u] \le z_2 \le 130\ [u]$, $100\ [u] \le z_3 \le 108\ [u]$

The actual production schedule, which does not include job rotation, is shown in table 4.

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Eliminato: reference cycle
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Table 4: Actual production schedule

p	*l*	z_{lph} *[u]*					z_p *[u]*
		h=1	*h=2*	*h=3*	*h=4*	*h=5*	
1	1	4	4	4	4	3	19
2	2	21	21	23	21	17	103
3	3	20	20	24	20	18	102

Under the made assumptions, in the actual scenario the production capacity is not fulfilled. Moreover, the OCRA index values (see table 5) reveal that the ergonomic risk is unbalanced among the different categories of worker, each of them being included in a different class of risk (RL_1=L - Low, RL_2= U - Uncertain, RL_3=A - Acceptable).

Table 5: Ergonomic risk estimation (OCRA index and Risk Level – RL) of the actual vs nominal production rate

l	*Nominal*		*Actual*	
	$OCRA_l$	RL_l	$OCRA_l$	RL_l
1	4,9	L	3,8	L
2	4,1	L	2,7	U
3	2,8	U	2,1	A
μ_{OCRA} *[u]*	3,95		2,87	
σ_{OCRA} *[u]*	1,04		0,86	
CV_{OCRA}	0,26		0,30	

If the system is forced to produce at a rate close to the nominal one, the increase in the risk level would not be acceptable for any of the worker categories (RL_1=L, RL_2=L, RL_3=U).

Results and discussion

In the industrial context it can be useful to investigate the capability of the model in searching for suitable job rotation schedules to maximize the total production, at the same time balancing and limiting the ergonomic risk.

The model has been applied in three different scenarios illustrated below. For the first and the second scenario, the maximization problem has been formulated assuming the following upper limit values of the OCRA indexes and of the coefficient of variation CV: ($OCRA_1^{MAX}$=3,5, $OCRA_2^{MAX}$=3,5, $OCRA_3^{MAX}$=2,2) and CV^{MAX}=0,25.

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1) JRMPS - Job Rotation Maximum Production with Skills

In this scenario the different skills and training levels of the workforce are considered. This can be the case, for example, with long-time running production platforms, with a mixed aged work force, assuming that age diversity leads to different cycle times, or in the case of complex sequences of manual tasks, for which different training and ability levels substantially differentiate the workers. In table 6 one of the optimal solutions of the scheduling problem (8) is shown, with the corresponding production output. The overall production performance is increased by 5,4% if compared with the actual scenario (see table 9). At the same time the mean value of the OCRA index is slightly increased (+2,4%) while the single worker OCRA index values show lower risk levels (RL_1=U, RL_2=U, RL_3=A). It is worth noting that due to the constraints (15) a good balance of ergonomic risk is achieved (CV_{OCRA} is reduced by 28,0%, see table 10).

2) JRMP - Job Rotation Maximum Production

In order to evaluate the influence of the workers' flexibility on the maximum achievable production rate, in this scenario the operators are considered fully interchangeable, thus expanding the numbers of the admissible job rotation schedules in the solution domain. The workers are therefore assumed as equally skilled (α_{lp}=1, l=1, 2, 3 and p=1, 2, 3).

Such a scenario can be hypothesized in newly established enterprises or with very frequent turn-over, where workers' age and training can be considered more uniform and older workers' expertise is not a major concern for the nature of the performed tasks or, equivalently, when the manual task is very simple and does not require the development of particular abilities. As an example, in table 7 the job rotation and production schedule of a solution in the set of optimal solutions of (8) is illustrated. In this scenario, the perfect inter-changeability of the operators leads to six possible permutations of an optimal schedule. In this scenario the best system performances are observed: the technological constraints are saturated; the nominal production rate is reached in each time slot; the ergonomic risk level for each operator decreases if compared with the actual schedule (RL_1=U, RL_2=U, RL_3=A); finally, a great workload balance is obtained (Δ_{CV} = -47,3%). In order to pursue this optimal solution it is therefore necessary to employ flexible workers equally trained in performing all tasks.

3) JRmR - Job Rotation minimum Risk

In order to fully investigate the potentiality of the model, in this scenario the problem is now formulated with the goal of minimizing the mean value of the risk (18) satisfying the production and risk balancing constraints (15). The risk balancing upper limit considered has now therefore

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been reduced to CV_{OCRA}^{MAX} =0.1 and the workers are assumed to be equally skilled. The scenario could be referred to as a labour-intensive work environment with a high management commitment to health and safety issues. Even in this case, the model is able to find optimal solutions (table 8). Although the problem is solved with a different goal, the model is able to find a solution characterized by not only the lowest risk level (RL_1= RL_2= RL_3=A) and the highest degree of balance (Δ_{CV} = -88,0%), but which also ensures an increased production level compared to the actual scenario (Δz = +12,5%) and a negligible decrement (-2,7%) compared to the JRMP scenario solution. These results show the capability of the model in identifying the opportunities of job rotation guaranteed by the greater flexibility of the operators.

Table 6: Job rotation and production schedule obtained in the JRMPS scenario

p	*l*	z_{lph} [u]					z_p* [u]
		h=1	*h=2*	*h=3*	*h=4*	*h=5*	
1	1	-	4	5	-	-	20
	2	4	-	-	4	3	
	3	-	-	-	-	-	
2	1	22	-	-	22	-	111
	2	-	26		-	-	
	3	-	-	23	-	18	
3	1	-	-	-	-	19	105
	2	-	-	26	-	-	
	3	20	20	-	20	-	

Table 7: Job rotation and production schedule in the JRMP scenario

p	*l*	z_{lph} [u]					z_p* [u]
		h=1	*h=2*	*h=3*	*h=4*	*h=5*	
1	1	-	-	5	4	3	20
	2	4	4	-	-	-	
	3	-	-	-	-	-	
2	1	-	-	-	-	-	130
	2	-	-	30	26	-	
	3	26	26	-	-	22	
3	1	21	21	-	-	-	108
	2	-	-	-	-	19	
	3	-	-	26	21	-	

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Table 8: Job rotation and production schedule in the JRmR scenario

p	l	z_{lph} $[u]$					z_p* $[u]$
		$h=1$	$h=2$	$h=3$	$h=4$	$h=5$	
1	1	-	-	-	4	4	17
	2	-	-	-	-	-	
	3	3	3	3	-	-	
2	1	-	-	-	-	-	127
	2	26	26	27	-	-	
	3	-	-	-	26	22	
3	1	21	21	26	-	-	108
	2	-	-	-	21	19	
	3	-	-	-	-	-	

Table 9: Production output estimation for different scheduling solutions

p	*Actual*	*JRMPS*		*JRMP*		*JRmR*	
	z_p $[u]$	z_p $[u]$	$\Delta z\%$	z_p $[u]$	$\Delta z\%$	z_p $[u]$	$\Delta z\%$
1	19	20	*5,3%*	20	*5,3%*	17	*-10,5%*
2	103	111	*7,8%*	130	*26,2%*	127	*23,3%*
3	102	105	*2,9%*	108	*5,9%*	108	*5,9%*
z_{TOT}	224	236	*5,4%*	258	*15,2%*	252	*12,5%*

Table 10: Ergonomic risk comparison (OCRA index and risk level – RL) for different scheduling solutions

l	*Actual*		*JRMPS*		*JRMP*		*JRmR*	
	$OCRA_l$	RL_l	$OCRA_l$	RL_l	$OCRA_l$	RL_l	$OCRA_l$	RL_l
1	3,8	L	3,3	U	2,8	U	2,1	A
2	2,7	U	3,3	U	3,0	U	2,2	A
3	2,1	A	2,2	A	2,2	A	2,1	A
				$\Delta\%$		$\Delta\%$		$\Delta\%$
μ_{OCRA} $[u]$	2,87		2,93	*2,3%*	2,65	*-7,6%*	2,12	*-26,2%*
σ_{OCRA} $[u]$	0,86		0,64	*-26,3%*	0,42	*-51,2%*	0,08	*-91,1%*
CV_{OCRA}	0,30		0,22	*-28,0%*	0,16	*-47,3%*	0,04	*-88,0%*

6. CONCLUSIONS

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In this paper, a dual approach to the ergonomic job rotation scheduling problem is proposed in work environments characterized by high repetitive - low load manual tasks with high frequency of repetition. Workload risk and its acceptability are evaluated by means of the OCRA method. The mixed integer nonlinear programming model takes into account the specific performance of the workers due to training levels and skills. The problem formulation and its solutions show great flexibility in choosing which one of the two inter-connected aspects should deserve major attention, e.g. finding production maximization solutions under ergonomic constraints or, vice-versa, average risk level minimization solutions, under production constraints. The production-oriented formulation of the problem maximizes the production rate while assigning most suitable operators to workstations in each working time slot of the shift. Results show how it is possible to increase productivity as well as to reduce and balance ergonomic risk through an appropriate rotation of workers. Conversely, the dual formulation of the problem makes it possible to significantly reduce the ergonomic risk maintaining the production level under given production constraints.

Results suggest that the effectiveness of the optimal solutions can be significantly increased when flexible workers are employed, thus demonstrating the importance of worker training for both productivity and ergonomic purposes.

Future work will include dynamic variability of human performance during the work shift, due to phenomena such as learning, forgetting, tiredness, and recovery. The integration of ergonomic issues in classical line balancing procedures is expected to be a new, wide field of interest especially in the view of an aging workforce .

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