A method to design job rotation schedules to prevent work-related musculoskeletal disorders in repetitive work

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Job rotation is an organizational strategy widely used in human-based production lines with the aim of preventing Work-related Musculoskeletal Disorders (WMSDs). These work environments are characterized by the presence of a high repetition of movements, which is a major risk factor associated with WMSDs. This article presents a genetic algorithm to obtain rotation schedules aimed at preventing WMSDs in such environments. To do this, it combines the effectiveness of genetic algorithms optimization with the ability to evaluate the presence of risk by repeated movements by following the OCRA ergonomic assessment method. The proposed algorithm can design solutions in which workers will switch jobs with high repeatability of movements with other less demanding jobs that support their recovery. In addition, these solutions are able to diversify the tasks performed by workers during the day, consider their disabilities and comply with restrictions arising from the work organisation.

Keywords: job rotation; OCRA index; upper-limb musculoskeletal disorders

1. Introduction

Job rotation is a preventive strategy that is increasingly used as an alternative to the

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redesign of critical jobs. It is an organizational strategy widely used in human-based production lines with assembly operations and manufacturing processes characterized by high repeatability of movements (Michalos et al., 2010; Asensio-Cuesta et al., 2011).

1.1 Job rotation and Work-related Musculoskeletal Disorders

Job rotation allows workers to occupy different positions throughout the day. Switching jobs, if the rotation plan is well designed, helps prevent Work-related Musculoskeletal Disorders (WMSDs) by reducing the amplitude of the risk and the duration of the exposure of workers to risk factors associated with these types of ailments, among them include: the repeatability of movements (Bernard, 1998; Occhipinti, 1998; Colombini 2002), load lifting (Waters et al., 1993), or the adoption of awkward or static postures (McAtamney et al., 1993). Furthermore, this technique allows including workers with disabilities (Costa and Miralles, 2009), reduces monotony and boredom (Azizi et al., 2010), decreases absenteeism, increases training of workers (Cunningham and Eberle, 1990) and satisfaction, and reduces stress (Risser et al., 2002).

The workers' exposure to repetitive movements is an important risk factor that can lead to WMSDs on the neck, shoulders (Ohlsson et al., 94), elbow, hand / wrist and even, to a lesser extent, in the back (Xiao et al., 2004), causing epicondylitis (Shir et al. 2006), tendonitis (Latka et al., 1999) or carpal tunnel syndrome (Bonfiglioli et al., 2007). Currently there are several ergonomic evaluation methods for determining the level of risk to which workers are exposed due to performing repetitive movements, such as: the JSI (Job Strain Index) (Moore et al., 1995) the OCRA method and Check List OCRA (Colombini et al., 2002), the Sue Rodgers' method (Rodgers, 1992) and the widespread method in the European automobile industry called European Assembly Worksheet (EAWS) (Otto and Scholl, 2011).

2.1 Optimization approaches

The design of rotating job schedules beneficial to the health of workers requires, in most cases, the application of combinatorial optimization techniques due to the large number of factors to consider. For example, Carnahan et al. (2000) develop a genetic algorithm to design schedules of rotation jobs to prevent back injuries. Carnahan´s algorithm calculates the risk level for lifting tasks in each workstation by means of the Job Severity Index ergonomic method (Liles, 1986). That index considers the ratio between the weight that the worker must raise and the weight that is enabled to rise. On the other hand, Triggs (Triggs et al., 2000) suggests the Job Strain Index (Moore et al., 1995) and the NIOSH equation (Waters et al., 1993) to classify workstations for designing job rotation schedules. The first method evaluates the repetitiveness risk level and NIOSH equation the risk level due to lifting tasks. Kullpattaranirun and Nanthavanij (2005) propose a heuristic algorithm for reducing noise exposure to workers. Yaoyuenyong and Nanthavanij (2006) present four solution algorithms (three approximations and one exact solution) for job rotation schedules that also minimize noise exposure for workers. Tharmmaphornphilas proposes a entire programming model (Tharmmaphornphilas et al., 2004) and a method that uses heuristics for developing robust job rotation schedules to reduce the likelihood of low back injury due to lifting (Tharmmaphornphilas et al., 2007), this author also evaluates the risk for lifting tasks in work stations with the Job Severity Index. Seçkiner applied a simulated annealing algorithm (Seçkiner et al., 2007) and an ant colony algorithm (Seçkiner et al., 2008) to generate rotation schedules to minimize the workload. Aryanezhad et al. (2009) developed a multiobjective integer programming model for designing rotation schedules to consider, simultaneously, the noise exposure and back injuries of workers. Diego-Mas et al. (2009) proposed a genetic algorithm to generate rotation schedules to prevent the accumulation of fatigue due to repetition of movements. Azizi et al. (2010) presented a mathematical programming model for job rotation in manufacturing systems that aims to ease employee's boredom and exploit the effect of rotation intervals on worker's skill learning and forgetting. Costa and Miralles (2009) proposed models and algorithms for obtaining rotation schedules focused on the integration of disabled workers. Asensio-Cuesta et al. (2011) proposed a genetic algorithm with the same goal. Michalos et al. (2010) developed an algorithm for obtaining rotation schedules that optimize multiple criteria such as skills, the accumulation of fatigue, repeatability, the distance between jobs, and cost. [Insert figure 1 about here]

This article presents a genetic algorithm (GA) to design rotation schedules that allow preventing WMSDs in environments characterized by high repeatability of movements. The proposed algorithm evaluates the level of exposure to the repetitive movement of workers in a rotation schedule using the OCRA (Colombini et al. 2002; UNE-EN 1005-5:2007, ISO 11228-3:2007). The OCRA method evaluates the main collective risk factors (frequency of action, awkward postures and movements of the upper limbs, excessive use of force, 'stereotypy' or lack of postural variation, inadequate recovery periods) based on their respective duration. Other additional factors are considered, such as mechanical, environmental, and organizational factors providing evidence of causal relationship with WMSDs. Taken together, these factors characterize the worker's exposure in relation to task duration (Colombini and Occhipinti, 2006). Therefore, OCRA method is a useful tool to calculate the workers exposure when they are assigned to different workstations every certain period of time following a job rotation scheduler. Besides OCRA method is widely used by technical specialists (occupational safety and health operators, ergonomists, methods and time analysts, production engineers) for risk management and for task/workplace (re)design purposes. Finally, the selection of the

OCRA method for assessing workstations´s repetitiveness risk level is due to its growing popularity and value in the field of ergonomics. This method is included in the UNE-EN 1005-5:2007 and ISO 11228-3:2007 standards.

2. Material and methods

The method presented in this work to design job rotation schedules is based on a GA. Before applying a GA to a particular problem, some items must be defined: the solutions (or individuals) encoding procedure, the process for generating the initial population of solutions, the function to assess the fitness of the solutions, the method for selecting individuals to form a new generation of solutions, and the crossover and mutation operators. Next, all these items and the GA proposed are described.

2.1. Encoding of solutions and generating the initial population

The initial population is obtained as a set of individuals (job rotation schedules) represented by arrays of size $\mathbf{n_{wor} \cdot n_{rot}}$, where $\mathbf{n_{wor}}$ is the number of workers and $\mathbf{n_{rot}}$ the number of rotations. Each cell in the array contains a value that indicates the position assigned to a worker $\mathbf{x}$ on a rotation $\mathbf{r}$. Positions are assigned to cells in the array at random, avoiding that the same position is repeated in the same column. Otherwise, this solution would not be valid since the same position had been allocated to different workers in the same rotation. Number of individuals of the initial population ($\mathbf{n}$) depends on the characteristics of the problem and its value should be determined experimentally.

2.2. Evaluation function (fitness)

In the algorithm proposed, computing the fitness (F) of a solution consists of three parts (Equation 1). The first part calculates the risk by repetition of movements for the right side of the body (**F_{right}**) and the second performs the same calculation for the left (**F_{left}**). The fitness for each side of the body is obtained using Equation 2. In general, movements required of a worker in a job are not symmetrical, and therefore, neither is their risk. The third part of Equation 1 (**$N_{rep} \cdot C_m$**) gives the degree of monotony in a solution. The fitness value increases with the number of positions that are assigned in more than one rotation to the same worker (**N_{rep}**) and a coefficient (**C_m**). This is intended to provide solutions that reduce the monotony, avoiding that workers are assigned to the same position throughout the day. The coefficient **C_m** allows to determine the importance to be given to the psychosocial factor "flatness" as opposed to the physical factor "repetition". The lower fitness value the better is the solution, so that, the algorithm will try to minimize F.

$$F = F_{right} + F_{left} + N_{rep} \cdot C_m \qquad (1)$$

Equation 2 calculates the risk by repetition of movements each side of the body. In this equation, **s** ϵ{right, left}, **F_s** is the fitness for the side **s** of the body, **n_{wor}** is the number of workers, **C_s** is the coefficient of relative importance of the side **s** of the body, and **u** is an uniformity coefficient. **OCRA(x)** is the multitasking OCRA index for the worker **x**, calculated by means of Equation 3, and **RLV(x)** the variability of the risk level among tasks assigned to the worker **x** along the rotations (Equation 6).

OCRA index calculates the risk level due to repetitive movements when a worker performs different tasks with different durations. It is therefore appropriate to assess the overall exposure of a worker who rotates among the different jobs each rotation period in which repetitive movements are required.

$$F_s = C_s \cdot \sum_{x=1}^{n_{wor}} (OCRA(x) + RLV(x))^u \tag{2}$$

$$OCRA(x) = \frac{ATA(x)}{RTA(x)} \tag{3}$$

The multitasking OCRA index is the quotient of two values (Colombini et al. 2002): **ATA(x)** (the number of technical actions performed by the worker **x**) and **RTA(x)** (the number of reference technical actions performed by the worker **x**). Equation 4 calculates **ATA(x).** In this equation **p(x, r)** is the position assigned to worker **x** in the rotation **r**, **FF(p(x,r))** is the number of actions per minute required by the job assigned to worker **x** in the rotation **r**, and **t(r)** is the duration of the rotation **r**.

$$ATA(x) = \sum_{r=1}^{n_{rot}} FF(p(x,r)) \cdot t(r) \tag{4}$$

RTA(x) is calculated by means of Equation 5, where **CF** is a "constant of frequency" of technical actions per minute fixed at 30 actions/min (ISO 11228-3:2007), **FM(p(x,r))** is the factor of strength risk for the job hold by the worker **x** in the rotation **r**, **PM(p(x,r))** is the factor of posture risk for the job hold by the worker **x** in the rotation **r**, **RM(p(x,r))** is the factor of repeatability risk for the job hold by the worker **x** in the rotation **r**, **AM(p(x,r))** is the factor of addtional risks for the job hold by the worker **x** in the rotation **r**, **RMc** is the risk factor about "lack of recovery periods" referred to all throughout the day. A recovery period is a period during which one or more muscle-tendon groups are basically at rest, such as: pauses (both official and non-official), including lunch break; periods during which the working tasks carried out leave the muscles previously employed in other tasks at rest (e.g., visual controls, administrative tasks) (Colombini et al. 2002). Finally, **DMu** is the factor for total length of repetitive tasks in a day.

$$RTA(x) = \sum_{r=1}^{n_{rot}} [CF \cdot (FM(p(x,r)) \cdot PM(p(x,r)) \cdot RM(p(x,r)) \cdot AM(p(x,r))) \cdot t(r)] \cdot (RMc \cdot DMu) \quad (5)$$

Table 1. Risk variability values

		Rotation **r+1** task risk level		
		Low	Medium	High
Rotation **r** task risk level	Low	Inc1	Inc1	Inc1
	Medium	Inc1	Inc2	Inc4
	High	Inc1	Inc3	Inc5

RLV(x), the variability of the risk level among positions assigned to the worker **x** along the rotations, used in Equation 3, is calculated by means of Equation 6.

$$RLV(x) = \sum_{r=1}^{n_{rot}-1} Variability(r, r+1) \cdot \frac{t(r) + t(r+1)}{D} - Dp_{r,r+1} \quad (6)$$

In this equation **Variability(r,r+1)** value depends on OCRA risk levels of the tasks carried out by worker **x** in two consecutive rotations. OCRA risk level of a task depends on the value of its OCRA index (Colombini et al. 2002). If OCRA index is lesser than 2.3 task risk level is *Low*. Risk level is *Medium* if OCRA index is between 2.3 and 3.5, and *High* if OCRA index is bigger than 3.5. **Variability(r,r+1)** takes values as it is showed in Table 1. Increases $\mathbf{inc_i}$ will take values depending on the problem and should be determined experimentally, but it must have: $\mathbf{inc_1} \leq \mathbf{inc_2} \leq \mathbf{inc_3} \leq \mathbf{inc_4} \leq \mathbf{inc_5}$. The increases ($\mathbf{inc_i}$) values affect the algorithm optimization search. For instance, if increases values are high the algorithm will considered variability criterion more important than reduction repetitiveness criterion. In the other hand, if increases values were too low, variability will be underestimated by the algorithm. This way is intended to be better valued solutions where there are transitions between levels of risk which could be beneficial to workers. That is, solutions with jobs that alternate medium/high risk level jobs with low risk level jobs will be better valued than those in which workers remain at medium/high risk levels in consecutive rotations. The *Variability* decreases ($\mathbf{Dp_{r,r+1}}$) if there is a pause between the rotations **r** and **r+1**, because in that case, though workers hold demanding jobs in consecutive rotations, the pause allows them to recover from cumulative fatigue before taking again a demanding job. The decrease $D\mathbf{p_{r,r+1}}$ will depend on the length of the pause.

Equation 2 uses the multitask OCRA index to determine the risk to which workers are exposed because of repeatability. Multitask OCRA index is a version of the OCRA index that determines the risk to a worker when performing several repetitive tasks throughout the day. Moreover, Equation 2 uses the OCRA indexes of jobs to determine the degree of variability between levels of risk present in a solution (**RLV(x)**). OCRA index associated with a position is obtained by considering the total length of repetitive movements in a day.

Multitask OCRA index applied to obtain the first term of Equation 2 (**OCRA (x)**) does not consider that the order in the allocations of jobs can influence the goodness of solutions. Thus, with the same conditions, two solutions $\mathbf{s_1}$ y $\mathbf{s_2}$ would be valued with the same OCRA index if: in $\mathbf{s_1}$ a worker is assigned to tasks with high repeatability on two consecutive rotations, and later was assigned to a task with little repeatability, while in $\mathbf{s_2}$ a worker first held a job with high repeatability, and after moved to a position of low repeatability, and finally, again occupied a position with high repeatability. However, from the standpoint of worker recovery, the solution $\mathbf{s_2}$ would be better than $\mathbf{s_1}$ as a light job could allow the worker to recover from accumulated fatigue before taking another demanding position. To facilitate the search for solutions that include such beneficial variation between risk levels, the second term (**RVL (x)**) has been included in Equation 2. The value of **RVL (x)** will be greater if workers are assigned, in consecutive rotations, to jobs with levels of high or medium risk, and lower if workers alternate jobs with levels of high/medium risk and jobs with low risk levels. In Equation 2 the coefficient $\mathbf{C_s}$ is introduced to favor risk minimization for one of the sides of the body. The coefficient **u** is defined to avoid unbalanced solutions, i.e., advantageous solutions for some workers from the rest.

2.2.1. Application of penalties

The evaluation function defined for the calculation of fitness would welcome a solution where there was a worker assigned to the same job with low risk level in consecutive rotations. This solution would not meet the alternation between different jobs needed to achieve the expected benefits of the rotation. A parameter $\mathbf{t_{max}}$ (maximum time of continuous stay in the same job) is introduced to avoid repeating the same task in consecutive rotations. If the total duration of holding the same task exceeds $\mathbf{t_{max}}$ the individual is penalized by increasing their fitness so that the probability of being selected to move to the next generation is zero.

There may be assignments that should be avoided because of incompatibilities between the capabilities of workers and physical, mental and/or communication demands of jobs. Organizational reasons may also discourage certain worker-job assignments. Unwanted assignments connected with abilities, along with those due to other reasons, are called "set of vetoed assignments". The algorithm evaluates each individual in the population and penalizes those that contain assignments included in this set preventing to be part of the new generation.

2.3 Selection and replacement procedure

Once assessed and penalized individuals in the population, we should select who will survive and advance to next generation (survivors), and those on which the operator "crossover" will act (parents). For this, the algorithm uses the roulette wheel selection (Goldberg, 1989). In this selection procedure the probability of an individual being selected is inversely proportional to its fitness, since the algorithm seeks to minimize this value.

Moreover, the best solutions of a generation are always selected to survive in the next (elite). The number of elite individuals is determined by the parameter $\mathbf{I_e}$. The parameter $\mathbf{p_c}$ (crossover probability) indicates the number of individuals of the next generation that will be created by crossover. In the new generation $\mathbf{n \cdot p_c}$ individuals will be offspring of the previous generation, $\mathbf{n \cdot (1- p_c) - I_e}$ will be surviving individuals of the previous generation, and $\mathbf{I_e}$ will be elite individuals.

2.4 Crossover

The crossing operator works by selecting $\mathbf{n \cdot p_c}$ parents at random and grouping in pairs. For each pair of parents, encoded as an array $\mathbf{n_{wor} \cdot n_{rot}}$, a crossing point is chosen as a random number between 1 and $\mathbf{n_{rot}-1}$. The offspring is obtained by combining the rotations (matrix columns) that are on the left and right of the crossing point in each of the parents. This way of making the crossover prevents a single worker is assigned to two different positions in one rotation.

2.5 Mutation

The mutation operator applies to randomly selected individuals from among the individuals forming the new generation offspring ($\mathbf{n \cdot p_c}$), survivors ($\mathbf{n \cdot (1- p_c)}$) and elite $\mathbf{I_e}$. The number of individuals to whom the mutation operator will be applied is determined by the parameter $\mathbf{p_m}$ (mutation probability), so that will mutate $\mathbf{n} \cdot \mathbf{p_m}$ individuals. The mutation operator works by randomly selecting one rotation and two workers and exchanging the jobs allocated to workers in this rotation. For each individual, as many exchanges are performed as specified by the parameter $\mathbf{i_m}$ (mutation intensity).

3. Case study

The case study is located in an automobile parts assembly line. The line has five critical jobs requiring a high repetition of movements, in particular the positions labelled 1, 2, 3, 6 and 12 (Tables 2 and 3).

Positions 1, 2 and 5 required to extend the right wrist more than 45º for more than half the cycle time[1]. Position 1 also caused compression of the skin to the worker throughout the cycle time. Positions 3, 6, 9 and 14 had a cycle time of less than 15 seconds. At position 11 there was very weak force application and required to wear gloves all the time cycle. Finally, position 12 required elbow pronation of more than 60° half of the cycle time and used a tool that transmitted vibration. In all other positions there were not observed inadequate working conditions according to the OCRA method.

To schedule rotations the responsible for production selected 14 line positions and 14 workers, each position was occupied by a single worker. All workers were able to perform the tasks required in all positions, however, the worker 14 was in a recovery process from a slight musculoskeletal injury at his elbow that did not advise to hold jobs with high risk level. Meanwhile the worker 7 had vision problems that kept him from holding the position 13, and some problems in the extension movement of the wrist

[1] Cycle time: time-lag from the time when an operator starts a cycle of work until that the same work cycle begins again.

prevented him to hold the positions 1, 2 and 5. Workers 6, 11, 2, 5 and 10 were exposed to high levels of risk holding all day critical positions 1, 2, 3, 6 and 12. This represented a probability of musculoskeletal disorders of more than double in a population not exposed to performing repetitive movements (ISO 11228-3:2007).

The working day was 8 hours (480 minutes) with an hour break for lunch. For organizational reasons it was scheduled 4 rotations, the first three of 2 hours and the last of 1 hour, placing the break after the second rotation.

Table 2. Values of the parameters used in the experimentation phase

	Parameter	Definition	Value
Genetic Algorithm	n_{wor}, n_{rot}	Number of workers. Number of rotations	16
	Gen	Number of generations after which the algorithm will stop	10000
	n	Individuals in each generation	50
	p_c	Probability of crossing	0.6
	p_m	Probability of mutation	0.3
	i_m	Intensity of mutation	2
	I_e	Intensity of the elitism	1
Problem Data	D	Turn duration (excluding breaks)	420 min.
	P_a	Breaks	60 min.
	t_{nr}	Non-repetitive work time	0 min.
	t_{rec}	Time of recovery work	0 min.
	D_u	Net total duration of repetitive work ($D\text{-}P_a$ t_{nr} - t_{rec})	420 min.
	t_1, t_2, t_3, t_4	Duration of rotation 1, 2 and 3	2 hours
	t_4	Duration of rotation 4	1 hours
	$p_{2,3}$	Pause between rotations 2 and 3	1 hour
	t_{sr}	Working time without recovery	4 hours
	t_{max}	Maximum consecutive stay in the same position	4 hours
Fitness calculation	C_{right}	Coefficient of relative importance of the right side	1
	C_{left}	Coefficient of relative importance of the left side	1
	C_m	Coefficient of importance of the monotony	1
	Inc1	Increment for shifting from a position with any risk level to a position with low risk or from a position with low risk level to a position with any risk	0
	Inc_2	Increment for shifting from a position with medium risk level to a position with medium risk	2
	Inc_3	Increment for shifting from a position with high risk level to a position with medium risk	2
	Inc_4	Increment for shifting from a position with medium risk level to a position with high risk	3
	Inc_5	Increment for shifting from a position with high risk level to a position with high risk	4
	$Dp_{2,3}$	Decrement if there is pause between rotations	1

Table 3. Values of multipliers and OCRA index for the jobs 1 to 7

		Job						
Multiplier	Definition	1	2	3	4	5	6	7
PM_R	Multiplier of posture (right)	0.6	0.6	1	1	0.6	1	1
PM_L	Multiplier of posture (left)	1	1	1	1	1	1	1
RM_R	Multiplier of repeatability (right)	1	1	0.7	1	1	0.7	1
RM_L	Multiplier of repeatability (left)	1	1	0.7	1	1	0.7	1
AM_R	Multiplier of additional factors (right)	0.9	1	1	1	1	1	1
AM_L	Multiplier of additional factors (left)	1	1	1	1	1	1	1
FM_R	Multiplier of force (right)	1	1	1	1	1	1	1
FM_L	Multiplier of force (left)	1	1	1	1	1	1	1
FFM_R	Frequency (right)	40	40	53	60	30	45	50
FM_L	Frequency (left)	30	30	53	60	30	45	50
DM	Multiplier of duration (8-h workday)	1	1	1	1	1	1	1
RM	Multiplier of recovery (4 h. without recovery)	0.6	0.6	0.6	0.6	0.6	0.6	0.6
$OCRA_R$	OCRA index single task (right)	4.12	3.7	4.21	3.33	2.78	3.57	2.78
$OCRA_L$	OCRA index single task (left)	1.67	1.67	4.21	3.33	1.67	3.57	2.78

Table 4. Values of multipliers and OCRA index for the jobs 8 to 14

		Job						
Multiplier	Definition	8	9	10	11	12	13	14
PM_R	Multiplier of posture (right)	1	1	1	1	0.7	1	1
PM_L	Multiplier of posture (left)	1	1	1	1	1	1	1
RM_R	Multiplier of repeatability (right)	1	0.7	0.7	1	1	1	0.7
RM_L	Multiplier of repeatability (left)	1	0.7	0.7	1	1	1	0.7
AM_R	Multiplier of additional factors (right)	1	1	1	0.9	0.9	1	1
AM_L	Multiplier of additional factors (left)	1	1	1	0.9	1	1	1
FM_R	Multiplier of force (right)	1	0.85	1	0.85	1	1	1
FM_L	Multiplier of force (left)	1	1	1	1	1	1	1
FFM_R	Frequency (right)	35	30	20	40	40	30	35
FFM_L	Frequency (left)	35	30	20	40	40	30	35
DM	Multiplier of duration (8-h workday)	1	1	1	1	1	1	1
RM	Multiplier of recovery (4 h. without recovery)	0.6	0.6	0.6	0.6	0.6	0.6	0.6
$OCRA_R$	OCRA index single task (right)	1.94	2.8	1.59	2.9	3.53	1.67	2.78
$OCRA_L$	OCRA index single task (left)	1.94	2.38	1.59	2.47	2.22	1.67	2.78

3.1 Runtime parameters

The number of parameters controlling a run of the proposed algorithm is high, given that, apart from the usual parameters of a GA (number of generations, population size, crossover and mutation probabilities), there are other parameters derived from specifications of the problem, the OCRA method used in the evaluation function (Tables 3 and 4) and the application of penalties. Table 2 shows the parameters used in the experimentation phase.

The OCRA method assesses risk based on the frequency of technical actions[2] required in the positions and the presence of the following risk factors: awkward postures, repeatability of movements, use of gloves, precision exercises, exposure to cold, application of force, duration of the workday and number of hours without recovery. The method associates a multiplier to each factor. The value of these multipliers are tabulated (UNE-EN 1005-5:2007, ISO 11228-3:2007) and reflects how much the actual working conditions in a position deviate regarding acceptable working conditions. Tables 3 and 4 collect the information needed to calculate the OCRA index (Equation 1).

3.2 Results

The time spent by the algorithm to complete 10 runs with the parameters given in Table 2 was 1 hour and 14 minutes on a PC with 2.27 GHz processor and 4 GB of RAM. In all runs the algorithm was able to find a suboptimal solution that met the constraints due to the existence of workers with disabilities and the maximum continuous stay in the jobs. The average fitness was 96.251 and the best fitness reached was 96 (Table 5). The average fitness for the right side was 62.132 and 34.115 for the left, indicating an increased risk to the right side. The best solution was found in the run 8 (E_8) with a

[2] Technical action: elementary manual actions required to complete the operations within the work cycle, such as maintaining, rotate, push, cut (ISO 11228-3:2007).

fitness of 95.99 (Table 6). The algorithm took 7 minutes to reach a solution after running 10000 generations.

Table 5. Summary of results for 10 runs of the algorithm.

Run	Generation	Time (minutes)	Fitness (right)	Fitness (left)	Fitness (F)
1	6588	8	62.38	34.91	97.29
2	5437	7	62.44	33.46	95.90
3	8378	8	61.94	33.52	95.47
4	7123	7	61.96	33.48	95.45
5	9815	8	62.5	34.07	96.56
6	8499	7	61.94	33.95	95.89
7	7489	7	61.87	34.5	96.37
8	**9983**	**7**	**61.93**	**34.06**	**95.99**
9	4373	8	61.89	34.96	96.85
10	3322	7	62.47	34.24	96.72
Average values	7100.7	7.4	62.13	34.11	96.24

Table 6. Best solution corresponding to run 8 (E_8).

Allocations (solution E_8)					Right		Left	
Worker	Rot. 1	Rot. 2	Rot. 3	Rot. 4	OCRA index	Variability	OCRA index	Variability
1	14	1	13	6	2.73	1.50	2.14	0.0
2	2	11	12	7	3.23	2.75	2.21	0.0
3	11	8	3	5	2.87	0.75	2.56	0.0
4	12	7	2	11	3.19	2.75	2.25	0.0
5	8	3	5	4	2.94	1.25	2.57	0.0
6	13	6	10	9	2.27	0.00	2.22	0.0
7	3	10	6	8	2.90	0.00	2.90	0.0
8	1	4	8	3	3.10	1.00	2.51	0.0
9	7	12	4	2	3.22	3.13	2.62	0.0
10	6	13	1	14	2.84	0.75	2.23	0.0
11	5	14	9	10	2.60	1.50	2.12	0.5
12	10	9	11	1	2.62	1.63	2.08	0.5
13	4	2	7	12	3.24	3.13	2.54	0.0
14	9	5	14	13	2.55	1.50	2.11	0.0
			Average		2.878	1.545	2.361	0.071
			Standard deviation		0.288	1.013	0.241	0.174
Fitness (F): 95.99; Fitness Right (F_{Right}): 61.93; Fitness Left (F_{Left}): 34.06								
Legend: ■ High risk ▒ Medium risk □ Low risk								

We compared the exposure levels of workers without rotation with the levels corresponding to the solution E_8 (Figure 2), and noted that the solution E_8 balanced risk exposure among workers. It was able to prevent workers be exposed to levels of unacceptable risk (with OCRA index greater than 3.5). Moreover, the solution E_8 introduced variability of risk levels so that workers assigned to high risk jobs were always assigned to tasks with less risk by helping their recovery (Table 6).

Since no study cases were found in the literature whose results could be compared with those provided by the algorithm, we decided to compare the values obtained in 10 runs with the values of 10000 suitable individuals randomly generated. For these individuals the same equipment and same parameters used in the 10 runs (Table 2) were used, except those specific to the genetic algorithm. We also considered the constraints on the allocation of workers 7 and 14. The 10000 random individuals were generated and evaluated in 3 hours and 44 minutes. Average fitness was 117.62 with a standard deviation of 3.59. Average fitness for the right side of body was 67.51 and 44.21 for the left side. The best fitness obtained was 105.28 (Table 7).

Table 7. Best solution of the 10000 random solutions (E_R).

Allocations (solution E_R)					Right		Left	
Worker	Rot. 1	Rot. 2	Rot. 3	Rot. 4	OCRA index	Variability	OCRA index	Variability
1	7	1	9	1	3.23	3.13	2.17	0.00
2	10	12	1	5	2.94	2.25	1.82	0.00
3	3	9	4	14	3.37	2.25	3.24	3.25
4	4	10	12	9	2.85	0.75	2.46	0.00
5	14	7	11	12	2.90	2.63	2.60	1.5
6	9	5	3	10	3.04	2.00	2.48	0.00
7	12	3	8	7	3.00	2.00	2.66	0.00
8	11	2	14	8	2.87	2.00	2.20	0.00
9	2	11	13	6	2.71	1.00	2.09	0.00
10	5	14	10	3	2.64	1.00	2.25	0.00
11	6	8	6	13	2.68	0.00	2.68	0.00
12	8	6	7	2	2.78	1.63	2.52	1.00
13	1	13	2	4	2.95	0.75	1.90	0.00
14	13	4	5	11	2.61	1.25	2.25	0.00
			Average		2.89	1.61	2.38	0.41
			Standard deviation		0.21	0.82	0.35	0.90
Fitness (F): 105.28;Fitness Right (F_{Right}): 63.20; Fitness Left (F_{Left}): 39.08								
Legend: High risk; Medium risk; Low risk								

The algorithm allowed to find a solution with better fitness (96) that the random procedure (105.29), and in much less time (7 minutes vs. 3 hours and 44 minutes). In the solution E_8 no worker held the same job more than one rotation, even in the case of workers with limitations, thus avoiding the monotony. However, in the solution E_R workers 1 and 11 repeated assignment to the same place and at high risk for the right side of the body. The solution E_8 presented for both sides of the body greater variability between levels of risk than the solution E_R, allowing workers to better recovery from cumulative fatigue. In E_8 no worker was assigned to tasks with high risk for right or left side of the body in consecutive rotations, while in E_R that situation was observed for the right side of the body for workers 2, 7 and 10. In E_8 two workers held jobs with medium levels of risk (right side) in three consecutive rotations, and in E_R such situation was observed for three workers.

Figure 1. Optimization techniques applied to generate job rotation schedules

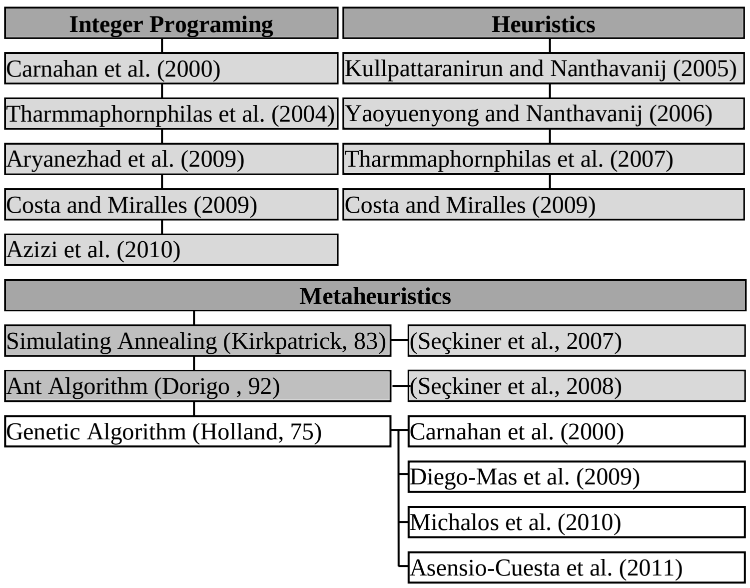
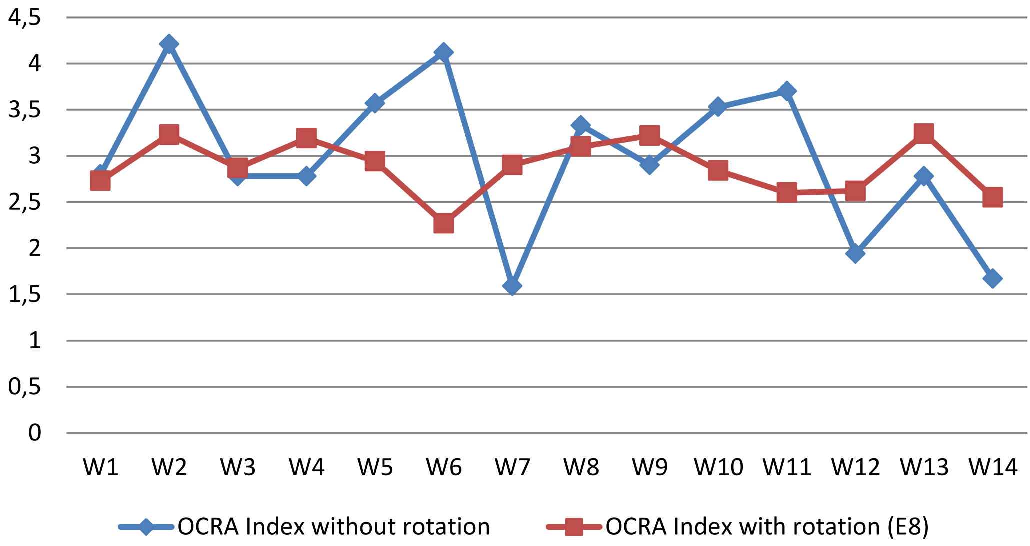


Figure 2. Multitask OCRA index without rotation and with rotation as defined E_8.



4. Discussion

The development of a rotation schedule is not an easy job due to the large number of criteria that must be considered, as well as the large number of restrictions that must be imposed in order to obtain practical results. If the number of involved workstations is high, the number of possible combinations is huge, and the best solution has to be searched among millions of feasible solutions. Planners must be careful when establishing a rotation schedule; if the rotation program is not properly designed, it can have a negative effect on the working conditions. In this sense, the proposed program helps the planner to decide considering all the factors involved in obtaining a good solution.

In evaluating the solutions, the algorithm presented in this paper considers not only the assignation of each worker in each shift, but also the assignment sequence. The order in the allocations of jobs can influence the goodness of solutions because could allow the worker to recover from accumulated fatigue. The algorithm also account for the temporary or permanent disabilities of workers for certain jobs.

The suggested procedure requires an initial effort for the evaluation of the workstations involved in the rotations. If this information is available from previous studies carried out by ergonomic staff of the plant, the calculation of different job rotation schedules is a simple task using the algorithm proposed in this study. OCRA method has been proposed as a standard for assessment of repetitive works in the UNE-EN 1005-5:2007 and ISO 11228-3:2007 standards, therefore, it is more and more used among industrial plants all over the world.

Nevertheless, a deeper study of certain aspects of the tool is needed. GAs are sensitive to execution parameters. For example, an inappropriate selection of the probabilities of mutation or crossover could cause a premature convergence of the algorithm to a local optimum or, on the other hand, an erratic search and the loss of orientation. A deeper study is needed on the sensitivity of the algorithm to the different parameters and on obtaining appropriate values for problems of different characteristics. The application of the algorithm proposed by the planners in industrial plants provides feedback on the results obtained with different values for the parameters. The analysis of these results will allow determining the optimal values to maximize the benefits of rotation. However, obtaining these data is a long term process, as a long time is required to check the impact of job rotation on health and motivation of the workers. Going even further, the duration and number of rotations and the pauses are established by the planner, based on the requirements of production and working hours of the plant. However, it would be interesting that the GA could help the planner in this task. The search for the distribution and duration of suitable rotations and breaks can be performed by the algorithm, adding them to the codification of each individual. Also, it would be advisable to consider other criteria for the assignation of workers to workstations in addition to the repetitiveness. Thus, lifting of weight in each workstation could be evaluated by means of the Job Severity Index (Liles, 1986) or the NIOSH equation (Waters et al., 1993), and adopting static postures could be evaluated for instance, with RULA method (McAtamney et al., 1993). The results of the application of each of these evaluation methods to the workstations could be included in the evaluation function.

Finally, proposed algorithm should be incorporated in software to permit planers management, exploitation, modification and re-utilization of information on workers, workstations, such as methods evaluations, and processes, as well as the storing of the job rotation schedules found and the production of reports on the latter.

5. Conclusions

The proposed algorithm seems to be an effective tool to design rotation schedule as a temporary alternative to the redesign of critical positions with high repeatability. In a short computing time, the algorithm can find solutions that balance the risk of repetition among workers, preventing workers permanently assigned to places with high levels of risk. In addition, the proposed solutions introduce variability in the levels of risk to which workers are exposed, thus helping its recovery. Moreover, the algorithm proposes solutions, if the problem constraints allow it, in which workers do not repeat the same position for the day. This increases their versatility, reduces boredom and increases the flexibility of the company. The algorithm also allows to consider workers disabilities for obtaining solutions that help their integration into the regular work.

However, it is important to note that job rotation is an administrative solution that should be temporary as to the presence of critical positions. The implementation of a rotation plan, although eliminates the existence of overexposed workers, should not replace the redesign of critical jobs to reach acceptable risk levels.

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