A MODEL TO DEFINE SETUP TIME SEQUENCE DEPENDENT FLOW–SHOP SCHEDULING CONSIDERING PRODUCTIVITY AND ERGONOMIC

Sabina Asensio-Cuesta[1], Pedro Gómez-Gasquet[2]

[1]UNIVERSITAT POLITÈCNICA DE VALÈNCIA. Instituto Universitario de Tecnologías de la Información y Comunicaciones (ITACA), C/ Camino de Vera s/n 46022 (Valencia). Tfno: +34 96 387 70 07. sasensio@dpi.upv.es
[2]UNIVERSITAT POLITÈCNICA DE VALÈNCIA. Departamento de Organización de Empresas. C/Camino de Vera s/n 46022 (Valencia). Tfno: +34 96 387 70 07. pgomez@cigip.upv.es

Received: 25/Oct/2017--Reviewed: 26/Oct/2017--Accepted: 23/Nov/2017--DOI: http://dx.doi.org/10.6036/NT8632

ABSTRACT:
The manufacturer industry is characterized by the presence of highly repetitive movements, which is a major risk factor associated with work musculoskeletal disorders (WMSDs). Moreover, this risk factor worsens when workers do not take adequate rest periods. This paper analyzes the problem and presents a mixed integer linear programming (MILP) mathematical model to minimize makespan in an n–job flow-shop problem with sequence-dependent setup times by considering recovery times. To this end, the model combines the effectiveness of MILP mathematical model optimization with the OCRA ergonomic assessment method. The model calculates work-recovery periods in workers´ schedules based on the OCRA included in standards UNE–EN 1005–5:2007 and ISO 11228–3:2007. Finally, a case study in a Food Sector Company is described.

Keywords: flow–shop, setup time, makespan, ergonomic, recovery time, OCRA index, upper–limb musculoskeletal disorders

RESUMEN:
La industria manufacturera se caracteriza por la presencia de una elevada repetitividad de movimientos de sus trabajadores, siendo éste un importante factor de riesgo asociado con los trastornos musculoesqueléticos (TME) de origen laboral. Además, dicho factor de riesgo empeora cuando los trabajadores no realizan períodos de descanso adecuados. Este artículo analiza dicha problemática y presenta un modelo matemático de Programación Lineal Entera Mixta (PLEM) para minimizar el makespan en un problema de secuenciación flow-shop de n-trabajos con tiempos de setup dependientes de la secuencia, considerando los tiempos de recuperación de los trabajadores. Para ello, el modelo combina la efectividad de la optimización del modelo matemático de PLEM con el método de evaluación ergonómica OCRA. El modelo calcula los períodos de recuperación de los trabajadores según el método OCRA incluido en las normas UNE-EN 1005-5: 2007 e ISO 11228-3: 2007. Finalmente, se describe un caso de estudio en una empresa del sector alimentario.

Palabras clave: taller de flujo, setup dependiente de la secuencia, makespan, ergonomía, tiempo de recuperación, índice OCRA, trastornos músculo esqueléticos de los miembros superiores

1.- INTRODUCTION

Production system design elements influence productivity and ergonomics (Neumann et al., 2006), hence the importance of simultaneously determining both production effectiveness and ergonomic conditions in a production system. Production managers should establish indicators and goals based not only on production criteria, but also on ergonomic improvement criteria while production systems are being designed.

Despite automation strategies having been applied to production in recent decades, the presence of repetitive tasks is still common in the manufacturing industry (Kaergaard and Andersen, 2000; Xiao et al., 2004; Shir et al. 2006; Bonfiglioli et al., 2007; Wang et al., 2010; Roja et al. 2013). Thus musculoskeletal disorders (MSDs) are frequent as a result of workers being exposed to repetitiveness (Spallek, 2010). MSDs have important socio-economic implications (Katz, 2002) as the direct and indirect costs attributable to MSDs are substantial (Summers et al., 2015). It has been estimated that the medical costs related to MSDs in the USA from 2004 to 2006 come to $576 billion, which is the equivalent to 4.5% of the gross domestic product (GDP).

As previously mentioned, excessively repetitive movements in the manufacturing industry is one of the most commonly reported risk factors that comes with “reasonable” evidence for causing work-related MSD (WRMDs) (DaCosta, 2010). Moreover, ‘lack of recovery periods’ increases muscle fatigue and, therefore, increases the likelihood of workers suffering MSDs (Colombini et al. 2002). Mathiassen (2006) states that proper muscle recovery is crucial to prevent musculoskeletal injuries from taking place, and breaks at work lower the likelihood of musculoskeletal pain (Rundcrantz et al., 91). Currently several ergonomic evaluation methods are used to assess the level of risk to which workers are exposed by performing repetitive movements. Some examples of these methods are: JSI (Job Strain Index) (Moore et al., 1995) the OCRA (Occupational Repetitive Actions) method and Check List OCRA (Colombini et al., 2002), Sue Rodgers’ method (Rodgers, 1992) and the widespread method applied in the European automobile industry called European Assembly Worksheet (EAWS) (Otto and Scholl, 2011).

Therefore, sustainable MSDs prevention in manufacturing should implement a link between both production and prevention management. Our proposal is based on setup time sequences that depend on flow-shop, where processing and setup times could increase due to ergonomic requirements. The ergonomic requirements that we focused on were workers´ adequate recovery periods. Ergonomic requirements modify sequences scheduling, thus the best non ergonomic sequences would not be the best ones now. Rest periods were added during a processing time, and the sublot concept emerged, which meant dividing a job into a number of smaller sublots, but without overlapping operations between successive machines.

This article presents a mixed integer linear programming (MILP) model to design setup time sequence-dependent flow-shop scheduling by considering productivity and ergonomics to prevent WMSDs in environments characterized by highly repetitive movements. A case study in a Food Sector Company is described. In a wide range of industrial situations, companies usually work according to flow-shop configurations, where there are m resources in series. Some papers, like (Framinan et al., 2004), (Ruiz and Maroto, 2005) and (Gomez-Gasquet et al., 2012), have contributed to bridge the gap between academic and real problems. Each job has to be processed on each m resource (worker or machine). All the jobs have to follow the same route; i.e., they have to be processed first by worker 1, then on machine 2, and so on. After completing one resource, a job joins the queue for the next resource (Brucker, 2004). Setups depend on not only the job to be next processed, but also on its immediately preceding job on the same machine. Different authors have published m machines flow-shop papers with sequence-dependent setup times to minimize the makespan as the objective function (Allahverdi et al., 1999) (Gupta and Stafford, 2006). In any case, no relevant paper has simultaneously addressed both production effectiveness and ergonomic conditions.

The proposed model calculated the risk level of workers’ exposure to repetitive movement and to work-recovery periods by applying the OCRA method (Colombini et al. 2002; UNE-EN 1005-5:2007, ISO 11228-3:2007). The OCRA method is included in standards UNE-EN 1005-5:2007 and ISO 11228-3:2007. It is also widely used by technical specialists (occupational safety and health operators, ergonomists, methods and time analysts, production engineers) for risk management and task/workplace (re)design purposes. The OCRA method has been included in previous research works about preventing work-related musculoskeletal disorders in repetitive production systems (Asensio-Cuesta et. al, 2014). Thus our selection of the OCRA method to assess repetitiveness risk levels was due to its growing popularity and its value in the ergonomics field.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

2.- OCRA METHOD OVERVIEW

The OCRA method assesses risk based on the frequency of technical actions[1] 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 (Colombini et al. 2002; 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. The OCRA index is the quotient of two values: **ATA** (Overall nº of technical actions carried out in the shift by the worker) and **RTA** (Overall nº of technical actions recommended in the shift), Equation (1) calculates OCRA index. 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 (Colombini et al. 2002).

$$OCRA\ index = \frac{ATA}{RTA} \quad (1)$$

Equation (2) calculates **ATA.** In this equation $\mathbf{F_j}$ is the number of actions per minute required by the task **j** and $\mathbf{D_j}$ is the duration of the repetitive task **j**. And **n** is the number of repetitive tasks in the shift performed.

$$ATA = \sum_{j=1}^{n} F_j \cdot D_j \quad (2)$$

RTA is calculated by means of Equation (3), where **CF** is a 'constant of frequency' of technical actions per minute fixed at 30 actions/min, $\mathbf{FoM_j}$ is the factor of strength risk for the task **j**, $\mathbf{PoM_j}$ is the factor of posture risk for the task, $\mathbf{ReM_j}$ is the factor of repeatability risk for the task **j**, $\mathbf{AdM_j}$ is the factor of additional risks for the task **j**. $\mathbf{D_j}$ is the duration of the repetitive task **j**. While **rc** 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). Finally, **DUM** is the factor for total length of repetitive tasks in a day. In Colombini et al. (2002), UNE–EN 1005–5:2007 and ISO 11228–3:2007 the tables to determine the factors multipliers values are described. The factors multiplier is 1 if the corresponding risk is acceptable level; the multiplier value is decreasing according with the level of risk.

$$RTA = \sum_{j=1}^{n} [CF \cdot FoM_j \cdot PoM_j \cdot AdM_j \cdot ReM_j \cdot D_j] \cdot rc \cdot DUM \quad (3)$$

3.- THE MODEL DEFINITION

In this section, a proposed Mixed Integer Linear Programming (MILP) for a flow–shop scheduling problem based on (Asensio-Cuesta et. al 2014) is presented. Sequence dependent setup time and operations standby for a recovery time when exceeding the maximum recommend continuous working period considering the ergonomic aspect are the main characteristics of the problem addressed. The objective function is minimizing the makespan and ergonomic requirements are included as model constraints setting a maximum value for OCRA index.

Using the classical notation the model will be presented as *n/F/SRW–OCRA, SDST/*C_{max}. This model consists in a flow-shop (F) with *r* stages (R), one worker at each stage, where *n* jobs (N) must be processed. The following

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

assumptions are made: (5) all jobs are available at time zero; (6) the processing and setup time of each item is known and deterministic; (7) no preemption is allowed; (8) machines are available at any time; (9) each machine can process at most one job at a time; (10) each job can be processed on one machine at a time; (11) sequence dependent setup times (SDST) are considered; (12) job operation could be paused, standby recovery worker (SRW) with limited ergonomic risk (OCRA); and, (13) each stage has to have assigned one and only one worker (no job rotation).

In the MILP model jobs are divided in sublots when some recovery time is required in order to reduce the ergonomic risk. In this case, sublots are separate by a fixed recovery period T_R. The transfer unit between operations is the job, not the sublot. In other case, one sublot by job is considered. Setup times are always considered for recovery the workers, so setup time are forced to be at least T_R period.

The problem is to decide the job schedule to minimize makespan. With the aim of define a general mathematical model, the information will be presented using the following indexes:

- i, t — index set of jobs {1..N}
- l, v — index set sublots $\{1..Z_i\}$ of *i* job in *r* stage
- r, k — index set of stages/worker on the shop {1..R}
- s — index {1..LRC=10} for RC (*ReCovery factor*), expressed as array with 2 sets with the same dimension RC_v set of bounds for the intervals of the maximum time without proper recovery, and RC_f set of factors for the corresponding RC_v interval. Both are determined by the OCRA rules and are; RC_v=[0, 60, 120, 180, 240, 300, 360, 420, 480, M] and RC_f=[1.0, 0.9, 0.8, 0.7, 0.6, 0.45, 0.25, 0.1, 0.0, 0.0]. Such that 0–60 is the first interval defined with $[RC\_v_1, RC\_v_2]$ which corresponds to RC_f_1=1.0 and 480–M is the last interval which corresponds to RC_f_9=0.0.

It must be taken into account that at each stage one and only one worker is assigned, so in index r, k is referred at time to stage and worker.

Parameters in the model are the data known beforehand:
Z_i (integer) number of units in job *i*
$P_{i,r}$ (real) processing time for one unit of job *i* at stage *r*
$S_{t,i,r}$ (real) setup time for job *i*, preceded by a job *t*, at the stage *r*
T_R (real) recovery time for any worker after a working period
F_r (real) number of technical action by minute (frequency) at stage r
K_r (real) strength, posture, repetitiveness and additional multipliers multiplying action frequency constant
DUM_r (real) value for multiplier of the effective workday parameter
$OCRAobj_r$ (real) maximum value for OCRA index for a worker at the assigned stage *r*
M (real) a positive number larger than expected makespan
MILP model determines the following (real) variables:
$x_{l,i,r}$ number of units in sublot *l* of job *i* at stage *r*
$c_{l,i,r}$ completion time of sublot *l* of job *i* at stage *r*
c_{max} maximum completion time at stage R
$s^X_{t,i,r}$ extended setup time for job *i*, preceded by a job *t*, at the stage *r*
o_r maximum operating time without proper for a worker at the stage *r*
rc_r factor corresponding to o_r

With this notation, the problem can be formulated as the following MILP model. The objective is to minimize makespan (4):

$$F.O.\ min\ z = c_{max} \tag{4}$$

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

The constraints of the model are presented below in two sets, each representing one type of system constraint. The model is subject to:

Precedence constraints: This set of constrains ensures the processing order of jobs and sublots.

$$c_{max} \geq c_{l,i,R} \quad \forall l, \forall i \quad (5)$$
$$c_{l,i,r} \geq c_{v,t,r} + P_{i,r} * x_{l,i,r} + s^{X}_{t,i,r} + M * (q_{t,i,r} - 1) \quad \forall l, \forall v, \forall t, \forall i, \ \forall r \ \ t \neq i \quad (6)$$
$$c_{l,i,r} \geq c_{v,t,r} + P_{i,r} * x_{l,i,r} + s^{X}_{t,i,r} - M * q_{i,t,r} \quad \forall l, \forall v, \forall t, \forall i, \ \forall r \ \ t \neq i \quad (7)$$
$$c_{l+1,i,r} \geq c_{l,i,r} + P_{i,r} * x_{l+1,i,r} + T_R * y_{l+1,i,r} \quad \forall l > Z_i, \forall i, \forall r \quad (8)$$
$$c_{l,i,r} \geq c_{v,i,r-1} + P_{i,r} * x_{l,i,r} \quad \forall l, \forall v, \forall i, \forall r > 1 \quad (9)$$
$$c_{l,i,0} \geq P_{i,0} * x_{l,i,0} \quad \forall l, \forall i \quad (10)$$

The constraint set (5) determines maximum completion time or makespan. Constraint (6) and (7) ensures that a job cannot start before the previous job at the same stage *r* has been completely processed. Note that the variable q can only take one value when the pair of jobs for which it is instantiated does not comply with the commented constraint. That value is 1 for equation 6 and 0 for equation 7. When the restriction is met, the value of q is indifferent. Constraint (8) ensures that any two sublots of any job are processed simultaneously and between both a recovery time T_R is added. Constraint (9) ensures that any sublot of a job can start in the next stage before all sublots have been completed in the actual stage. Constraint (10) ensures first sublot start time is not negative.

Constraints related to sublot sizes and duration of working and recovery periods:

$$\sum_{l=1}^{Z_i} X_{l,i,r} = Z_i \quad \forall i, \forall r \quad (11)$$
$$x_{l,i,r} \leq Z_i * y_{l,i,r} \quad \forall l, \forall i, \forall r \quad (12)$$
$$x_{l,i,r} > (y_{l,i,r} - 1) \quad \forall l, \forall i, \forall r \quad (13)$$
$$s^{X}_{t,i,r} \geq S_{t,i,r} \quad \forall t, \forall i, \forall r \ \ i \neq t \quad (14)$$
$$s^{X}_{t,i,r} \geq T_R \quad \forall t, \forall i, \forall r \ \ i \neq t \quad (15)$$

Constraint (11) ensures that all the units are processed for all jobs at all the stages. Constraints (13) and (14) ensures that only if a sublot l is processed ($x_{l,i,r}$>0) then the value of $y_{l,i,r}$ let add a recovery time T_R in constraint (8). And constraint (15) and (16) ensures setup time considered between two jobs includes at least a recovery time period, and must be consider ergonomic requirements.

Constraints related to maximum time without proper recovery parameter (ergonomic aspect):

$$P_{i,r} * x_{l,i,r} \leq o_r \quad \forall l, \forall i, \forall r \quad (16)$$
$$(o_r - \mathrm{RC\_v}_s) - \mathrm{M} * (1 - \beta_{s,r}) \leq \ (\mathrm{RC\_v}_{s+1} - \mathrm{RC}_{\_vs}) * \beta_{s+1,r} \ \ \forall s < LRC - 1, \forall r \quad (17)$$
$$\mathrm{RC\_v}_s * \beta_{s+1,r} \leq o_r \quad \forall s < LRC - 1, \forall r \quad (18)$$
$$\sum_{s=1}^{LRC} \beta_{s,r} = 1 \quad \forall r \quad (19)$$

The constraint (16) set the time without proper recovery that corresponds with maximum continuous operation time. Constraint (17), (18) and (19) help to fit the proper parameter for *o* variable, and set β equal 1 only if and only if time without proper recovery belongs to s interval in the set RC_v. In other words, if o_r belongs to [RC_v_s..RC_v_{s+1}[. Although in theory the *o* variable can take infinite value to meet the restriction in practice it will take the lowest possible value for the overall model forces a minimization of this value.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

Constraints related to OCRA conditions (ergonomic aspect):

$$rc_r \le RC\_f_{s,r} + (1 - \beta_{s,r}) \quad \forall s\ \forall r \tag{20}$$

$$F_r \le K_r * DUM_r * rc_r * OCRAobj_r \qquad \forall r \tag{21}$$

The constraint (20) associates a value for factor multiplier corresponding to the effective working time without recovery time. In order to minimize the objective function rc_r must reach a value as large as possible. The constraint (21) ensures OCRA corresponding to each worker never will be major than the OCRA objective.

4.- TRANSFERRING OCRA PARAMETERS TO THE MODEL

The proposed model considers that each worker is assigned to a single stage *r* in which a single repetitive task *r* is performed. Therefore the OCRA index for a worker is the same as the OCRA index for a stage. Equation (22) shows the OCRA index calculations for a stage *r*.

$$OCRA_r = \frac{F_r \cdot D_r}{[K_r \cdot D_r] \cdot DUM_r \cdot rc_r} \tag{22}$$

The Equation (22) defines the value of OCRA, and as it is observed the multiplier D_r can be removed from the equation. This situation is possible because only simple tasks are considered. From this consideration arises equation (23) in which the value of OCRA is no longer a variable but a parameter and it will determine the behavior of equation (23) by limiting the value of *Fr* (number of technical action by minute (frequency) at stage *r*).

$$F_r \le K_r \cdot DUM_r \cdot RcM_r \cdot OCRAobj_r \qquad \forall r \tag{23}$$

This means that given a particular problem, once the tasks risk factors are known and measured from OCRA method tables, *Kr* can be calculated. Also multiplier *DUMr* can be obtained from the OCRA corresponding table adding theoretical processes times of works performed in stage r. These processes times are the worker net repetitive time at stage r (DN_r).

The only parameter that remains to be calculated is the recovery multiplier rc_r. However, because setup times are mandatory breaks between works a minimum and maximum value of rc_r can be obtained from Table 1. According with the OCRA method the optimal distribution ratio of repetitive task and recovery periods seems to be 50 minutes ‘work and 10 minutes ‘recovery. On the basis of this optimal distribution it is possible to design criteria to evaluate the presence of risk in a concrete situation: the risk may be due to the lack, or inadequacy, recovery periods distribution. OCRA assigns for every hour without an adequate recovery period a corresponding factor (Table 1).

Nº of hours without adequate recovery	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
OCRA Multiplier factor (rc_r)	1	0,9	0,8	0,7	0,6	0,45	0,25	0,1	0

Table 1: OCRA elements for the determination of the recovery period multiplier factor (rcr) for each stage r.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

5.- ANALYZING THE MODEL: A FOOD SECTOR COMPANY

The applied model came from a Food Sector Company that is organized into three divisions: Manufacture and Packaging, Food Services and Ingredients. The main health problem identified in the company is incidence of MSDs. The company's ergonomic evaluations state that the main ergonomic risk factor associated with MSDs is repetitiveness. The highest percentage of MSDs corresponds to upper limb body parts: necks and shoulders (25%), arms and elbows (20%), hands and wrists (20%). The company's accidents data clearly show that MSDs disorders occur mainly in the Packaging Section in the Manufacture and Packaging Division. As a result of this situation, the company is involved in ergonomic improvements to reduce MSDs.

In the Packaging Section under study, there are three different lines with various product processing, packing and palletizing types. The model was applied to the line with the highest MSDs prevalence. Three workers are assigned on that line and shifts last 8 h. The line comprises three stages (workstations) that require repetitive movements. Each stage corresponds to one workstation. The movements required in workstations are symmetric for the right and left side of the body, which means that the OCRA index value was the same for both sides of the body. Thus the model can focus on OCRA right side optimization.

To validate the model, four cases were identified and were organized into two cases studies, Scenarios A and B. All the scenarios were flow-shop workshop with three stages, three workers, five jobs and setup times, depending on the sequence. The essential variation between Scenario A and B was the job's processing times. In each scenario two different situations were chosen. The first one, Case 1, when the job's processing times were identical in all stages (Cases A.1 and B.1). Then Case 2, in which the process times of each job varied from one stage to another (Cases A.2 and B.2).

For both Scenarios A and B, an OCRA index value above 2.2 (medium risk level (yellow)) was indicated as being a realistic objective. So the following values of the OCRA index aims were set for stage r: OCRAObjr = {2.2, 2.2, 2.2}. Given the organization requirements, the sequence had to include at least one job that lasted 150 minutes, which had to be the longest.

On the packaging line three repetitive tasks are performed:

- **Type 1 packaging task:** All the risk factors are at the OCRA acceptable level and their multipliers values are 1. The task cycle time is 120 sec.
- **Type 2 packaging task:** During the task, workers have to apply weak force, level 2 according to the Borg CR–10 scale (Borg, 1998). Thus the force multiplier is 0.65 (FoM) according to the corresponding OCRA table. The task cycle time is 24 sec.
- **Screening task:** During the task, workers apply 70º wrist flexion during 80% of the cycle time. Hence the posture multiplier is 0.70 (PoM) according to the corresponding OCRA table. The task cycle time is 126 sec.

5.1.- SCENARIO A CASES

In Case A.1 the processing time was common for the five jobs in all stages. Settings included jobs with different process times. Thus according to the OCRA objective, some jobs could be divided into one stage. In Case A.2, the processing time of the five jobs varied with stage. A case that involved major imbalance between the processing times of a give job from one stage to the next was searched to evaluate model capability. Table 2 lists the parameters that define Scenario A, and also for each Case A.1 and A.2. The minimum and maximum OCRA indices for each stage in Scenario A are included in Table 2.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

Turn duration (min)		480					
Action constant frequency (cf)		30					
Side of the body		RIGHT					
Stage Nº		**Stage 1**		**Stage 2**		**Stage a 3**	
Worker Assigned		**Worker 0**		**Worker 1**		**Worker 2**	
A.1 SCENARIO	**Time job processing (min)**	{150; 45; 60; 45; 60}					
	Net repetitive work time (min)	360					
A.2 SCENARIO	**Time job processing (min)**	{150;45;60;45;60}		{60;150;60;120;60}		{150;45;120;30;120}	
	Net repetitive work time (min)	360		450		465	
Task		**Packing type 1**		**Screening**		**Packing type 2**	
OCRA index Min/Max		**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Nº of hours without adequate recovery		0	2	0	2	0	2
Recovery multiplier (rc)		1,0	0,8	1,0	0,8	1,0	0,8
Force multiplier (FoM)		1,00	1,00	0,65	0,65	1,00	1,00
Posture multiplier (PoM)		1,00	1,00	1,00	1,00	0,70	0,70
Aditional risk multiplier (AdM)		1,00	1,00	1,00	1,00	1,00	1,00
repetitiveness multiplier (RM)		1,00	1,00	1,00	1,00	1,00	1,00
strength, posture, repetitiveness and additional multipliers multiplying action frequency constant (Kr)		30,00	30,00	19,50	19,50	21,00	21,00
Cycle time (sec.)		120,0	120,0	24,0	24,0	126,0	126,0
Frecuency (Technical actions per minute) (Fr)		60	60	30	30	40	40
Duration multiplier (DUMr)		1,0	1,0	1,0	1,0	1,0	1,0
OCRA index		2,00	2,50	1,54	1,92	1,9	2,38

Table 2: Parameters and OCRA index values in scenario A

From the minimum and maximum OCRA indices in Scenarios A.1 and A.2, it was possible to analyze the options that could be explored to go below the OCRA index target, as illustrated in Figure 1.

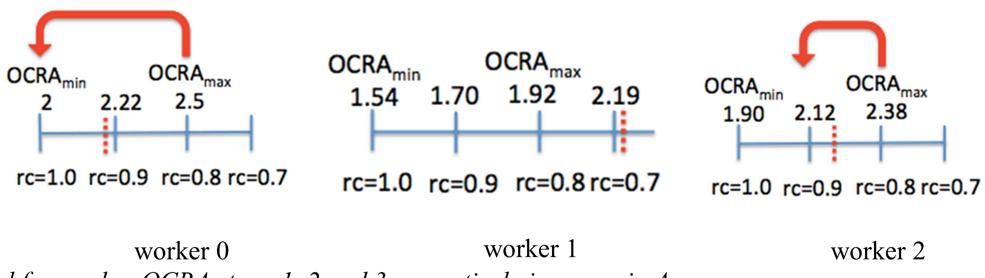

Fig. 1. Potential for worker OCRA stage 1, 2 and 3 respectively in scenario A

Based on the analysis of the previous figures, and as all the workers should be below the 2.2 OCRA index value, the possible rc values were:

$$OCRAlim_r=\{2.00,1.92,2.12\} \text{ if } rc_r=\{1,0.8,0.9\} \quad (24)$$

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

Worker 0 (stage 1) had only one option to lower the OCRA below 2.2, that of including a break after working 50 minutes. Worker 1 (Stage 2) did not need to take any breaks between jobs to achieve the OCRA objective. Worker 2 (Stage 3) could simply rest every 110 minutes to meet the OCRA target. This implied that the model had one choice for Worker 0, three choices for Worker 1, and two choices for Worker 2. This meant six possible rc combinations.

5.2.- B SCENARIO CASES

In Scenario B, the task performed in each stage was changed. Thus the "Packing type 1" task was in Stage 3, "Screening" was in Stage 2 and "Packing type 2" was performed in Stage 1. In Case B.1, the processing time was common for the five jobs in all stages. In Case B.2 the processing time of the five jobs varied according to stage. Table 3 shows the parameters that define Scenario B.

Turn duration (min)		480					
Action constant frequency (cf)		30					
Side of the body		RIGHT					
Stage Nº		**Stage 1**		**Stage 2**		**Stage a 3**	
Worker Assigned		**Worker 0**		**Worker 1**		**Worker 2**	
B.1 SCENARIO	**Time job processing (min)**	{150; 45; 60; 45; 60}					
	Net repetitive work time (min)	360					
B.2 SCENARIO	**Time job processing (min)**	{150;45;60;45;60}		{60;150;60;120;60}		{150;45;120;30;120}	
	Net repetitive work time (min)	360		450		465	
Task		**Packing type 2**		**Screening**		**Packing type 1**	
OCRA index Min/Max		**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Nº of hours without adequate recovery		0	2	0	2	0	2
Recovery multiplier (rc)		1,0	0,8	1,0	0,8	1,0	0,8
Force multiplier (FoM)		0,65	0,65	1,00	1,00	1,00	1,00
Posture multiplier (PoM)		1,00	1,00	0,70	0,70	1,00	1,00
Aditional risk multiplier (AdM)		1,00	1,00	1,00	1,00	1,00	1,00
repetitiveness multiplier (RM)		1,00	1,00	1,00	1,00	1,00	1,00
strength, posture, repetitiveness and additional multipliers multiplying action frequency constant (Kr)		19,5	19,5	21,00	21,00	30,00	30,00
Cycle time (sec.)		24	24	126	126	120	120
Frecuency (Technical actions per minute) (Fr)		30	30	40	40	60	60
Duration multiplier (DUMr)		1,0	1,0	1,0	1,0	1,0	1,0
OCRA index		1,54	1,92	1,90	2,38	2,00	2,50

Table 3: Parameters and OCRA index values in scenario B

In this new Scenario B, the options that allow going below the target OCRA are illustrated in Figure 2:

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

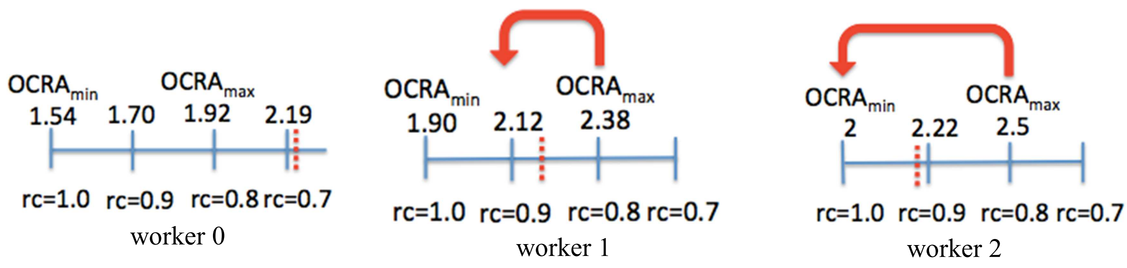

Fig. 2. Potential for worker OCRA stage 1, 2 and 3 respectively in scenario B

Now the rc enabled values are:

$$OCRAlim_r=\{1.92,\ 2.12,\ 2.00\}\ if\ rc_r=\{0.8,0.9,1\} \qquad (25)$$

To achieve the OCRA objective, Worker 0 (Stage 1) would not need to take breaks between jobs, it would be enough for Worker 1 (Stage 2) to rest every 110 minutes, and Worker 2 (Stage 3) should include a break every 50 minutes for the OCRA to go below 2.2.

5.3.- RESULTS

Based on the case study following the proposed hypothesis to execute the model:

1. The proposed model is able to solve job allocation and to optimize the sequence to achieve a minimum makespan for a few jobs.

2. By setting an ergonomic restriction of a maximum OCRA index value, the makespan and the production sequence are affected. Moreover, the makespan increment is offset by the benefits of lowering the yearly WRMDs incidence (per 100 exposed individuals).

5.3.1.- Scenario A results

The model results for Case A.1, both with and without ergonomic constraints, are shown in Figure 3. The main conclusions from these results are:

- Sequences differ between ergonomically unrestricted and restricted settings. The longer job changes from the last position in the unrestricted setting to become the first to be sequenced in the restricted environment.
- The makespan with ergonomic restrictions rises about 67 minutes, which is an approximate 8.5% increase compared to the unrestricted setting.
- In the restricted setting, 'Worker 0' includes seven additional 10-minute breaks between jobs; two for each long job (150 min. and 105 min.) and one for each short job (60 min.); Worker 1 takes no additional breaks in the ergonomic setting. Worker 3 takes only two additional breaks in long jobs (150 min. and 105 min.).

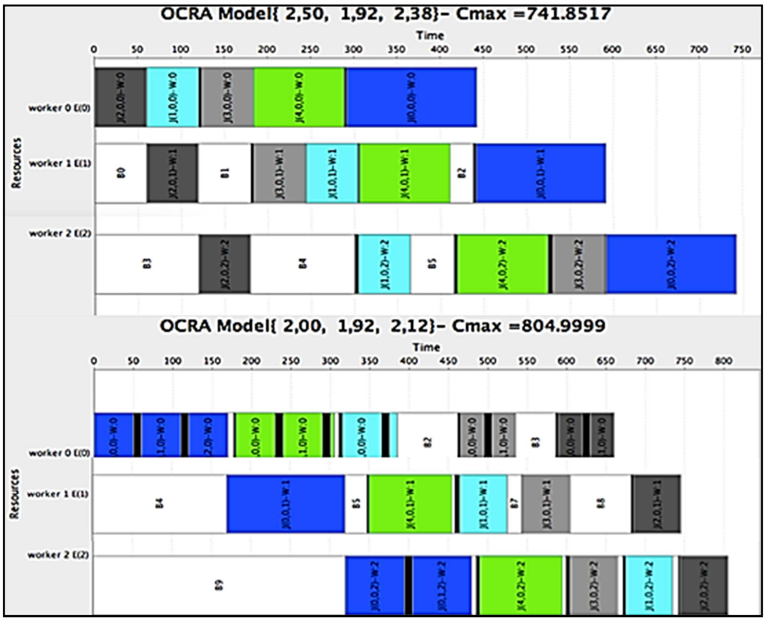

Fig. 3. Case A.1: results without ergonomic constraints (top) and with ergonomic constraints (bottom)

As indicated in the previous section, in A.2 the processing time of works varied with stage. This occurred when a major imbalance took place between the job processing times from one stage to the next. Figure 4 graphically shows the results of running model Case A.2 with and without ergonomic constraints. The main conclusions drawn from the A.2 results are:

- Sequences vary in the model resolution with and without ergonomic constraints.
- The makespan with ergonomic restrictions rises about 69 minutes compared to the unrestricted setting, which shows an approximate 11.5% increase.
- Worker 0 takes four additional 10–minute breaks between jobs, one for each long job (150 min. and 120 min.) and one for each short job (60 min.). Worker 1 takes no additional breaks, while Worker 2 includes only three additional breaks, one for each long job (150 min., 120 min. and 120 min.).

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

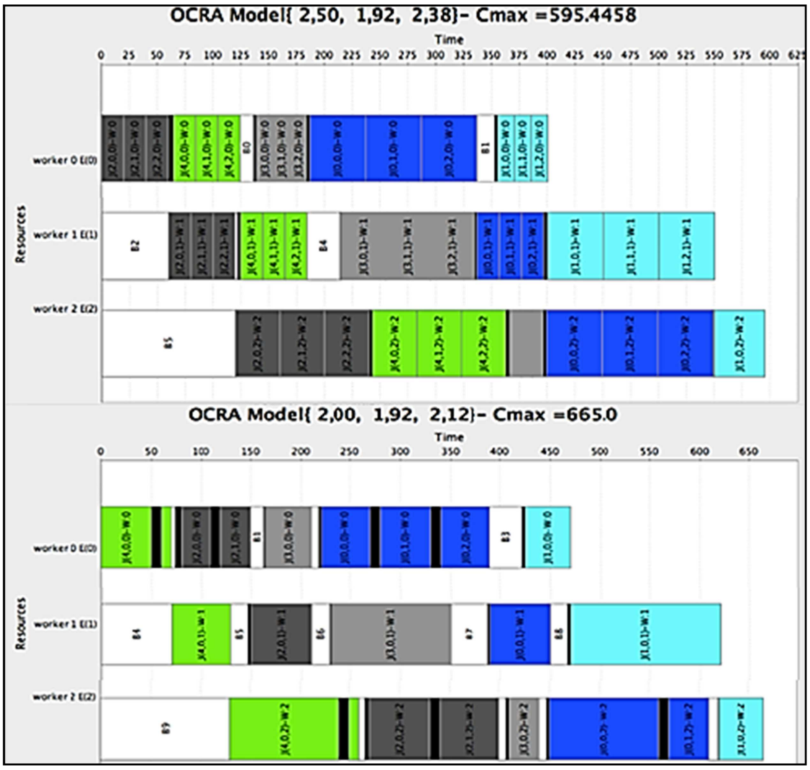

Figure 4. Case A.2: results without ergonomic constraints (Top) and with ergonomic constraints (bottom)

The following table compares the OCRA index values obtained for case study A. These OCRA indices are equal in both Cases A.1 and A.2. In the sequences without ergonomic constraints, the average WRMDs incidence percentages vary between 67% and 86%, while those percentages with ergonomic constraints vary between 58% and 77%. Thus the average WRMDs incidence percentage lowers by 9% for the ergonomic solutions.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com

CASE A	OCRA index without ergonomic	% INCIDENCE WRMDs		
		Min.	**Central**	**Max**
	2,5	75%	84%	94%
	1,92	55%	65%	74%
	2,38	70%	80%	89%
MEAN % INCIDENCE OF WRMDs	**2,26**	**67%**	**76%**	**86%**
	OCRA index with ergonomic	**Min.**	**Central**	**Max**
	2	58%	67%	77%
	1,92	55%	65%	74%
	2,12	62%	71%	81%
MEAN % INCIDENCE OF WRMDs	**2,01**	**58%**	**68%**	**77%**
DIFERENCE OF MEAN % INCIDENCE OF WRMDs		67%–58%=**9%**		

Table 4. Percentages of WRMDs incidence in case A.

5.3.2.- Scenario B results

The model results for Case B.1 are shown in Figure 5. The B.1 and A.1 results are close in terms of makespan and OCRA index values. However, jobs schedules differ to achieve a similar makespan.

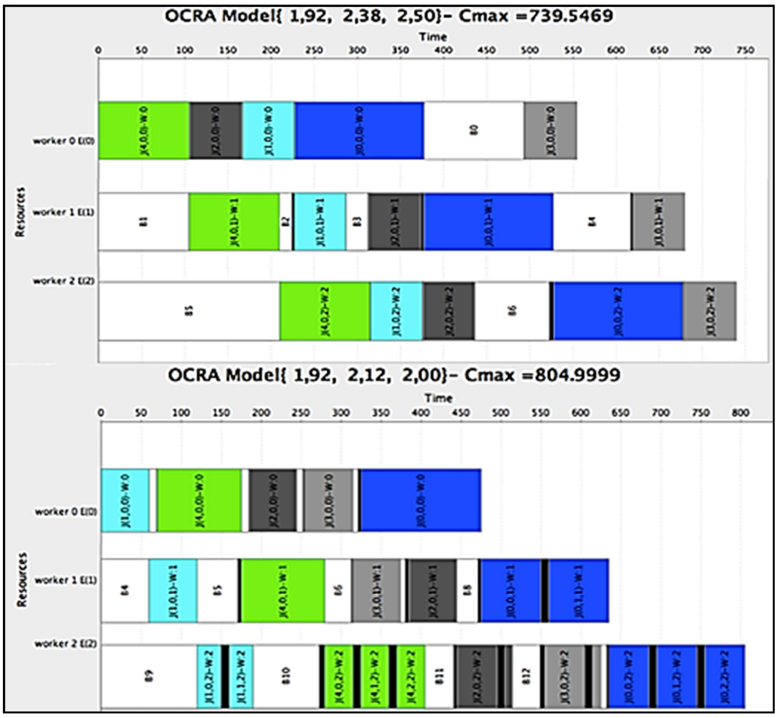

Fig. 5. Case B.1: results without ergonomic constraints (Top) and with ergonomic constraints (bottom)

Finally, Figure 6 shows the Case B.2 results. From those figures, we conclude that:

- The makespan with ergonomic restrictions rises about 89 minutes, which is an increase of about 15%.
- As in Scenario A.1, the average WRMDS percentage lowers by 9%
- The breaks included in the work are the same as in Case A.2. However, the makespan ergonomic constraint increases by 20 minutes despite the makespan without ergonomic constraints being practically the same as in Case A.2.
- The sequences vary in the model resolution with and without ergonomic constraints.

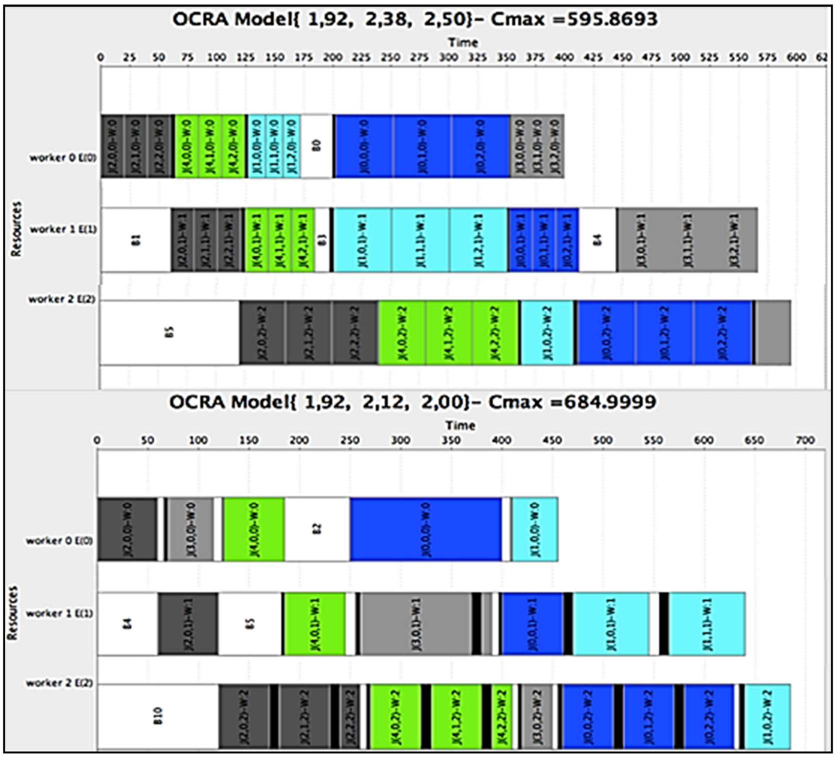

Figure 6. Case B.2: results without ergonomic constraints (Top) and with ergonomic constraints (bottom)

6.- CONCLUSIONS

From the Food Sector Company under study, the proposed model provides solutions where minor increases in the makespan are translated into a lower predicted WMSDs incidence. So the proposed model proves to be an effective tool to design shop-flow schedules where the makespan is minimized and, at the same time, ergonomic work-recovery periods are included to prevent work-related WMSDs.

The model is able to obtain ergonomic schedules by minimizing the makespan increase when yearly WMSDs incidences lower. Although making an effort is required to make OCRA method evaluations of the workstations involved in the model's schedule, it seems worthwhile in WMSDs prevention terms. After comparing a flow-shop with and without considering ergonomic aspects, we conclude that the presented problem is, as highlighted in the Results section, an interesting challenge from a research point of view. In any case, a wide variety of cases of scientific and practical interest in the industrial field were not taken into account in the studied case herein. For example, other types of workshops or other ergonomic problems, such as employee turnover, could be considered. In this paper a mathematical model is proposed that can be extended to other situations without making much effort.

Furthermore given the complex industrial reality, the model approach might improve companies' production efficiency and, at the same time, their WMSDs prevention.

BIBLIOGRAPHY

[1] Allahverdi, A., Gupta, J. N., Aldowaisan, T. (1999). A review of scheduling research involving setup considerations. Omega, 27(2), 219–239.

[2] Asensio–Cuesta, S., Diego–Mas, J.A., Cremades–Oliver, L.V., González–Cruza mc. 2012. A method to design job rotation schedules to prevent work–related musculoskeletal disorders in repetitive work. International Journal of Production Research, 50(24), 7467–7478.

[3] Asensio–Cuesta, S., Gomez–Gasquet, P., Andrés C., Alemany M. M. E. 2014. A Model of Makespan Flow–shop Scheduling under Ergonomic Requirements. Managing Complexity. Springer. 105–112.

[4] Bonfiglioli, R., Mattioli, S., Fiorentini, C., Graziosi, F., Curti, S., Violante, F.S., 2007. Relationship between repetitive work and the prevalence of carpal tunnel syndrome in part–time and full–time female supermarket cashiers: a quasi–experimental study. International Journal of Occupational and Environmental Health, 80, 248–253.

[5] Borg, G. 1998. Borg's perceived exertion and pain scales. Human Kinetics. Ilinois.

[6] Brucker, P. (2004). Scheduling Algorithms. 4th edition Springer. Berlin Heidelberg New York.Diego–Mas, J.A., Asensio–Cuesta, S., Sanchez–Romero, M. A., Artacho–Ramirez, M.A. 2009. A multi–criteria genetic algorithm for the generation of job rotation schedules. International Journal of Industrial Ergonomics, 39(1), 23–33.

[7] Colombini, D., Occhipinti, E., Grieco, A. 2002. Risk Assessment and Management of Repetitive Movements and exertions of upper limbs. Elsevier. 111–117.

[8] Da Costa, B. R., Vieira, E. R. 2010. Risk factors for work – related musculoskeletal disorders: A systematic review of recent longitudinal studies. American Journal of Industrial Medicine, 53(3), 285–323.

[9] Framinan, J.M., Gupta, J.N.D., Leisten, R. 2004. A review and classification of heuristics for permutation flow-shop scheduling with makespan objective. Journal of the Operational Research Society, 55 (12), 1243–1255. Gomez-Gasquet, P., Andres, C.,. Lario, F.C. 2012. An agent-based genetic algorithm for hybrid flowshops with sequence dependent setup times to minimise makespan. Expert Systems with Applications. 39(9): 8095-8107.

[10] Gomez-Gasquet, P., Andres, C., Lario, F.C. (2012). An agent-based genetic algorithm for hybrid flowshops with sequence dependent setup times to minimise makespan. Expert Systems with Applications. 39(9): 8095-8107.

[11] Gupta, J. N. D., & Stafford Jr., E. F. (2006). Flowshop scheduling research after five decades. European Journal of Operational Research, 169(3), 699–711. Kaergaard, A., Andersen, J.H. 2000. Musculoskeletal disorders of the neck and shoulders in female sewing machine operators: prevalence, incidence, and prognosis. Environmental and Occupational Medicine, 57, 528–534.

[12] ISO 11228–3:2007. Ergonomics. Manual handling. Part 3: Handling of low loads at high frequency. 2007.

[13] Kaergaard, A., Andersen, J.H. 2000. Musculoskeletal disorders of the neck and shoulders in female sewing machine operators: prevalence, incidence, and prognosis. Environmental and Occupational Medicine, 57, 528–534.

[14] Katz, W. A. 2002. Musculoskeletal pain and its socioeconomic implications. Clinical Rheumatology, Supplement, 1, S2–S4.

[15] Mathiassen, S.E. 2006. Diversity and variation in biomechanical exposure: What is it, and why would we like to know? Applied Ergonomics, 37, 419–427.

[16] Moore, J.S., & Garg, A. 1995. The Strain Index: A proposed method to analyze jobs for risk of distal upper extremity disorders. American Industrial Hygiene Association Journal, 56, 443–458.

[17] Neumann, W.P., Winkel, J., Medbo, L., Magneberg, R., Mathiassen, S.E. 2006. Production system design elements influencing productivity and ergonomics: A case study of parallel and serial flow strategies. International Journal of Operations & Production Management. 26(8), 904 – 923.

[18] Otto, A., & Scholl, A. 2011. Incorporating ergonomic risks into assembly line balancing. European Journal of Operational Research, 212, 277–286.

[19] Rodgers, S.H. 1992 A functional job evaluation technique, Ergonomics, Occupational Medicine: State of the Art Reviews. 7(4): 679-711.

[20] Roja Z., Kalkis V., Roja I., Kalkis H. 2013. The effects of a medical hypnotherapy on clothing industry employees suffering from chronic pain . Journal of Occupational Medicine and Toxicology. 8(25): 1–15.

[21] Ruiz R., Maroto C. 2005. A comprehensive review and evaluation of permutation flowshop Heuristics. European Journal of Operational Research, 165 (2), 479–494.

[22] Rundcrantz, B.L., Johnsson, B., Moritz, U. 1991. Occupational cervico–brachial disorders among dentists. Analysis of ergonomics and locomotor functions, Swedish dental journal, 15(3):105–15.

[23] Shir, R., Viikari–Juntura, E., Varonen, H., Heliövaara, M., 2006. Prevalence and Determinants of Lateral and Medial Epicondylitis: A Population Study. American Journal of Epidemiology, 164, 1065–74.

[24] Spallek M., Kuhn W., Uibel S., Van Mark A., Quarcoo D. 2010. Work–related musculoskeletal disorders in the automotive industry due to repetitive work – implications for rehabilitation. Journal of Occupational Medicine and Toxicology, 5(6).

[25] Summers K., Jinnett K., Bevan S. 2015. Musculoskeletal Disorders, Workforce Health and Productivity in the United States. Center for Workforce Health and Performance.

[26] UNE–EN 1005–5:2007. Seguridad de las máquinas. Comportamiento físico del ser humano. Parte 5: Evaluación del riesgo por manipulación repetitiva de alta frecuencia). 2007.

[27] Wang, P.C., Harrison R.J., Yu F., Rempel D.M., Ritz B.R. 2010. Follow–up of neck and shoulder pain among sewing machine operators: The Los Angeles garment study. American Journal of Industrial Medicine, 53(4), 352–360.

[28] Xiao, G.B., Dempsey, P.G., Lei, L., Ma, Z.H., Liang, Y.X. 2004. Study on musculoskeletal disorders in a machinery manufacturing plant. Occupational and Environmental Medicine, 46, 341–346.

DYNA New Technologies
c) Mazaredo nº69 -4º 48009-BILBAO (SPAIN)
Tel +34 944 237566 – www.dyna-nuevastecnologias.com - email: info@dyna-nuevastecnologias.com