Considering workers' features in manufacturing systems: a new job-rotation scheduling model

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Abstract: The European manufacturing industry is entering a new era in which working populations are ageing. The E.U. had set itself strategy objectives to increase the labour market participation of older workers. However, practical limits arise, and a complete re-thinking of operation management strategies and manufacturing systems design and management is needed. As underlined in several works, older workers have not the same physical capacity as the younger ones. Consequently, they are more subjected to develop work-related musculoskeletal disorders despite younger colleagues. On the other hand, they might present higher skill levels in doing some specific tasks due to their considerable experience. Thus, they can be employed in teaching or training younger or unskilled workers. Starting from these initial considerations, in this paper, we develop a new age-oriented job rotation scheduling model. Both physical capacity and experience level aspects are included in the mathematical model aiming to maximize daily productivity. We quantify physical fatigue by using the energy expenditure rate and the maximum acceptable energy expenditure. Then, the rest allowance concept is evaluated according to the workers' age and the shift work duration. Variable execution times of each job according to the workers' experience level and mandatory training activities for unskilled workers are also taken into consideration. Finally, a numerical case derived by a real application is proposed to validate the model and demonstrate benefits we can achieve by applying it.

Keywords: Ageing workforce; costs; job rotation; human skills; mathematical model

1. INTRODUCTION

The European population is projected to grow from 507.2 million in 2013 to 522.8 million in 2060, with the percentage of seniors (65 years or older) forecasted to grow by 10% (E.U., 2017). A similar trend is observed in the USA (Collins and Casey, 2017) where population over 65 years is projected to grow by about of 0.6% per year until 2026 reaching the 25% of the adult population (over 16 years) while, in Japan, seniors could represent the 40% of the whole national population in 2060 (Debroux, 2016). Consequently, also, the workforce is ageing. The European Labour Force Survey stated that, by 2030, workers aged 55-64 will be more than the 30% of the entire workforce in many European countries (Remesal et al., 2019). It is mainly due to the choice of many E.U. countries to increase the official retirement age up to 65 years for both men and women. Moreover, according to Varianou-Mikellidou et al. (2019), fewer young people are entering the labour force.

The effects of an ageing workforce affect both the health and safety of workers and the efficiency and productivity of companies. Therefore, even if today robots, automatic machines, or Industry 4.0 solutions can perform tasks previously executed by humans, workers still perform manually several tasks that require capabilities that only humans can provide. Automation does not necessarily imply high flexibility level. Moreover, even if an acceptable level of flexibility could be achieved, the related costs could be too high. Consequently, workers cannot always be replaced by robots, especially for high-value activities, such as the assembly process. For this reason, companies should guarantee safe and comfortable workplaces to avoid accidents or injuries (Battini et al., 2011). During lasts years, several strategies have been applied aiming to improve workers' well-being as defined in Otto and Battaia (2017). More recently, Finco et al. (2018) proposed several heuristics aiming to minimise workers' fatigue during the balancing of assembly line. In 2020, Finco et al. (2020a) included recovery time in smoothness index. Finally, in Finco et al. (2019, 2020b) the vibration risk exposure has been included during assembly line design since it is considered as one of main ergonomic risk for some assembly systems and it can cause an excessive fatigue level especially for older workers. The ageing factor in operation management is becoming more relevant since older workers do not have the same features as the younger ones. Therefore, their physical and psychological characteristics should be evaluated and included in the design process of new workstations to create human-friendly solutions (Battini et al., 2011). Focusing on physical capabilities (Finco et al., 2019b), when age increases the maximum acceptable physical effort decreases. The consequences related to the reduction of physical capabilities are mainly the following: older workers require longer rest times or additional breaks (Ilmarinen, 2001) and, from a company perspective, the workers' availability could decrease as well as the production rate.

By considering the level of experience and skills, older workers have much higher competences respect to younger ones. For this reason, they are suitable for jobs that necessitate high-quality standards. On the contrary, younger workers, due to their lower labour experience, need more time to execute some tasks and in some cases, a training period is mandatory. Thus, companies must allocate extra economic resources for training. Therefore, older workers, with higher skill levels, could be engaged to train new labour workforce according to company standards. Thus, if from one hand, the productivity rate of an older worker decreases since more breaks are required, on the other hand, also the younger worker productivity could be limited by his/her inexperience and training needs. In this context, aiming to reduce the inefficiency linked to ageing or unskilled workers, companies can apply the job rotation paradigm (Weichel et al., 2010). Moreover, job rotation has been demonstrated to be an optimal approach to avoid unbalanced workload and increase efficiency.

For this reason, in this paper, we consider workers' age and experience level in a job rotation scheduling model aiming to maximise the daily productivity. We evaluate the effects that experience level and maximum acceptable physical effort could have in the job assignment phase and related workforce productivity. Moreover, additional constraints able to guarantee the acceptable production rate are included in the model to achieve the efficiency that companies could require.

The paper is structured as follows. Section 2 provides a short literature review focus on the effects of an ageing workforce and previous works in job rotation scheduling problem. Section 3 proposes the new mathematical model, while Section 4 presents a numerical example derived by a real case and discusses the achieved results. Finally, conclusions and future works are defined in Section 5.

2. BACKGROUND

Older workers have specific competencies that make them suitable for critical and more complicated jobs. Moreover, despite the younger workforce, they have a greater dedication at work (Varianou-Mikellidou et al., 2019). On the contrary, they could present higher ergonomics risks in some heavy jobs, they could take a longer time to recover from injuries, and they are more prone to chronic diseases (Benjamin et al., 2008). Consequently, their work-ability index (WAI), defined as the ability of a worker to fit his/her job, could decrease (Ilmarinen, 2007). As defined in Ilmarinen (2001), older worker's ability can be influenced by three factors: excessive physical activity; unsafety workplaces; poor organisation of work. Thus, both companies and academics should provide new and innovative solutions able to improve older worker' ability index. In this paper, we focus the attention on two factors that affect the older worker capacity: the physical activity and the organisation of work.

Focusing on physical activity, previous studies (Åstrand et al., 2002; Finco et al., 2019b) demonstrated that the maximum physical work-load capacity, also called Maximum Acceptable Energy Expenditure (MAEE), decreases for older workers and when working times increase. Consequently, by considering the same task and the related physical effort, a lower MAEE implies higher recovery time. It means that an older worker requires more rest despite a younger one to perform the same activity. According to Price's formulation (1990) for 8 hours of continuous work, the recovery time, also called rest allowance (R.A.) can be defined as follows:

$$RA = \max(0; \frac{EE - MAEE}{MAEE - ER}) \quad (1)$$

Where E.E. is the energy expenditure (or the mean working rate) related to the job to perform. It is expressed in Watt or kcal/min. MAEE for an "average" healthy worker is equal to 4.3 kcal/min, while E.R. defined as the energy expenditure in rest conditions generally assumes a fixed value equal to 1.86 kcal/min if worker rests in stand position. However, as demonstrated by Finco et al. (2019b), if the worker's features change, the Price's formulation can underestimate the rest time required by the worker. Thus, it is better to adapt Eq. (1) as follows:

$$RA = \max(0; \frac{EE - MAEE(WT;OP)}{MAEE(WT;OP) - ER}) \quad (2)$$

Where MAEE assumes different values according to the working time (W.T.) and the worker's features (O.P.) such as age, gender, body mass index, or the sedentary level. For more details, please refers to Finco et al. (2019b).

By an organisational point of view, job rotation strategy can be a straightforward and economical approach that companies can successfully apply to deal with workers variability. Job rotation is a strategy used to rotate workers from a workstation to another one at specific time intervals (Otto and Scholl, 2013).

During the last decades, academics have increased their interest in this strategy for several reasons. Firstly, it could be used to train multi-skilled or cross-functional workers (Ayough et al., 2012). Then, a reduction of absenteeism, boredom, monotony, cumulative-trauma, or physical risk could be reached by applying job rotation (Leider et al., 2015). Finally, managers can jointly achieve increments of efficiency, productivity and workers' safety (Otto and Scholl, 2013). In the last years, ergonomics risk indexes have been included in job rotation scheduling models to assure lower musculoskeletal disorders and higher productivity levels. One of the first attempts to include ergonomics assessment in job rotation is the study provided by Carnahan et al. in 2000. Then, several works have been developed, as summarised in the literature review provided by Otto and Battaia (2017).

However, to the best of our knowledge, only a few works focus their attention on the ageing effect in job rotation. In 2000, Gaudart analysed job rotation strategies that could be applied in a manufacturing plant focusing on the effects that age has on training and motivation of workers. Niessen et al. (2010) proposed an empirical study. Two questionnaires were proposed to employees of two multinational companies to evaluate the effects that job rotation can have in older workforce. Similar work has been conducted by Weichel et al. (2010). They analysed the effects of job rotation in an automotive company. In both works, they found that older workers rotate less than younger ones due to their high experience level. Jeon et al. (2016) evaluated, through surveys, eleven job rotation strategies in an automotive assembly plant. In their works, workers tend to perceive job rotation as a helpful method to enhance satisfaction, productivity and product quality more so than the actual production data suggests. However, according to the results of the surveys, job rotation was especially effective in preventing MSDs for workers aged under 45, while its effects were not apparent for the workers aged 45 years or older. To minimise risks and maximise productivity levels through job rotation strategy also some mathematical models have been already proposed. Boenzi et al. (2015) represented the first attempt to include age into a job rotation scheduling model. In their model, they maximised the overall system performance, including skills, experience and endurance limit. Workers have been categorised in homogenous groups according to their age. Results suggested that job rotation could be an adequate tool to achieve a high production rate and balance of workload jointly. However, their work presents some limits since inside an age category worker cannot have the same experience level, skills or physical capabilities. Finally, Botti et al. (2020) proposed a job rotation bi-objective model aimed to reduce the ergonomic risk by varying the required movements and their intensity from a side and by assigned to workers activities that better fit their skills. However, the model has not been tested in numerical or real cases. In both cases, authors do not consider labour costs even if they represent a critical issue for companies.

Thus, starting from the current state of the art, in the next section, a new job rotation scheduling model is proposed. In particular, we will integrate physical capacity and the experience level in the job rotation scheduling model with the final goal to maximise the daily productivity. In such a way, we will propose, for the first time, an integrated approach aiming to consider the required training, if necessary, and the workers' features (age and gender).

3. MATHEMATICAL MODEL

In this section, the mathematical model is proposed.

We assume to have *n* jobs to execute in a working day. A working day is composed by *s* working-shifts. Each job, *j*, has a nominal duration T_j while each shift, *k*, has a duration S_k. Workforce is composed by *M* workers with various features (age, skills, experience). The MAEE of each operator is known, and it varies according to worker *i* and shift duration *k*, $MAEE_{ik}$. Moreover, we assume to know the energy expenditure required by worker *i* to perform a job *j,* and we set this value equal to EE_{ij}. Since the workers' skills and the experience level are included in our model, we assume to know for worker *i* by performing job *j* his/her experience factor, and we set it as α_{ij}. It can assume values greater than or equal to 1 if a worker requires more time than the nominal one to execute the job correctly. If a worker cannot perform a job α_{ij} assumes a big value since we must avoid the assignment of the job to that worker.

We introduce the training factor δ_{ij} since in real industrial contexts unskilled, or low experienced workers, could require some training activities to execute a job correctly. It assumes a value equal to 1 if worker *i* requires training to perform the job j correctly. Otherwise, it is equal to 0.

According to the training factor, high skilled workers must support the unskilled during the execution of some jobs if it is required. In this case, the training factor, φ_{ij}, is used since it sets which worker *i* can support another one when job *j* is performed. It assumes a value 1 if he/she can support another worker, 0 otherwise. Moreover, each time a worker is involved in supporting, monitoring or controlling unskilled workers his/her physical effort can be negligible, and he/she is not available to execute other jobs. According to the years of experience, for each worker, a labour cost is defined and named C_i. Finally, for each job, *j,* a minimum number of items is required, z_j.

The decision variables of our model are:

- x_{ijk}, it assumes a value equal to 1 if worker *i* is assigned to job *j* during shift *k*, 0 otherwise;
- y_{ijk}, it assumes a value equal to 1 if worker *i* must support a colleague during job *j* in shift *k*, 0 otherwise;
- z_{ijk}, the number of items produced by worker *i* during job *j* in shift *k*;

The mathematical model is defined as follows:

$$\max \sum_{k \in S} \sum_{j \in J} \sum_{i \in W} z_{ijk} \quad (3)$$

Subject to:

$$\sum_i (x_{ijk} + y_{ijk}) \le 2 \ \forall j,k \quad (4)$$

$$\sum_i x_{ijk} \le 1 \ \forall j,k \quad (5)$$

$$\sum_j (x_{ijk} + y_{ijk}) = 1 \ \forall i,k \quad (6)$$

$$\sum_k x_{ijk} \le 1 \ \forall i,j \quad (7)$$

$$y_{ijk} \le \varphi_{ij} \ \ \forall i,j,k \quad (8)$$

$$\sum_i x_{ijk}\delta_{ij} = \sum_i y_{ijk} \ \forall j,k \quad (9)$$

$$\sum_k \sum_i z_{ijk} \ge z_j \ \ \forall j \quad (10)$$

$$0 \le z_{ijk} \le \left\lfloor \frac{x_{ijk} S_k}{\alpha_{ij} T_j (1 + RA_{ijk})} \right\rfloor \forall i, j, k \quad (11)$$

$$x_{ijk}, y_{ijk} \in \{0;1\}; z_{ijk} \in \mathbb{N} \ \forall i, j, k \quad (12)$$

Where objective function (3) maximises daily productivity. Constraint (4) and (5) assure that for each shift and job maximum two workers can be assigned. However, if they are two, one of them must help the other one. In each shift, the same worker can be employed to execute a job or to train an unskilled worker as defined in (6). Constraint (7) guarantees job rotation since the same worker must execute the same job only for one shift. Constraints (8) assures that only expert workers can perform training activities while constraint (9) guarantees that, for each shift and job, unskilled workers are supported by the skilled ones if required. Constraint (10) sets the respect of the minimum number of items required for each job. Constraint (11) sets the number of items produced by each worker in each job and each shift. Please note that in constraint 11 the number of items is influenced by the skill factor α_{ij} and the rest allowance that varies among workers and among tasks as defined by Equation (2). Finally, constraint (12) sets the type of variables.

4. CASE STUDY AND RESULTS

In this section, a numerical study derived from a real application of this model is proposed to test and validate the proposed model. The solver Cplex V12.8.0 with default parameters is used to solve the mathematical model.

We consider four shifts. They have a duration equal to S1=150[min], S2=120[min], S3=90[min], and S4=120[min]. Two short breaks, one in the mid-morning and one in the mid-afternoon, and the lunch break are planned.

Table 1. Job characteristics

JOB	t [min]	$Z_{\min}$	$\overline{EE}$ [kcal/min]
J1	6.9	20	5.15
J2	11.4	20	4.2
J3	14	20	4.99
J4	4	20	3.92
J5	7.5	20	5.62
J6	9.5	20	5.48

We assume to have six jobs to execute during the working day in six parallel workstations.

In Table 1, we report the nominal time, *t*, required to perform each job, and the minimum number of items required by each job. Each job requires a physical effort. However, as defined in Section 2, the energy expenditure for each job varies among workers and for this reason, in Table 1 we report the mean energy expenditure value. There are six workers, and they have distinctive features (age, years of experience, labour cost, MAEE) as defined in Table 2. Please note that each worker has an $\bar{\alpha}$ that is the mean value of α values of jobs. In the same way, $\overline{MAEE}$ is the mean value of MAEE related to shifts. The labour cost varies according to the years of experience. In Table 3, for each worker and job, δ_{ij} is given. As we can see, worker 1 requires support for all jobs ($\delta_{1j} = 1 \quad \forall j = 1,..,6$) since he/she is a new employee. Workers 2 and 3 have more experience; however, for some jobs, they still require training. Finally, we assume that workers W4, W5, W6 can be categorised as high-skilled workers due to their high experience level. Thus, they can support unskilled workers as defined in Table 4.

Table 2. Workers' features

WORKER	Age	Experience [year]	Labour cost [€/min]	$\bar{\alpha}$	$\overline{MAEE}$ [kcal/min]
W1	21	0	0.16	1.34	6.1
W2	32	4	0.23	1.15	6
W3	44	1	0.20	1.25	5.31
W4	48	15	0.32	1.07	5.19
W5	54	10	0.26	1.06	4.84
W6	59	20	0.37	1.05	4.62

Table 3. Training requirements [δ_{ij}]

WORKER/JOB	J1	J2	J3	J4	J5	J6
W1	1	1	1	1	1	1
W2	0	1	0	0	1	0
W3	1	0	1	0	1	1
W4	0	0	0	0	0	0
W5	0	0	0	0	0	0
W6	0	0	0	0	0	0

Table 4. Supporting experience [φ_{ij}]

WORKER/JOB	J1	J2	J3	J4	J5	J6
W1	0	0	0	0	0	0
W2	0	0	0	0	0	0
W3	0	0	0	0	0	0
W4	1	1	1	1	1	1
W5	1	1	1	1	1	1
W6	1	1	1	1	1	1

By applying the mathematical model proposed in section 3, we obtain the optimal job rotation plan, as illustrate in Table 5. In this case, the maximum daily productivity we can achieve is equal to 263 items.

Table 5. Optimal rotation plan

WORKER/SHIFT	S1	S2	S3	S4
W1	J1	J3	J2	J6
W2	J3	J6	J1	J4
W3	J2	J4	J3	J1
W4	J4	J5	J2*	J2
W5	J5	J1	J4	J1*
W6	J1*	J3*	J3*	J6*

As we can see in Table 5, W6 is always employed in training activities. During the first, second and the fourth shift, he helps worker 1 while in the third one he helps worker 3. Workers 4 and 5 are also employed in training activities but only for a shift. Worker 4 trains worker 1 during shift 3 while worker 5 helps worker 3 in the third shift.

Moreover, in order to evaluate how energy expenditure influences both daily productivity and job assignment, we conduct additional tests. We assume that jobs require different energy expenditure value, and we analyse the effect that energy expenditure can have on daily productivity. Additionally, we evaluate the impact of energy on the unit cost of each item. All workers are employed for 8 hours, and each of them must perform a job or training during each shift. Consequently, the mean unit cost of each item can be defined as the ratio between the total daily workforce cost and daily productivity. According to the costs of each worker defined in Table 2, the total daily labour cost is equal to 740 €/day.

Table 6. Objective function value for variable energy expenditure rates

$\overline{EE}$ [kcal/min]	O.F. [ITEMS]	UNIT COST [€/ITEM]
3.43	272	2.72
3.91	270	2.74
4.40	268	2.76
4.64	265	2.79
4.89	263	2.81
5.38	258	2.87

As depicted in Table 6, by increasing the mean energy expenditure, daily productivity decreases. If jobs have low energy expenditure rates, the number of items produced by workers is higher since they cannot require recovery time. Moreover, for low energy expenditure rate younger workers surely do not require rest time and consequently they are employed to execute tasks even if they require training. On the other hand, for high physical intensity jobs productivity tends to decrease for two main reasons. Firstly, for higher energy expenditure, all workers require rest allowance. Then, older workers are mainly employed in training activities despite production one since their productivity rate can be equal or lower than that one of a younger one even if they have higher experience level. This is mainly due to the reduction of physical capacity with an increment of required rest allowance to cover the physical fatigue spends during task execution.

In table 7, the number of shifts involved in the production (P-S) and those employed for training (T-S) of high-skilled workers are defined. We can see that worker 6 is always involved in training for more than 2 shifts, even if the mean energy expenditure is low. Moreover, we can note that for each mean energy expenditure value the total number of shifts employed for training is always 6. In fact, by maximising productivity we should avoid assigning tasks that require training to unskilled workers. However, in our case, worker 1 requires training for all jobs and consequently a high-skilled worker must support him in each shift. Worker 2 and worker 3 requires support only for some jobs. Thus, jobs that do not require support are suitable for selection than others since in these cases, high-skilled workers can be employed for production activities. However, in all cases we have tested, high-skilled workers are employed in training worker 2 and worker 3 for a shift. It happens because the productivity rate of unskilled workers is always higher than the skilled one because of recovery time.

Table 7. Number of shifts involved in production or training

$\overline{EE}$	Worker 4		Worker 5		Worker 6	
[kcal/min]	P-S	T-S	P-S	T-S	P-S	T-S
3.43	3	1	2	2	1	3
3.91	2	2	2	2	2	2
4.40	4	0	3	1	1	3
4.64	3	1	3	1	0	4
4.89	4	0	1	3	1	3
5.38	4	0	1	3	1	3

5. CONCLUSIONS

The ageing workforce phenomenon is an issue that needs to be included during the design of new production systems. In this way, from a hand companies can reach their efficiency level while, to the other hand, older workers can work in safe and comfortable workplaces.

However, the design of new workstations is not always possible since production systems may already exist. In this last case, re-design strategies may require high economics investments and time to quantify the benefits for both companies and employees. For this reason, if a short-term period is investigated, other solutions may be applied by including workers features. One of the most useful strategies that companies may apply is job rotation, and for this reason, in this paper, a new job rotation scheduling model is proposed. Both physical ageing effects and experience level are included considering workers' age and experience factors. The application of the model to a case study validates our model for several reasons. Firstly, for jobs that require high physical effort, younger workers are preferable than older ones since they require a lower rest time.

The model here proposed can be applied in all industrial contexts since the input data required to solve it can be easily collected with smart technologies such as a smartwatch. Moreover, we have demonstrated the necessity to integrate several aspects to better plan job rotation strategies. In fact, positive results can be achieved by balancing important trade-offs such as those ones here analysed: physical capacity and experience level.

As future works, a sensitivity analysis will be proposed to define drivers that majorly impact on productivity. Moreover, we will apply the model to several instances by proposing helpful guidelines for managers and practitioners. Then, the unit cost will be defined separately for each job and each shift in order to identify how labour cost impacts on the job rotation. Finally, Industry 4.0 solutions and smart technologies will be investigated in order to find solutions able to reduce both physical effort and training time (Grosch et al., 2020). Moreover, innovative solutions will be analysed to improve the productivity of all workers and reduce training made by high-skilled workers. For the training activities, augmented reality could be introduced. In this way, older workers could be employed in production activity despite supporting ones with benefits for both workers and managers. On the other hand, to reduce physical effort and improve general workers' well-being passive exoskeletons or collaborative robots could be applied to test if the energy expenditure required to perform a job decreases or not.

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