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### ► To cite this version:

Nicola Berti, Christian Artigues, Olga Battaïa, Romain Guillaume, Daria Battini. Heuristic approaches for scheduling manufacturing tasks while taking into account accumulated human fatigue. 9th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2019, Aug 2019, Berlin, Germany. pp.963-968, 10.1016/j.ifacol.2019.11.319 . hal-02962577

**HAL Id: hal-02962577**

**<https://hal.science/hal-02962577v1>**

Submitted on 9 Oct 2020

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# Heuristic approaches for scheduling manufacturing tasks while taking into account accumulated human fatigue

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**Abstract:** Human factors are often ignored in scheduling algorithms despite the fact that the majority of manufacturing systems still employ human operators. In particular, ergonomic studies shown that human fatigue has an important impact on worker performance and as a consequence it should be taken into account in the modelling of the system performance. This study investigates the problem of the integration of accumulated human fatigue into scheduling algorithms. A new optimization problem is defined and several constructive heuristics are developed to solve it. Their performances are evaluated through a numerical experiment. The conclusions of this analysis and future research directions are discussed.

*Keywords:* Scheduling, human factors, fatigue, constructive heuristics, optimization.

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## 1. INTRODUCTION

Decision-making process behind the scheduling of manufacturing tasks plays a fundamental role in industrial environment. Nowadays its impact on the system performance is more and more investigated due to the availability of manufacturing data (Pinedo, 2016). The main purpose of scheduling is to organize the manufacturing process in the best way that a performance function is optimized and existing constraints of the manufacturing environment are respected (Pinedo, 2005). Such performance indicators can be expressed in different ways such as flow time, work in progress and throughput (Digiesi et al., 2009), but also makespan, total weighted completion time, maximum lateness, and the total number of tardy jobs (Ferjani et al., 2017). However, most of them are profit/cost oriented. Only recently new models were proposed in order to optimize the working conditions such as to reduce physical workload (Mossa et al., 2016; Otto and Battaïa, 2017). It shows an important gap in scheduling literature where the impact of scheduling decisions on human performance and health is usually ignored (Lodree et al., 2009).

To fill this gap, a significant effort on modelling of human factors has to be made. This study is dedicated to the integration of one of such factors, human accumulated fatigue in scheduling decision-making process. The objective is to assign (and schedule) a set of given tasks to a number of human operators taking into account their fatigue and their need to have a break.

The remainder of this article is organized as follows. Section 2 presents the existing mathematical models used to evaluate human fatigue in manufacturing. Section 3 provides the new optimization problem we introduce and a small example of the considered problem. Section 4 presents the algorithms that we have developed to solve the introduced optimization problem. Section 5 reports the results of the computational experiments. Finally, Section 6 provides conclusions and suggestions for future research.

## 2. STATE-OF-THE-ART

Lodree et al. (2009) stated that in scheduling literature human factors are often ignored although their impact on the performance of the manufacturing system is considerable. The authors even claimed that the scheduling research and the human factors research literature represent two disjoint sets because of the rarity of collaborations between researchers of these communities.

However, Grosse et al. (2017) showed that recently the number of studies that try to integrate human factors into decision support models have increased because of the awareness on the impact of these factors on the final performance of the manufacturing systems. In particular, such human factors as physical ergonomic risks are more and more integrated in such optimization problems as assembly line balancing and job rotation as revealed a recent survey (Otto and Battaïa, 2017).

Regarding the human fatigue, some studies have already been conducted to identify fatigue causing factors which reduce the performance of workers, and consequently, the productivity of the manufacturing system. In the following, we overview the mathematical models the most frequently used for evaluating fatigue in the literature on manufacturing systems.

Eilon (1964) presents two formulas modeling the loss in production due to fatigue and the gain in production rate due to a recovery time. They found the net gain (call it  $p$ ) of production between these two conditions. Thus, a rest period is worthwhile if the gain exceeds the loss, then they found the maximum value of  $p$ . They also found at what point in time it is most beneficial to introduce a rest period.

Gentzler Jr et al. (1977) aim to maximize the function  $W(x)$  which is

$$W(x) = \frac{\phi(x)}{x + \theta}$$

where  $\phi(x)$  is the amount of work produced in one work period,  $x$  is the length of time of a work period and the length of a rest period and  $\theta$  is a constant long enough to ensure that the work rate of the next work period starts at  $v(0)$ , the unfatigued state. Setting  $W'(x) = 0$  states that the optimal time to introduce a rest period is when the average work rate of a cycle is equal to the instantaneous work rate.

Maximum endurance time (MET) is the duration for which a specific body posture (or muscular effort) can be sustained by a worker before his/her capability limits are reached. In Jaber et al. (2013), it is a function of the level of the force being applied i.e.,  $f_{MVC}$ , which is a fraction of the muscle's maximum voluntary contraction (MVC) when performing a specific task.  $MET = \beta_0 \cdot e^{\beta \cdot f_{MVC}}$  or power forms, e.g.,  $MET = \alpha_0 \cdot f_{MVC}^{-\alpha}$  where  $\alpha_0$ ,  $\alpha$ ,  $\beta_0$  and  $\beta$  are model-specific parameters and MET is measured in minutes. The model used in (Jaber et al., 2013) to evaluate fatigue is as follows:

$$F_{i+1}(t) = R(\tau_i) + (1 - R(\tau_i))(1 - e^{-\lambda(t_n - t_i)}) \quad (1)$$

- $R(\tau_i)$  is the residual fatigue carried forward into cycle  $i + 1$ ;
- $\lambda$  is a fatigue exponent, specifying fatigue rate;
- $t_n$  is the production time of the cycle  $i$ ;
- $t_i$  is determined by projecting the value of  $R(\tau_i)$  on the fatigue curve as:

$$t_i = \frac{-\ln(1 - R(\tau_i))}{\lambda} \quad (2)$$

Glock et al. (2019) use the description of fatigue accumulation above for developing a biomechanical model to estimate the expected fatigue-recovery parameters in manual packaging process. Moreover, the authors perform a sensitivity analysis of the fatigue parameter  $\lambda$  evaluating how the value of this parameter changes for modifications of %MVC by 10% and 20% (plus/minus).

The study of Perez et al. (2014) proposes the following behavior of fatigue accumulation while trying to simulate a dynamic process using static MET models:

$$F_t = fF_{t-1} + \frac{\Delta t}{MET_i} + \frac{\Delta t}{R_j} \quad (3)$$

The fatigue accumulation after  $task_i(F_i)$  is calculated as follows:

$$F_{i+1} = (F_{i-1} + fF_i) \cdot (1 - fR_i) \quad (4)$$

- $F_i$  is the fatigue rate after  $task_i$ ;
- $fF_i$  is the fraction of fatigue contribution per  $task_i$ ;
- $fR_i$  is the fraction of recovery received after  $task_i$ ;
- $R_i$  is the recovery time (in seconds) needed after  $task_i$  to bring fatigue down to 0.

In Givi et al. (2015), the fatigue accumulation in the “learning–forgetting–fatigue–recovery model” (LFFRM), is modelled by an exponential model of the following form:

$$F(t_i) = R(t_{i-1}) + (1 - R(t_{i-1}))(1 - \exp(-\lambda t_i)) \quad (5)$$

where  $F(t)$  is the accumulated fatigue over time  $t_i$ ,  $R(t_{i-1})$  is the residual fatigue after a break carried along cycle  $i - 1$ , and  $\lambda$  is the fatigue index describing the severity of the work performed,  $t_i$  is the length of the current production cycle and  $t_{i-1}$  is the length of the previous one. At time  $t = 0$ , fatigue is zero and as time increases, fatigue converges asymptotically to 1. A recovery function can be also defined.

Fruggiero et al. (2017) propose the following model to evaluate the amount of physical stress  $L_t$  accumulated by a worker  $L_t$  after time  $t$ .

$$L_t = \sum f_i \cdot t_i - \frac{L_{max}}{RA_i \cdot MET_i} \cdot b_i \quad (6)$$

where  $f_i$  is the amount of physical stress for executing task  $i$  of duration  $t_i$ ,  $b_i$  is the break time following task  $i$ ,  $L_{max}$  is the maximum fatigue index,  $RA_i$  (Rest Allowance) required for task  $i$  as a fraction of  $MET_i$ .

Ferjani et al. (2017) associate a penalty coefficient  $d_j$  to each machine  $j$  to model the difficulty of work on that machine, such that  $0 \leq d_j \leq 1$ . This coefficient  $d_j$  expresses the speed of fatigue accumulation. The value of  $G_i(\theta)$  characterizes how the level of fatigue of a worker increases.  $G_i(\theta) = 1 - e^{-d_j \cdot \theta}$  where  $\theta$  is the duration.  $F_i(t_i)$  is the worker initial fatigue at time  $t_i$ .  $\Delta_{ij}(t_i, t)$  expresses the increase of fatigue generated during a new task on machine  $j$ , between its beginning  $t_i$  and the current time  $t$ , which can be expressed as follows:

$$\Delta_{ij}(t_i, t) = (1 - F_i(t_i))(1 - e^{-d_j(t-t_i)}) \quad (7)$$

As a consequence, from time  $t$  to  $t_i$ , the level of fatigue is updated as follows:

$$F_i(t) = F_i(t_i) + \Delta_{ij}(t_i, t) \quad (8)$$

Since the aim is to correct the theoretical processing times to take the fatigue level into account, they suggest that these processing times increase according to a logarithm function, i.e.  $T'_{kj}(t_i)$  represents corrected processing time of the task waiting in the  $k$ -th position on machine  $j$  to which the worker  $i$  can be assigned at the instant  $t_i$ , as follows:

$$T'_{kj}(t_i) = T_{kj}(1 + \delta d_j(\ln(1 + F_i(t_i)))) \quad (9)$$

The parameter  $\delta$  represents the influence of fatigue. Typically, it allows a maximum degradation time to be considered, given that when it is zero then fatigue does not influence the task duration. They also develop an heuristic to dynamically assign workers to machines so as to reduce the mean flowtime. The proposed approach takes the impact of fatigue into consideration.



$$\tau_{r_k} = \frac{-\ln(\dot{E}_R) + \ln F(t_w)_k}{\mu} \quad (17)$$

It represents the time necessary to reach 1.86 Kcal/min from the value of energy the operator reaches when the threshold is exceeded. While the operator is restoring energy until the value of  $\dot{E}_R$ , a small amount of fatigue has to be considered in the total value of accumulated fatigue. This value is calculated with the formula:

$$\int_{t_{w_k}}^{t_{w_k} + \tau_{r_k}} R(\tau)_k = \frac{F(t_w)_k}{-\mu} \cdot e^{-\mu \cdot t_{w_k}} \cdot (e^{(-\ln F(t_w)_k) + \ln(\dot{E}_R)} - 1) \quad (18)$$

This amount of fatigue "accumulated during a break" can be considered as negligible, a fixed value is added each time an operator needs a break, for a precise estimation of the total accumulated fatigue.

In the next section, we present the constructive heuristics that we developed in order to find a compromise between the total makespan and the distribution of the fatigue among the operators.

#### 4. CONSTRUCTIVE ALGORITHMS

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**Algorithm 1** Calculate  $Makespan_{max}$

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*op, task* - read input data  
L is the list of unscheduled tasks, initialized with the set of given tasks  
**while** L is not empty **do**  
    *j* ← select Task (L, *op, task*)  
    *o* ← select Operator (*j, op, task*)  
    Schedule (*j, o, L, op, task*), Update L  
**end while**  
**return**  $Makespan \forall o \in op$   
**return**  $AccumulatedFatigue \forall o \in op$

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The pseudo-code of the general algorithm is represented by Algorithm 1. This algorithm uses 8 different rules for selecting next task. All of them use two criteria, if a tie occurs according to the first criterion, the second one is applied to select a task.

- (1) Max task duration & Min task energy
- (2) Max task energy & Min task duration
- (3) Min task duration & Min task energy
- (4) Min task energy & Min task duration
- (5) Max task duration & Max task energy
- (6) Max task energy & Max task duration
- (7) Min task duration & Max task energy
- (8) Min task energy & Max task duration

Algorithm 1 uses 9 different rules for selecting next operator: the criteria are applied in the specified order.

- (1) Min operator makespan & Min value of  $\lambda$
- (2) Min operator makespan & Max value of  $\lambda$
- (3) Min number of tasks already assigned & Min operator makespan & Min value of  $\lambda$
- (4) Min number of tasks already assigned & Min value of  $\lambda$  & Min operator makespan
- (5) Min number of tasks already assigned & Min value of fatigue & Min value of  $\lambda$
- (6) Min number of task already assigned & Min operator makespan & Max value of  $\lambda$

- (7) Min value of fatigue & Min Number of tasks already assigned & Min value of  $\lambda$
- (8) Min value of accumulated fatigue & Min number of tasks already assigned & Max value of  $\lambda$
- (9) Min value of accumulated fatigue & Min number of tasks already assigned & Min value of  $\lambda$  & Max value of  $\mu$

In the next section, we study the performances of these rules in a numerical experiment.

#### 5. COMPUTATIONAL EXPERIMENTS

##### 5.1 Example of solution

Figure 1 presents a short example of scheduling of 12 tasks and 5 operators following the rule 1 for task selection and rule 1 for operator selection. Parameters of tasks are given in Table 1. The personal characteristics of 5 operators are given in Table 2 as well as the makespan and total accumulated fatigue obtained as results of scheduling. The maximal difference in the accumulated fatigue among the operators is equal to  $358.85 - 127.01 = 231.84$ .

Task	1	2	3	4	5	6
$t_w$	15.0	8.7	12.6	17.5	6.8	10.5
$\dot{E}_w$	3.2	5.3	2.7	7	5.2	6.1
Task	7	8	9	10	11	12
$t_w$	9.7	13.6	18.3	15.9	7.7	16.5
$\dot{E}_w$	4.8	4.1	2.6	8.1	6.3	4.9

Operator	$\lambda$	$\mu$	Makespan	Accumulated fatigue
1	4.0	1.5	39.78	358.85
2	3.5	2.0	38.32	127.01
3	2.5	1.5	41.22	299.47
4	6.0	2.5	39.28	315.73
5	4.5	1.0	43.01	158.52

Table 1. Task and Operators' parameters

Figure 1 shows the obtained schedule of 12 tasks including the breaks required by Rest Allowance when the energy threshold is exceeded (value > 4.3). Final short breaks show how long should be the rest to return the energy expenditure rate to the initial value of 1.86 Kcal/min.

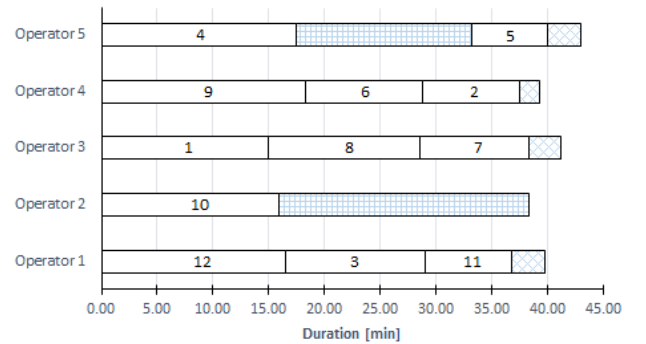


Fig. 1. Example of scheduling of 12 tasks

##### 5.2 Instance generation

Fifteen problem instances have been randomly generated for this numerical experiment. Each problem instance contains 24 tasks to be assigned to 5 operators. Each operator





order to solve this scheduling problem with the objectives to minimize the makespan and the maximal accumulated fatigue, 72 constructive heuristics have been developed and evaluated through a numerical experiment. The obtained results showed that the best task selection rules mix the most longest and the most difficult task selection. However, this approach has to be further developed in several directions. First of all, the heuristic rules can be integrated in a metaheuristic or hyperheuristic approach. Secondly, the impact of variability of personal characteristics of operators and difficulty of their exact measurement should be evaluated and this uncertainty should be integrated in the problem model.

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