Workers’ availability definition through the energy expenditure evaluation

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Abstract – This paper aims to evaluate worker’s availability for tasks and general activities that require a high level of physical effort, in order to study human availability in the industrial context. According to many studies, when physical effort for a specific working time is higher than a threshold value, workers are subjected to fatigue and so recovery time is mandatory to avoid injuries or accidents. However, the threshold value is influenced by workers’ characteristics like age, body mass, height, gender or level of aerobic exercises and for this reason, recovery time can assume several values according to workers’ features. Moreover, the workers’ availability cannot be the same for workers with different characteristics. For this reason, this paper proposes a new approach to define workers’ availability considering the worker’s age and the working time as two main features. Results are very interesting as they could help managers and practitioners to assign activities to workers according to their characteristics in order to maximize their productivity, reducing injuries and idle time at the same time.

1. Introduction

Nowadays, even if the automation processes are always more relevant, there are some activities, especially in production and logistics reality which must be performed manually and, sometimes they can require a lot of effort by operators’ point of view. For these reasons, a study regarding human availability in industrial realities, as machines one, is needed. Human activities that require a physical effort are often cause of injuries, accidents and musculoskeletal disorders as emphasized by [1]. For this reason, in last years, several types of research have been conducted to assure the workers’ well-being during the execution of manual warehousing, assembly and maintenance activities and the integration of ergonomics aspects in production processes has had an increasing interest also by company point of view [2]. Another important aspect that needs to be considered is the ageing of the working population in several countries. According to some available estimation, in Europe, the number of people aged 65 or older is about to grow from 85 million today to more than 151 million in 2060, with a decrease of 20 million in the number of workers [3]. In this way, the reduction of physical ergonomic risks has emerged as a priority topic on the agenda of production and operational managers to assure to the ageing workforce better working conditions and to maintain the desired productivity. To achieve this goal, companies need to evaluate ergonomic risks and to define corrective actions to reduce them. Nevertheless, improvements in workplace ergonomics are often translated into higher financial investments and this limits managers’ decisions. However, some economic but effective approaches can be used to reduce the worker’s physical effort and, consequently, to increase the ergonomics level. One of the mentioned strategies consists in considering the variability of work situations, namely in giving to workers the needed allowances to cope with the work elements variation. For this reason, during last years, operator’s fatigue level, both muscular and cardiovascular, has been considered in some relevant researches as an instrument to monitor workers’ comfort and to ameliorate the ergonomic level. In fact, monitoring the fatigue it is possible to define the adequate recovery time to return to the pre-stressor level of functioning [4]. Generally, muscular fatigue is used by academics, however, by a company point of view it is very difficult to monitor it due to the required instrumentation. However, interesting information can be collected considering cardiovascular fatigue, especially for activities that required the use of the whole body, such as the assembly of big-size products, picking activities. In this last case, the fatigue could be easily estimated using [5] or it could be measured by a heart rate monitoring [6].

Recently, [7] have proposed an approach to evaluate workers’ availability considering the number of injuries and their gravity and the ergonomic level at the same time. However, workers’ features are not considered as input variables.

For this reason, in this paper, considering the cardiovascular fatigue associated with the work level, we provide a new approach to evaluate the worker’s availability. Furthermore, we propose a framework to schedule the working activities that each worker must perform in a fixed working time starting from the energy expenditure required to perform the set of tasks. The age and gender are considered as variables worker’s features as they are the two main aspects that can impact cardiovascular fatigue. To the best of our knowledge, this is a first attempt to introduce the workers’ ageing problem in the activity definition phase.

The paper is structured as follows. Section 2 provides the necessary background to evaluate worker’s availability considering the energy expenditure associated with the activity to perform and the available working time. In Section 3 worker’s availability formulation is defined while Section 4 provides a new framework to assign activities to workers in order to maximize their efficiency considering their availability. Finally, conclusions and future researches are presented in Section 5.

2. Background

The approach developed to evaluate workers' availability considers energy expenditure as a criterion to evaluate their work capacity, their maximum acceptable energy expenditure for defined working time and the rest time required if fatigue arises. For this reason, in the following sub-sections, we present the theories and models to evaluate the individual work capacity, the Maximum Acceptable Energy Expenditure and the Rest Allowance (RA).

2.1 Maximum individual work capacity

The individual work capacity depends on its maximum aerobic capacity which is defined as the rate of maximum oxygen consumption (VO_{2MAX}) or the maximum energy expenditure (EE_{max}) spent in a minute by a person [8].

These maximum values can be obtained with the testing procedure or predicted by experimental equations. One of the most used by researches is defined in (1) [9]. As we can see in (1) the EE_{max} is affected by:

- age (Y);
- gender (G): 1 for man and 0 otherwise;
- body mass index (BMI) which is obtained by dividing the body mass (kg) by the square of the height (m);
- body mass (W);
- level of aerobic capacity (SRE) which depends on the physical activity performed by an individual in his free time. For example, according to Jackson and Ross's study [10] if a man, during his free time, weight lifting for 10 to 60 min per week his SRE is rated as 2.

$$\mathrm{EE_{max}} = 4.86\ \mathrm{W}\ [56.363 + (1.951\ \mathrm{SRE}) - (0.754\ \mathrm{BMI}) - (0.381\ \mathrm{Y}) + (10.897\ \mathrm{G})]/1000 \quad (1)$$

As the aim of this paper is to investigate the effect of the age in the worker's availability in Table II the EE_{max} has been calculated for several ages maintaining fixed the other impact factors according to Table I.

As we can see the maximum energy expenditures for both man and woman tend to decrease when age increases and this implies a lower physical effort admissible for an ageing workforce. This also explains the current trend to integrate collaborative robots to ameliorate working conditions [3].

TABLE I. Fixed workers' characteristics

Parameter	***Man***	***Woman***
Height [m]	1.80	1.65
Body mass [kg]	80	60
BMI	24.69	22.04
SRE	2	2
Gender	1	0

TABLE II. Maximum energy expenditure values [kCal/min]

Age	***25***	***30***	***35***	***40***	***45***	***50***	***55***	***60***
Man	16.62	15.89	15.15	14.41	13.68	12.94	12.21	11.47
Woman	9.89	9.34	8.78	8.23	7.68	7.13	6.58	6.02

2.2 Maximum Acceptable Working Duration (MAWD) and Maximum Acceptable Energy Expenditure (MAEE)

According to [11] for 8 hours of continuous work an individual can work without fatigue effects if his energy expenditure (EE) is between 30% and 40% of his EE_{max} and a typical fixed value used in high intensity work, as defined in [12], is equal to 33% of the EE_{max}. In particular, when the EE value is lower than 33% of workers are not subjected to fatigue and they can continue to work. On the contrary for an EE value higher than 33% of workers are subjected to fatigue effects and a continuous work could produce injuries or accidents.

However, for a lower continuous working time or for a higher intensity work the threshold value suggested by literature can underestimate or overestimated the fatigue level. For this reason, according to [8], a maximum acceptable work duration (MAWD) should be applied in such circumstances. Equation (2) defines the estimated MAWD considering the relative energy expenditure (REE).

$$MAWD(\mathrm{min}) = -2.09 + e^{6.59-5.6REE} \quad (2)$$

Where $REE = \frac{EE_{WORK}-EE_{REST}}{EE_{max}-EE_{REST}}$ and it is the relative energy expenditure while EE_{WORK} is the energy expenditure required to execute the activity and EE_{REST} is the energy expenditure in rest condition. Generally, the EE_{REST} is considered as a constant value for each age and it varies only by the gender. For men it is fixed to 1.64 kCal/min while for women, it is equal to 1.45 kCal/min.

Equation (2) can give important information about the maximum time that a worker can use to perform a set of tasks without fatigue effects. However, REE is considered as an input parameter and this can limit its application in real context since EE_{WORK} cannot be know a priori and can differ according to the execution time.

For this reason, arranging Equation (2) we consider the working time as an input parameter. Consequently, we evaluate the Maximum Acceptable Energy Expenditure (MAEE) that a worker can be subjected to a specific continuous working-time (WT) expressed in minutes. In this case, we obtain the following equation:

$$MAEE(WT) = EE_{REST} + (EE_{max} - EE_{REST})\left(\frac{6.59-\ln(WT+2.09)}{5.60}\right) \quad (3)$$

In Figure 1 the MAEE for man is illustrated considering several ages. We can see that for an increase of age a decrease of MAEE especially when the WT is less than 100 minutes. On the other side, for a higher WT the MAEE tends to decrease and, consequently, a high-intensity activity for a long period can be unfeasible.

According to [13], the threshold value linked to 33% of the EE_{max} is not relevant if the WT is less than 8 hours. Moreover, 8 hours of continuous work are not allowable as workers typically have two short breaks, also called mid-breaks, and the main one corresponding to the lunch time. Moreover, for high intensity and physically demand work activities workers can at least continuously work up to 6 hours.

For this reason, in Table III, for some relevant typical continuous WT, the MAEE is defined both for man and for a woman. These values will be useful to define the rest allowance as we will see in the next section. Additionally, we can note that the MAEE for a woman is lower than that one of the man colleagues. Consequently, the charging level or the maximum physical effort admissible for a woman will be considerably lower than this one for a man.

2.3 Rest allowance

Rest allowance (RA), also called rest time or recovery time is defined as the time required to cover the fatigue spent in the execution of tasks or high physical demand activities. In literature, especially in the last years, the concept of RA has an increasing interest by academics. As defined in [12] two main type of rest are permissible during the working time. The first one is considered as a fixed time linked to the personal needs and the basic fatigue while the second one depends on the type of activity to perform and to the available time to execute it. For this reason, this last type of rest, corresponding to the RA is the more relevant but at the same time the hardest to define due to the high number of factors that can influence it.

RA can be linked to muscular or cardiovascular fatigue. Considering the muscular fatigue an interesting literature review about RA is provided by [14] while for the cardiovascular fatigue, and so the fatigue linked to the energy expenditure, the most used formulations are those provided by [14] and [15].

Figure 1. Maximum Acceptable Energy Expenditure for man workers

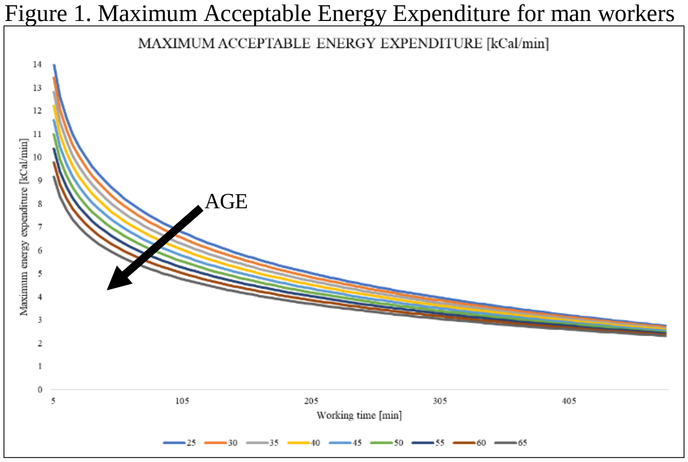


TABLE III. Maximum Acceptable Energy Expenditure [kCal/min] for different ages and working time [men (women) values]

Age	***Working Time***				
	60	***120***	***180***	***240***	***360***
25	8.23 (5.16)	6.42 (4.13)	5.35 (3.54)	4.59 (3.11)	3.51 (2.50)
30	7.90 (4.92)	6.18 (3.96)	5.17 (3.40)	4.44 (3.00)	3.42 (2.43)
35	7.58 (4.67)	5.95 (3.79)	4.98 (3.26)	4.30 (2.89)	3.33 (2.36)
40	7.26 (4.43)	5.71 (3.61)	4.80 (3.13)	4.15 (2.78)	3.23 (2.29)
45	6.93 (4.19)	5.48 (3.43)	4.62 (2.99)	4.01 (2.67)	3.14 (2.23)
50	6.61 (3.95)	5.24 (3.26)	4.44 (2.85)	3.86 (2.57)	3.05 (2.16)
55	6.29 (3.70)	5.01 (3.08)	4.26 (2.72)	3.72 (2.46)	2.96 (2.09)
60	5.96 (3.46)	4.78 (2.91)	4.07 (2.58)	3.57 (2.35)	2.87 (2.02)

In our case, we use the Murrel's formulation as defined in (4) on which the rest time depends on the WT and its associated MAEE, the mean energy expenditure expressed in kCal/min, and the energy expenditure in rest condition as defined in the previous section.

$$RA = WT \ \frac{EE_{WORK} - MAEE(WT)}{EE_{WORK} - EE_{REST}} \quad (4)$$

As we can see the formula assumes that no rest-time is necessary if the energy expenditure related to the WT is lower than the MAEE which represents the endurance limit. Additionally, considering the workers' characteristic RA varies and, in particular, it tends to increase when the same task is performed by an ageing worker rather than a younger one. For this reason, in the next Section, we will define a new strategy to evaluate the worker's availability integrating the RA concept.

3. Human's availability

Considering a production or a logistic system characterized by high-intensity human work, human availability and, consequently, the productivity of the system depends on the level of effort required by them to perform works. In this way, in the same way of machine availability, the worker's one can be defined as follows:

$$HA\% = \frac{WT}{WT + RA} \quad (5)$$

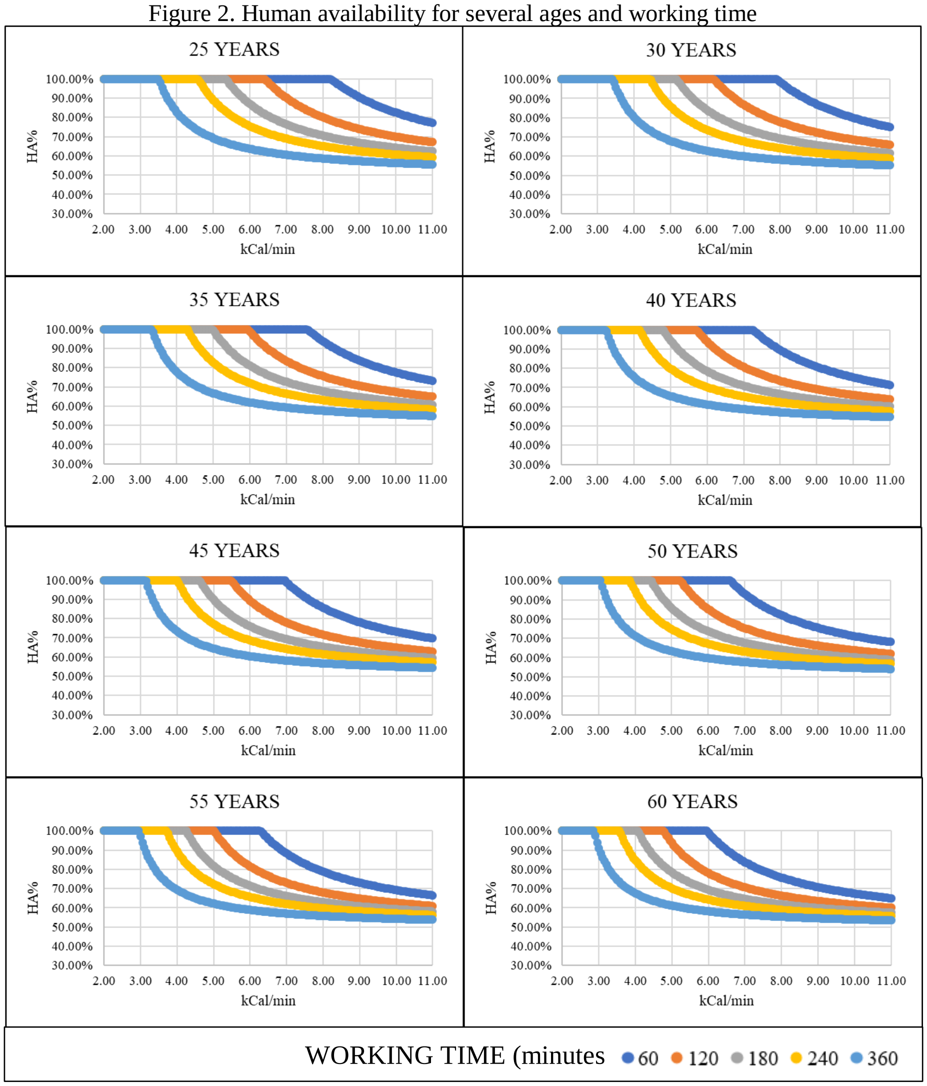
Where:

- WT is the time spent by the operator to perform the set of activities (value-added activity). It can be considered as the Up Time;
- RA is the extra time to give to the worker to cover the fatigue spent during the WT (no value-added activity). It can be used as the Down Time.

Consequently, RA has a crucial role to define the HA% as for a fixed WT a high RA determines a low HA%. In Figure 3 the HA% for several workers' ages and WT activities is illustrated.

In order to evaluate the effect of the energy expenditure in HA%, we consider the following simple example. A general warehousing activity requires 6 kCal/min. With this value, we enter in Figure 2 and we can see that for a worker of 25 years old his HA% is equal 100% if the WT is lower than 180 minutes. On the contrary, for prolonged WT the HA% decrease and it becomes about 64% if the activity is performed continuously for 360 minutes. In this last case, that is also an extreme case, the HA% value means that 360 minutes represents the 62% of the total time required by the worker to perform the activity because after the execution additional time is required to achieve the initial condition. To obtain the total time, that includes also the recovery time, we consider the ratio between the WT and the HA%. Furthermore, if we select another worker, older than the first one considered we can see that the HA% tends to decrease for a lower consecutive WT and it decreases rapidity for the ageing category workers (over 45 years old). As an example, for worker 60 years old the HA% varies from 99% (for a WT of 60 minutes) to 58% (for a WT of 360 minutes).

Figure 2. Human availability for several ages and working time



4. Framework to select the type of activities

The HA% can be helpful to check if activities that workers currently perform are balanced with an acceptable recovery time or not. At the same time, it can be considered as an instrument to select the type of activities that each worker can perform during a working day to avoid an excessive reduction in his availability. For this reason, we propose an innovative framework, as illustrated in Figure 3, to select the suitable worker from a selected team of available operators for a set of activities that are repetitively performed for a defined WT. After the team selection, the WT and the activities definition phase it is necessary to evaluate the total EE required to perform the set of activities according to [5] and [6]. For each member of the team, according to Eq. (3) the MAEE(WT) is defined and if the EE required to perform the activities is higher than this value the RA, through Eq. (4), is calculated. After that, the HA%, through Eq. (5), is evaluated and, finally, the worker that has a greater value of HA% is selected to perform the activity in the WT. In this way, it is minimized the non-value-added time associated with recovery the cardiovascular fatigue arises during the execution of the working activity. This implies two main benefits that involved both the company and workers. In fact, from the workers' side they have the appropriate time to cover the fatigue spent while, by the company point of view the recovery time is minimized and, consequently, the cost linked to this non-value-added activity is minimized. Additionally, from the company point of view the integration of the rest pause can be used to increase the production quality and to reduce the errors as defined in [16] or to decrease the risk of injuries or accidents caused by fatigue during the working time [4] Also, the workers' features are considering and, so, managers can better set the activities by workers' category. This framework can be used also as an instrument to evaluate when it is necessary to re-design or to change the way to execute some works. In fact, if a minimum value of worker's availability is set, managers can use it to define which type of activities have to be analyzed or which type of innovations can be used to reduce the operator's effort.

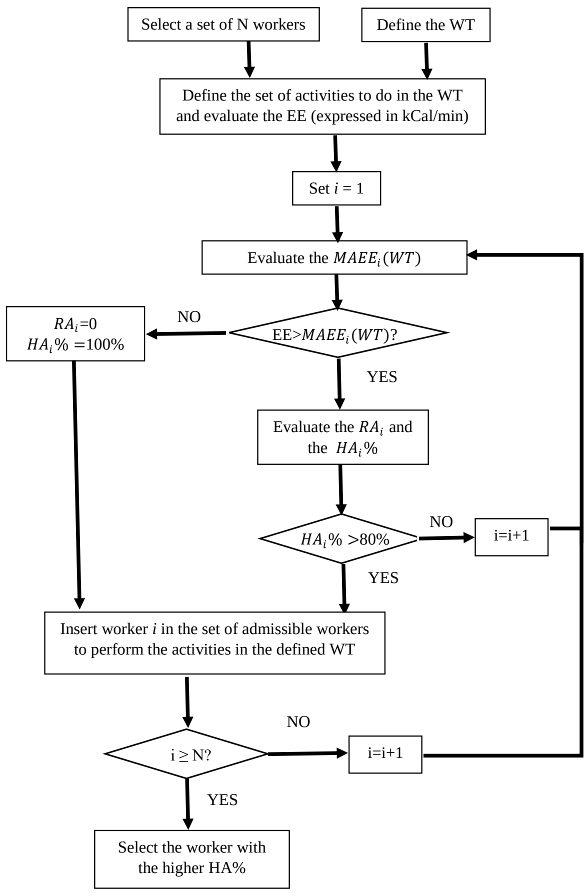


Figure 3. The process to select the more performant worker

5. Conclusion

In this work, we propose a new approach to evaluate the worker availability for working activities that require a high physical effort causing in this way a physical fatigue. In order to recover the fatigue spent during the working time period, according to the maximum acceptable energy expenditure rate of operators, the rest time concept is considered and it is used to evaluate the workers' efficiency. Moreover, the labourer's age is introduced as a variable parameter and its effect on the availability values is analyzed. The MAEE tends to decrease for increasing age and consequently, the rest time tends to increase causing a reduction of HA%. As future research steps, other models developed to evaluate the maximum aerobic work capacity will be considered and compared with the here proposed one. Furthermore, the application of the framework here proposed will be applied in a real application to better investigate the positive effects to evaluate the worker's fatigue and a cost model will be developed.

6. References

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