UNIVERSITA' DEGLI STUDI DI PADOVA
DEPARTMENT OF MANAGEMENT AND ENGINEERING

PH.D. SCHOOL IN MECHATRONICS
AND PRODUCT INNOVATION ENGINEERING
Curriculum: Industrial Plants and Logistics
Cycle: XXXI

HUMAN FACTORS IN INDUSTRIAL CONTEXTS:

FATIGUE AND RECOVERY MODELLING FOR MANUAL MATERIAL HANDLING ACTIVITIES

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Research sponsored
by Cassa di Risparmio di Padova e Rovigo

Human Factors in Industrial Contexts:
Fatigue and Recovery Modelling for Manual Material Handling Activities

by

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Submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy in

Mechatronics and Product Innovation Engineering

Department of Management and Engineering
University of Padova-Italy

October 2018

ABSTRACT

Many companies still rely on the humans for carrying on the activities in the production system. Subsequently in recent years there is an increasing interest in the understanding of how human issues can influence the performance of the system and of how the operators can be prevented from facing injuries or a decreasing of their performance. All the factors related to the human characteristics are generally known as "human factors", which are defined as follows:

"the scientific discipline concerns with the understanding of interactions among humans and other elements of a system in order to optimize human well-being and overall system performance".

Subsequently the human factors are related to physical, cognitive and the psychosocial interaction with the workplace. Recent literature has put in evidence the need of considering more these factors because there is a bilateral influence between the technical and organizational design features and the human effects such as their health and attitudes, their physical workload and their quality of work life and safety.

However, the influence of the factors related to humans on the production system is a topic which remains still uncovered by the literature because of the difficulty in quantifying the impact of something strictly linked to the kind of operator.

In relation to this, this PhD thesis aims at considering the human factors related to the physical fatigue experienced by the operators in order to improve the assignment of the activities to the operators. In fact, still now little literature has focused on the

consideration of the physical fatigue experienced by the operators in the workers assignment problem (WAP).

This thesis aims at solving this main research question by modelling the physical fatigue and recovery of operators performing manual material handling activities with the involvement of the whole body. In addition, it suggests the kind of device to be used for having feedbacks regarding the level of physical fatigue an operator is experiencing and it validates it by carrying tests firstly in a laboratory and after in a real industrial context. The data of these tests are the base for the proposed model of fatigue and recovery.

In relation to this, the PhD thesis structure is as follows:

1. State of the art analysis of the recognised impacts of human factors on manual material handling activities and of the recognised methods for monitoring the physical fatigue and for estimating the time the operator needs to recover according to level of fatigue cumulated.

2. Proposal of the heart rate monitor as the device to be used for a real-time monitoring of the physical fatigue of operators performing manual material handling activities. In relation to this, a real application is carried on in the laboratory and in an industrial field and the output of such device is compared with other existing technologies. Moreover, it is put in evidence how the only use of such device can help practitioners having a first indication of the best design of the workplace and of how to assign activities to the operators.

3. The influence of physiological factors relate to the operators are put in evidence thanks to the use of the heart rate monitor. This helped to model fatigue and recovery for each operator and to create a new formulation to set the time the operator has to recover according to his/her level of fatigue which is called "Rest Allowance". The differences between the proposed model and the existing ones in relation to manual material handling activities are put in evidence.

4. The proposed formulations for modelling fatigue and recovery are further developed for considering the way in which physical fatigue is accumulated by the operator if he/she has to carried on a certain number of activities sequentially without having the necessary time to recover. The developed formulation allowed to evaluate, case by case, if an improved operators activities assignment is required, and to quantify the effects of physiological factors and kind of activities on the best activities' assignment.

The data used for setting the model are obtained with the collaboration of the physiological department of the University of Padova and with several tests performed in an industrial field for different kinds of operators.

SOMMARIO

Molte aziende ancora oggi si affidano molto agli operatori per lo svolgimento delle attività produttive. Infatti, in questi anni c'è un crescente interesse relativo alla comprensione di come i fattori legati all'uso degli operatori possa influenzare le performance del sistema produttivo e di come si possa prevenire alla forza lavoro il rischio di infortuni o di un decremento delle loro capacità dovuto alle tipologie di attività svolte. Tutti i fattori legati alle caratteristiche proprie di ciascun individuo sono conosciuti come "fattori umani" e definiti come segue:

"la disciplina scientifica che riguarda la comprensione delle interazioni tra gli umani e gli altri elementi di un sistema produttivo al fine di ottimizzare il benessere umano e le prestazioni generali del sistema"

Si possono quindi legare i fattori umani a tutti gli aspetti che riguardano gli individui e la loro relazione con il luogo di lavoro, siano essi fisici, cognitivi o sociali. La letteratura recente ha messo in evidenza la necessità di considerare maggiormente questi fattori tenendo conto dell'influenza reciproca tra le caratteristiche tecniche e organizzative del posto di lavoro e gli effetti sugli operatori umani legati alla loro salute, al loro carico di lavoro fisico, alla loro sicurezza e alla qualità della vita lavorativa.

Sebbene la riconosciuta influenza dei fattori umani sul sistema produttivo, questo tema rimane ancora un argomento non molto sviluppato dalla letteratura. Questo è anche dovuto alla difficoltà intrinseca nel quantificare aspetti così strettamente legati alle caratteristiche individuali.

Lo scopo di questa tesi è di considerare più attentamente i fattori umani legati alla fatica fisica percepita dagli operatori durante lo svolgimento delle loro attività al fine di migliorarne l'assegnazione delle attività stesse. Infatti, finora poca letteratura si è focalizzata sull'influenza della fatica fisica in quello che è definito WAP (Workers Assignment Problem).

Nella presente tesi questa principale domanda di ricerca viene risolta modellando l'andamento della fatica fisica e del recupero per operatori che svolgono attività manuali che coinvolgono il movimento generale di tutto il corpo. Viene inoltre suggerito e validato attraverso test svolti in laboratorio e in vero contesto industriale lo strumento da utilizzare per avere un monitoraggio in real-time delle condizioni fisiche degli operatori. Sui dati raccolti si basa il modello proposto per la modellazione della fatica fisica e del recupero di ciascun operatore.

La tesi si struttura quindi come segue:

1, Stato dell'arte sull'analisi dell'impatto dei fattori umani sulle attività manuali, dei metodi esistenti riconosciuti per il monitoraggio della fatica fisica e per stimare il tempo di recupero degli operatori in base al loro livello di affaticamento

2. Analisi dell'uso del cardiofrequenzimetro come strumento per avere un monitoraggio in real-time del livello di fatica fisica degli operatori che svolgono attività manuali. Viene anche presentata l'applicazione di questo strumento in test svolti in laboratorio e in un contesto industriale. L'uso di questo strumento viene comparato che altre tecnologie esistenti e viene messo in evidenza come l'uso possa aiutare a dare una prima indicazione dell'influenza del design del posto di lavoro sugli operatori e di come assegnare loro le attività.

3. Modellazione della fatica e del recupero per ciascun operatore considerando l'influenza dei fattori fisiologici di ciascuno, messi in evidenza dall'uso del cardiofrequenzimetro. Viene proposto una nuova formula per la stima del tempo di recupero di ciascun operatore, chiamata in letteratura "Rest Allowance". Vengono

messe in evidenza le differenze tra questo modello e quelli esistenti in relazione alle attività manuali.

4. Le formulazioni relative alla modellazione della fatica e del recupero sono sviluppate per considerare come la fatica fisica si accumuli se l’operatore deve svolgere più attività in sequenza senza avere la possibilità di riposarsi il tempo adeguato. Questo ha permesso di analizzare in quali casi sia meglio focalizzare l’attenzione sul miglioramento dell’assegnazione delle attività agli operatori e come i fattori fisiologici degli operatori e la tipologia di attività da svolgere possono influenzare l’assegnazione delle attività.

I dati utilizzati per lo sviluppo del modello sono stati ottenuti con la collaborazione del dipartimento di fisiologia dell’Università degli Studi di Padova e attraverso diversi test svolti su più operatori in un contesto industriale.

ACKNOWLEDGMENTS

Three years have gone from the beginning of this PhD. Three years of new and challenge experiences, three years in the world of research with the aim of trying to perform something new in the world of existing knowledge. Last but not least three years of personal and professional growth that have given me the possibility of discovering myself and the others through the professional collaborations built and carried on during these years. It’s now the right time to thank all the people who have walked with me during this path, with their personal and professional support. First of all, I want to thank my supervisor Professor Alessandro Persona for having believed in me before all the others, for the enthusiasm and the interest he succeeds to transmit and finally for his capacity of finding good in people. Moreover, I want to thank Professor Fabio Sgarbossa and Martina Calzavara for their constant collaboration, for their suggestions and for having helped me understanding that the obstacles are only the possibility of growth. A thank also to Professor Daria Battini for giving me the possibility of discovering the world of research through several experiences. Thank also to Ilenia, Serena, Silvia, Francesco and Amine for the nice time spent together in the PhD office and for their support. Last but not least a sincere thank to my family and my companion for their constant support in this path.

No goal can be reached by yourself. It's collaboration with others, knowing how to learn from others, knowing how to help and asking for help that makes you reach great goals.

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I. Introduction

1.1 Human factors in industrial contexts

Wilson (2000) defines Human Factors (HF) as "the theoretical and fundamental understanding of human behaviour and performance in purposeful interacting socio-technical systems, and the application of that understanding to the design of interactions in the context of real settings". The human factor is a considerable agent that has a relevant impact on the productivity both in term of time and quality in industrial contexts, especially in those ones that require several types of manual activities with a different level of experience and knowledge. In recent years, experts and practitioners have increased their research on the impact that human factors could have in final productivity to improve productivity and to guarantee better ergonomic conditions in the workplaces. Following as define in Otto and Battaia (2017) workplace ergonomics depends on three main aspects: physical, cognitive and organizational factors. The physical aspects play the most significant role and for this reason, they are also those ones most used by companies to evaluate the workers' ergonomic conditions. In fact, a better ergonomic workplace could guarantee a higher workers' well-being and increasing performance of the global organization. On the contrary, a poor ergonomic design of a general workplace can generate a large number of sick leaves due to musculoskeletal disorders (MSDs). In addition to these aspects, it is necessary to take into account the presence of highly skilled elderly workers not easily interchangeable with robots. 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 (EC, 2014). The EUROSTAT estimates that by 2060, 30% of the population of the 27 EU countries will be over 65 years old. This means that the ratio of productive individuals to retired people will be 2:1, versus the current ratio of 4:1. According to some estimation, about 44 million workers in Europe suffer from occupational musculoskeletal disorders (Nunes, 2009). They represent the 38% of occupational diseases with a cost up to 2% of the Gross National Product in the EU. For these reasons, the increasing of ergonomics conditions is closely linked to a general reduction of costs. Different studies have been conducted to define in which way a worker could be affected by MSDs. David (2005) provides an overview of the range of methods that have been developed for the assessment of exposure risk factors for MSDs. There are three main dimensions that can impact the physical work: level, time and frequency of different forces and shifts. Another important aspect to consider in the evaluation of physical work is the operator's characteristics and for this reason, it is very difficult to define a general model able to evaluate the execution risk of a task or work (Dode et al., 2016). Different studies have been conducted to evaluate in a quantitative way the risk associated to a particular type of work and different methods have been developed to analyse the ergonomic risk for a particular part of the human body (NIOSH, RULA, REBA, OCRA, EAWS are the most important).

Even though, companies have continuously tried to reduce the ergonomic risk of jobs that are manual and repetitive such as assembly activities, less attention has been paid to activities where the whole body is involved such as manual material handling activities in considering the impact of human factors on the performance of the production system (Grosse et al., 2015). Such performance can be related to the physical aspects (e.g. the posture of operators and physical fatigue), to the mental aspects (e.g. the competency of operators) and to the psychosocial aspects (e.g stress and motivation of the operators).

1.2 Manual material handling activities

Manual material handling activities are the ones related to the activities of lifting, lowering, pushing, pulling, carrying and holding. Any combined manual material handling task (MMH) is composed of a mix of the kind of activities cited (Rajesh; 2016).

Even though, there is an increase of the use of mechanization in industrial contexts the manual material handling activities are still performed by humans and they are the major cause of lost work, increased cost and human suffering in the workforce (Waters and Putz-Anderson, 1996; Rajesh, 2016). In fact, manual material handling activities are the most frequent and costly category of compensable losses: they imply 36% of the claims and the 35% of the total cost. The injuries due to these kinds of activities are lower back injuries, which consist of the 22% of all the work injuries, hip and shoulder injuries, strains and sprains. The cause of occupational injuries is recognised in the overexertion, which accounts for the 31% of all the injuries (Waters and Putz-Anderson; 1996).

In the handling of an object the risk of injury is affected by the material characteristics and the task characteristics. But these are not the only factors which need to be taken into account. In fact, equal attention should be paid to the operator characteristics and the environmental conditions, in which the operator has to carried on the activity.

The material characteristics are related to the weight and size of the object to be moved: higher weights increase the force requested to the operator and consequently the loading on muscles and joints. In addition to the characteristics of the object to be moved, the task characteristics have also an influence on the capability of the operator of carrying on manual material handling activities. In fact, tasks with high frequency and long duration increase the physical demand requested by the task. But these are not the only task variables to be considered. An increase of the risk of injuries and a decrease in the performance of the operator is also attributable to the speed at which the movement is performed, to the position of worker and to the range of movements required during the performance of a task. Related to this, it has been put in evidence that the biomechanical load increases if the operator assumes awkward positions during the performance of the activity and if he has to lift in different ranges.

Considering the importance of humans for carrying on such kind of activities, their personal characteristics can have an impact on the way in which MMH activities are performed. These characteristics are not only related to the general health conditions but also to the physical factors such as height, reach, flexibility, strength, body weight, aerobic capacity and to the psychological factors such as stress and motivation. In this sense, it needs to be taken into consideration also the pre-existing musculoskeletal problems and the way in which the specific operator interacts with the given equipment.

Moreover, the environment can affect the operators' capabilities of performing the task: extreme conditions of heat, cold or humidity increase the physiologic demands of the body, physical obstacles can increase the distance travelled and constraints to the movements can increase the difficulty of lifting and give disadvantages in the use of proper lifting techniques. Finally, there is the influence of the organizational characteristics which are linked to the production rates established and to the operating policies set by the organization in addition to the ones related to the operators incentives and to their training.

According to this, in Table I.1 it is summarized the factors affecting the biomechanical demand requested by a worker.

Table I.1 Factors influencing the performance of MMH activities

TASK CHARACTERISTICS	OPERATORS CHARACTERISTICS	ENVIRONMENTAL CHARACTERISTICS	ORGANIZATIONAL CHARACTERISTICS
Frequency of the activity Duration of the activity Weight of the object Size and shape of the object Location of the load Postural requirements	Gender Body weight Height Aerobic capacity Preexisting musculoskeletal problems Physical fitness and training Medical history Psychosocial factors	Temperature Humidity Light Noise Vibration	Production rates Incentives policies Training policies Operating policies

There exist several techniques for the analysis of manual material handling tasks as put in evidence in Ciriello and Snook (1999): biomechanical, psychophysical, physiological and epidemiological techniques.

In the biomechanical techniques it is evaluated the biomechanical impact to the spine caused by sudden loading (Ning et al., 2014) in order to understand how the activity can, in case, be redesigned for reducing the average muscle activation and the spinal compression force and for increasing the spinal stability. According to this, there have been created dynamic models for modelling the segments of the body and the external load and in some cases the forces are estimated with validated devices such as electromyography (EMG). For such models it is necessary to know the trunk kinematics and geometry and the subject-specified moment arms and cross-sectional areas (Ning et al., 2014).

Instead, in psychophysical techniques (Snook and Ciriello, 1991), it is considered the psychophysical methodology with the measurements of oxygen consumption, heart rate, and anthropometric characteristics for the setting of the tables related to the maximum acceptable weights and forces. In such techniques, the frequency of the tasks, the distance, the height and the duration, the object size and handles are considered as independent variables.

On the other side, in physiological techniques such the one of Garg, Chaffin and Herrin (1978), a manual material handling task is evaluated by knowing its metabolic rate by creating a metabolic rate prediction model for a wide variety of manual material handling tasks. In such models all the factors except the ones related to the environment and the training of the work are taken into account.

Finally, the last technique used for the assessment of MMH activities, the epidemiological one, try to suggest quantitative assessment of mechanical exposure by finding the relationship between mechanical exposures and musculoskeletal disorders for large population.

All these techniques do not consider the effect that a specific activity, with its duration and intensity can have on a specific operator with his/her personal characteristics. In addition, most of them are focused on the mechanical load and the musculoskeletal disorders instead of considering the changing of energy expenditure rate of the operator during the performance of the activity (Garg, Chaffin and Herrin, 1978).

1.2.1 Impact of human factors in manual material handling activities

As put in evidence in the paragraph before, a lot of variables related to the characteristics of the task, of the operator and of the environment take part during the performance of manual material handling activities. Their effect has been analysed by existing literature in order to give suggestions related to how the activity should be redesigned.

In relation to the characteristics of the task it has been evaluated the optimal positions of boxes in relation to their size and to the manual handling position (Jung, 2010). As far as lifting and lowering activity is concerned, it has been analysed for the first the impact of box size, frequency and horizontal reach on the maximum acceptable weigh (Ciriello, 2003), for the second the effect of the box size, vertical distance and height (Ciriello, 2001).

Moreover, for pushing activities it has been put in evidence the effect of the height of the cart load on the force requested to an operator (Al-Eisawi et al., 1999).

In addition, regarding the influence of operators' characteristics, recent literature has put in evidence the influence of the gender on the maximum acceptable weight and forces for lifting, lowering, pushing, pulling and carrying (Ciriello et al., 2011).

Subsequently, recent literature has tried to take into account the impact of the variables put in evidence in the paragraph before, also by introducing new technologies such as a wearable motion capture system for evaluating the physical exposure in MMH tasks (Kim and Nussbaum; 2013) and by considering the load limit for the individual subjects performing a combination of material handling tasks using the oxygen consumption protocol (Dempsey et al., 2008).

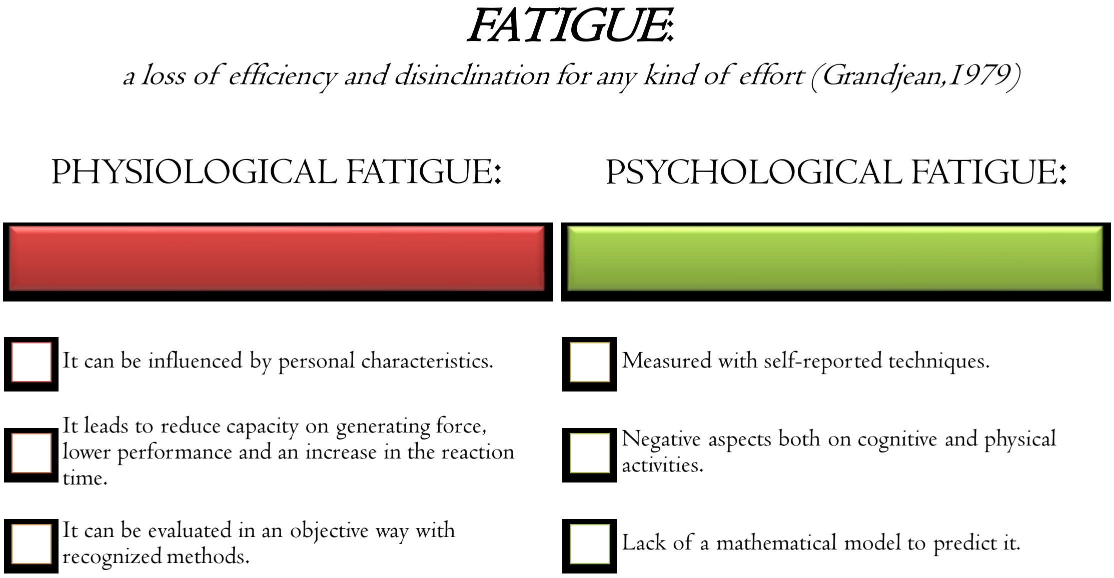
Even though, much attention has been paid by considering the effects of the tasks characteristics in order to redesign the activity, less attention has been paid to the managing of the operators' manual material handling activities by considering the effect that a predetermined activity can have on the fatigue experienced by a specific operator. This analysis has become important because an overuse of operators' capabilities can lead to musculoskeletal disorders in the long- term period in addition to a slowing down of the performance in the short term.

1.3 Physical Fatigue

The Fatigue is defined by Grandjean (1979) as *"a loss of efficiency and disinclination for any kind of effort"*. Generally, the fatigue experienced by operators is divided into physical and mental fatigue. The first one is due to physical efforts which reduces the maximal capacity of the operator in generating force or power output. On the other side the second one caused in the operators feelings of stress and disinclination for any kind of efforts. As put in evidence in Figure 1.1 these two kinds of fatigue are distinguished by different characteristics.

A job can have both the influence of these two kinds of fatigue but normally there is a predominance of one of them in relation to the kind of activity to be performed. Generally, for a material handler the physical fatigue influences more the performance than the mental one (Konz, 1998a). The physical fatigue is due to static or dynamic exertion and its value is affected by personal characteristics of the operators such as sex, age, weight, level of training, health status. Its accumulation can cause an increase in the time necessary for the contraction of the muscles and in the performance of the movement to be carried on.

On the other side the mental fatigue is linked to the individual's ability to concentrate and can be evaluated only by asking the operator a subjective evaluation of his/her level of mental tiredness through the use of self-reported techniques.



FATIGUE:

a loss of efficiency and disinclination for any kind of effort (Grandjean,1979)

PHYSIOLOGICAL FATIGUE:

☐ It can be influenced by personal characteristics.

☐ It leads to reduce capacity on generating force, lower performance and an increase in the reaction time.

☐ It can be evaluated in an objective way with recognized methods.

PSYCHOLOGICAL FATIGUE:

☐ Measured with self-reported techniques.

☐ Negative aspects both on cognitive and physical activities.

☐ Lack of a mathematical model to predict it.

Figure I.1 Physiological and psychological fatigue

Considering the major impact of physical fatigue rather than the mental one and the possibility of evaluating it through objective ways the focus of the analysis of human factors in manual material handling activities will be how to monitor this kind of fatigue and how can be set the level of fatigue of an operator. In fact, there exists several recognised devices to be used for evaluating the level of physical fatigue: the electromyography (EMG), the maximum endurance time (MET), the heart rate, the blood pressure, the blood perfusion and the levels of oxygenation. Related to this, the physical fatigue can occur on different parts of the body causing different levels of reduction of the force in different parts of the body. In fact, as stated by Konz (1998b) there exists the general body fatigue for activities where the whole body is involved causing more or less the use of all the body parts, both the upper and the lower part of the body and the muscular fatigue that is linked to the continuous used of the same group of muscles during repetitive activities. According to this, these two kinds of fatigue need to be monitored in different ways. The general body fatigue normally has an effect on the cardio-vascular system and is monitored with the analysis of the energy expenditure rate of the specific activity taken into account. On the other side the muscular fatigue can be better evaluated by considering the condition of the group of muscles used during the performance of the physical effort requested to the operator. Subsequently, the most used units of measures of this kind of fatigue in the literature are recognised as the Maximum Voluntary Contraction (MVC), which is the peak force produced by a muscle when it contracts and the Maximum Endurance Time (MET) which is the maximum time that a muscle can sustain a load during an isometric contraction.

For manual material handling activities, in addition to the predominant influence of the physical fatigue, it needs to be considered that the whole body is used. For example, in order picking activities both the upper and lower part of the body are used for reaching the item, picking it (normally with the two hands) and putting it on the pallet. Subsequently, in the analysis of fatigue of the following thesis the focus will be the general body fatigue caused by manual material handling activities, which level is stated by knowing the energy expenditure rate (Figure 1.2).

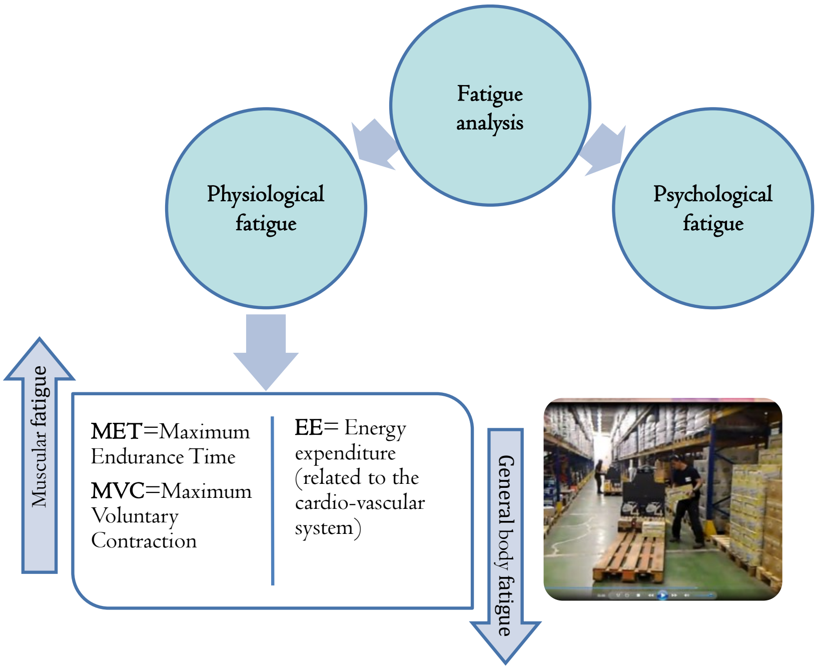


Figure 1.2 General body and muscular fatigue

In fact, as can be seen in Figure 1.3, even if activities characterised by repetitive movements of the same body parts (such as assembling activities) have similarities to the manual material handling ones in relation to the use of human resources, of the impact of both physical and physiological fatigue and the consequently necessity of an adequate time to recover, they differ substantially one from the other.

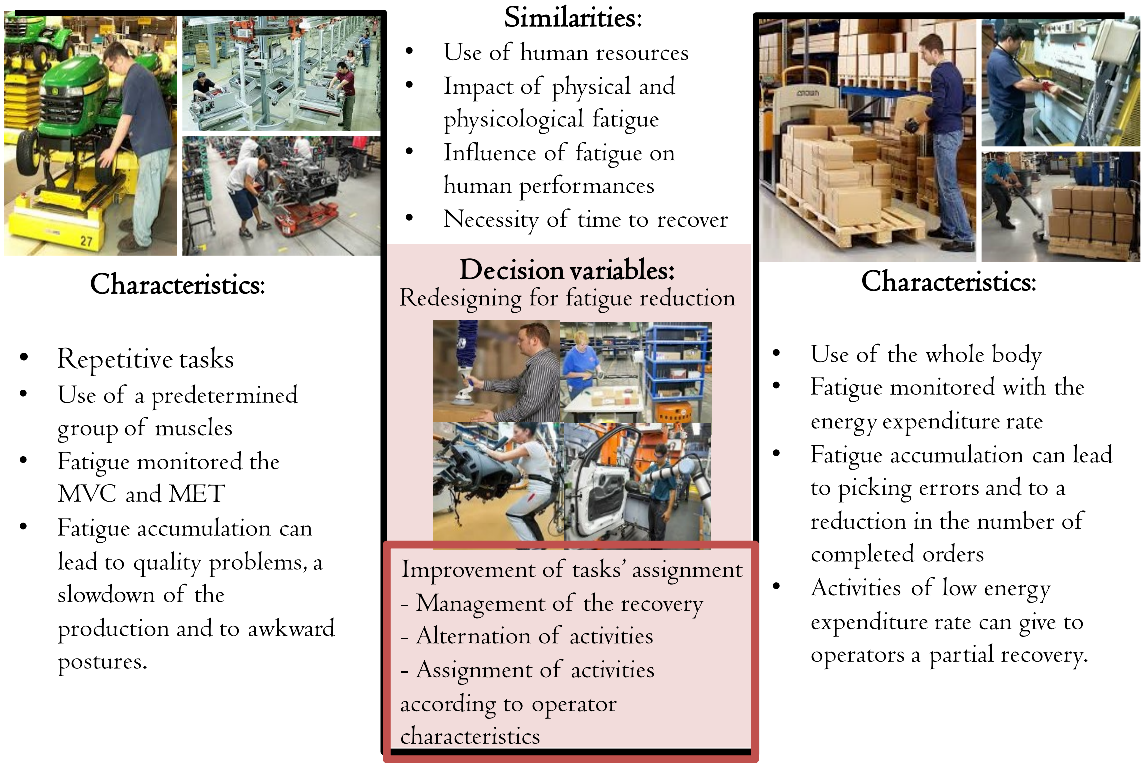


Figure 1.3 Comparison between repetitive tasks and MMH activities

Considering the existing literature, focused on the consideration of the factors influencing manual material handling activities for giving information to practitioners regarding how to redesign the workplace and the tasks to be performed by the operators, there is the necessity, on the other side, of a better understanding of how the tasks should be assigned to operators (Figure 1.3).

Related to this, more attention should be paid on human factors related to the influence of the personal characteristics of the operators and on the management of the sequence of activities to be given to each operator, considering also the necessity to have some time for recovering.

1.4 Methods and devices for monitoring the physical fatigue

Muscle fatigue reduces the ability to exert a force in a voluntary effort. Reduction of forces and fatigue lead to ergonomic risks and work-related MSDs. The worker's fatigue level can also affect the final product quality and the production rate with a cost incrementation for the companies (Otto and Battaia, 2017). It is possible to define two main type of fatigue: general fatigue and muscle local fatigue. The general fatigue can be evaluated through the human energy expenditure index. In Garg et al. (1978) energy expenditure index for common manual tasks and body movements is evaluated and it is composed of two terms. The first one represents the energy required to maintain a body posture while the second one represents the energy required to perform a specific activity. A high energy expenditure is associated with a high risk of musculoskeletal disorders (Hoozemans et al. 1998).

Instead, the muscular fatigue can be quantified through the Muscular Endurance Time (MET) models. As defined in Imbeau and Farbos (2006), MET is defined as the maximum time that a muscle can sustain a mechanical load during a static exertion. Generally, the fatigue index is expressed as a differential equation, depending on the maximum voluntary contraction (MVC) and the external load or the forces to which the muscle is subjected. Muscular recovery is complementary to muscular fatigue accumulation.

There are several aspects that impact in the local muscular fatigue. In Ma et al. (2009) the forces and torques applied to the human body are considered with the total load to carry or to move to assembly parts. Another aspect to evaluate is the repetitiveness of some tasks and the tasks execution scheduling. In order to reduce the local muscle fatigue, Michalos et al. (2010) propose a re-scheduling model that integrates workers' competences, fatigue, distance travelled, costs and repetitiveness of tasks. In order to decrease the local muscle fatigue, special tools have been created to generate particular job scheduling analysis and to underline the more critical parts of the body.

To integrate workers' fatigue evaluation in the work design digital human modelling (DHM) technique has been used more and more in the industry taking human as the centre of the work design system (Chaffin, 2002).

Forceful exertions have been considered to be the most important cause of musculoskeletal disorders related to the upper extremity. In the literature, there are different methods for assessing the magnitude of physical exertions, but not all of them can be put into practice during the design phase of the workstation. In addition, these methods can be grouped into qualitative and quantitative methods. The first are based on the prediction of the workload basing on subjective evaluations of the workplace or on predictions based on the workstation layout, the second rely on the data that can be recorded by using validated devices. Consequently, for a practitioner, it is not easy to establish which is the best method to be used for making decisions. In relation to manual material handling activities, there still lacks the indication of the kind of device to be used by a practitioner for having a feedback regarding the fatigue an operator is experiencing.

1.4.1 Qualitative methods

Qualitative methods could consist of subjective evaluations which are based on verbal estimation given by the operators during the performance of the activity. The advantages of using such techniques are related to low costs in terms of money in comparison of the investment necessary for buying an instrument and in terms of time needed to understand how to use and how to test it in the specific industrial context. Moreover, as put in evidence in Borg (1998) subjective evaluations can give a feedback not only regarding the stress of the muscles and joints during the activity but also of the central nervous system. Despite these advantages, they are influenced by subjectivity and this leads to the difficulty of assessing the accuracy and the variability of the measure between different operators. In fact, the evaluation of an operator for the same load can be different if he performed previous physical efforts and he experienced fatigue accumulation on the muscles. In addition, the precision of the measure is different if the operator has previous exposure to the benchmark (Marshall et al., 2004). The accuracy of verbal estimation of the load can increase if the operator performed a maximum exertion before the evaluation of the intensity of the force related to the load (Marshall et al., 2004). According to this, in Jakobsen et al. (2014) it is analysed the relation between the exertion perceived by the operator with Borg's scale (Borg, 1998) and the cardiovascular and muscular workload assessed with the ECG (Electrocardiography) and with the EMG (Electromyography) for lifting tasks. Subjective evaluations can be put in practice not only in the existing workstations but also in the design phase if the loads to be lifted, pushed or pulled are available or if they can be reproduced. In addition, it can be considered as qualitative methods the existing tools which can predict the workload and the time with the information regarding the layout of the workstation with simple biomechanical regression models and Methods-Time Measurement (Greig et al., 2017). This tool, which permits to estimate the %MVC, is a kind of observational method and can be put into practice easily in the design phase in a hypothetical virtual environment where the design input parameters are known. The disadvantage that such a tool has is that it can be applied only on workstations where the operator is fixed in a workstation and there is only the movement of arms and shoulders for assembling the item in the workbench.

Moreover, there is the possibility, for a practitioner, to apply digital human modelling simulation for estimating the load reproducing the real activity in a virtual environment. The simulation permits to evaluate a task months before having the real components available or during the designing of the workplace. But the simulation tool needs to be further developed to be applied in an industrial context because more data need to be recorded in the field for different kinds of activities and there is the need of matching these data with the ones recorded with validated devices such as a dynamometer.

1.4.2 Quantitative methods

Quantitative methods are related to the real measurement of the load through the use of existing devices such as the EMG or the dynamometer. As put in evidence in Lee et al. (1991) the activity of pushing and pulling have an effect on the lower back. Generally, the pushing determines a smaller lower-back loading in comparison with pulling. For both the activities, there is an influence of the weight and height of the subject who has to perform the activity and of the handle height of the cart to be pushed or pulled. The body weight influences more the pulling than pushing and for each activity, there is a proper handle height for minimizing lower-back load (Lee et al., 1991). In addition, the cart characteristics can also affect the push and pull forces (Al-Eisawi et al., 1999). It has been put in evidence that the minimum push and pull forces are proportional to the weight of the cart and inversely proportional to the wheel diameter. Even more recent literature (Garg et al., 2014) has put in evidence the important factors that should be considered by industries in the design phase: the friction, wheel and weight and handle height of the cart, the grade or slope of the floor and the trunk posture, the feet placement of the operator and the pushing and pulling frequency and distance.

Consequently, for pushing and pulling activities it is necessary to carry on proper evaluations in each industrial field of application in order to understand the effect of such kind of activities for different operators with the use of different kinds of carts. For having these measures of load in an objective way the EMG and the dynamometer are the most used devices. Even though the measurement of the load with this kind of instruments is considered the gold standard, the reliability coefficient is 0.77 because different operators can perform the same activity with different techniques causing a difference in the actual force application (Bao et al., 2009). For example, the same operation can be performed with one or two hands and, as a consequence, the final force applied to perform it is different. The EMG is a tool used for detecting electrical activity in the muscles and it consists on the placement of electrodes on the skin surface above the muscle of which it has to be monitored the contraction in order to evaluate the % of MVC of the muscle during the performance of the activity. The disadvantages of the EMG are the influence of other muscles movements, of the interference of electrical supply and of mechanical problems on the recorded measurements of MVC. Even though a relationship has been found between self-reported load estimation method (such as Borg CR-10 scale) and the grip force measured with the EMG (Buchholz et al., 2008), there could be lack of correlation between the two measures due to the wording of the self-reported questions. Moreover, the questions could be not specific enough to match a single direct measurement. In addition, the EMG implies some problems related to the application because different individuals can use different groups of muscles for the same task and it is difficult to interpret the measure of MVC for multiple muscle groups. As far as the disadvantages are concerned, this technology is complex and costly to be applied in an industrial context.

The dynamometer is a tool to measure the peak and average force in kilograms for carrying, pushing and pulling activities. It is fixed to the object to be carried, pushed or pulled and any kind of slipping has to be avoided. Before the use, it is important to understand the direction of forces that represent the movement path of the operator (Massolino et al., 2017).

The application of this device is easy to be performed and from the output data, it can be revealed the kind of movement that the specific operator performed in addition to the influence of the height and weight of the item. The use of wearable sensors for evaluating physical fatigue in the workplace is becoming the focus of recent literature (Maman et al., 2017). Related to this, the combined use of heart rate monitor and accelerometers or inertial measurement units (IMUs) for assembly tasks and manual material handling tasks has been analysed (Maman et al., 2017).

1.5 Recovery time for alleviating fatigue

As stated in Konz (1998a) there exist actions to be made for preventing and avoiding the accumulation of fatigue. These actions can be seen in Table 1.2.

Table 1.2 Generic guidelines for fatigue prevention and reduction

FATIGUE PREVENTION	FATIGUE REDUCTION
• Avoid the overtime and long shifts • Avoid irregular hours of work • Avoid too much or too little stimulation of the brain • Avoid the level of fatigue becomes to great to be overcome • Give to operators a rest before the level of fatigue increases too much	• Give to the operators breaks to reduce their level of fatigue. This can be obtained by making the operator use a different part of the body than the one fatigued. • Give to the operators frequent short breaks to reduce the accumulation of fatigue • Maximize the recovery rate by guarantee to the operator the best working conditions

The recovery time, defined in Swaen et al. (2003) as *"the time necessary to recuperate from work induced fatigue"*, is considered the way for reducing the level of fatigue of operators and it is considered as recovery also the possibility of given to the operator an activity which permit to stress a different group of muscles in comparison to the efforts made previously. As can be seen in Figure 1.4 the need of some time to recover can be attributed both to physical and mental fatigue and a break to the operator can be given at the end of the whole work content or before. The position of the recovery generally is predetermined by company and it is not linked to the kind of person who has to carried on the activity.

RECOVERY TIME:

The time necessary to recuperate from work induced fatigue
(Swaen et al., 2003)

☐ It is caused by excessive workloads both on mental and physiological activity level.

☐ If not fully satisfied it contributes to exacerbate the accumulation of fatigue.

☐ There is not a proper time to recover: the recovery can be done after each task or at the end of the day-shift.

☐ In the literature different methods have tried to predict the recovery need through the definition of rest allowance (RA).

Figure 1.4 Main concepts on recovery time

Generally, the time the operator needs to recover is taken into account for the setting of the standard time, which is the sum of the normal time necessary to carry on an activity (determined by time studies or predetermined time standards) and of personal, delay and fatigue allowances (Konz, 1998a). The personal allowances are the ones related to physiological needs of the operators. Considering these needs, normally it is given to operators a break of 15 minutes every two hours. Instead, the delay allowances vary with the task and not with the operator because they take into account the machine breakdowns, the interrupted material flow and the machine maintenance and cleaning.

On the other side the fatigue allowances are given to the operator for compensating the time lost due to fatigue. If there is no fatigue, there is no need of fatigue allowances. The International Labor Office (1986) divided the fatigue allowances into there categories: physical, mental and environmental. As far as manual material handling activities is concerned, as stated in the paragraphs before, all these aspects affect the performance of the operators and should be taken into consideration. The physical fatigue allowances consider the whole-body load and the local muscle load

(Konz, 1998a), subsequently the general body fatigue and the muscular one. The mental fatigue allowances consider the mental demand, the concentration requested by the task and the visual strain. Finally, the environmental allowances consider the climate, the presence of noise and vibration and the kind of illumination of the workplace. An overview of these existing allowances can be seen in Figure 1.5. The research on manual material handling activities should be better focused on the estimation of the allowances related to general body fatigue because, as put in evidence in the paragraphs before, for such kinds of activity the operators experience more this kind of fatigue than the mental or muscular one.

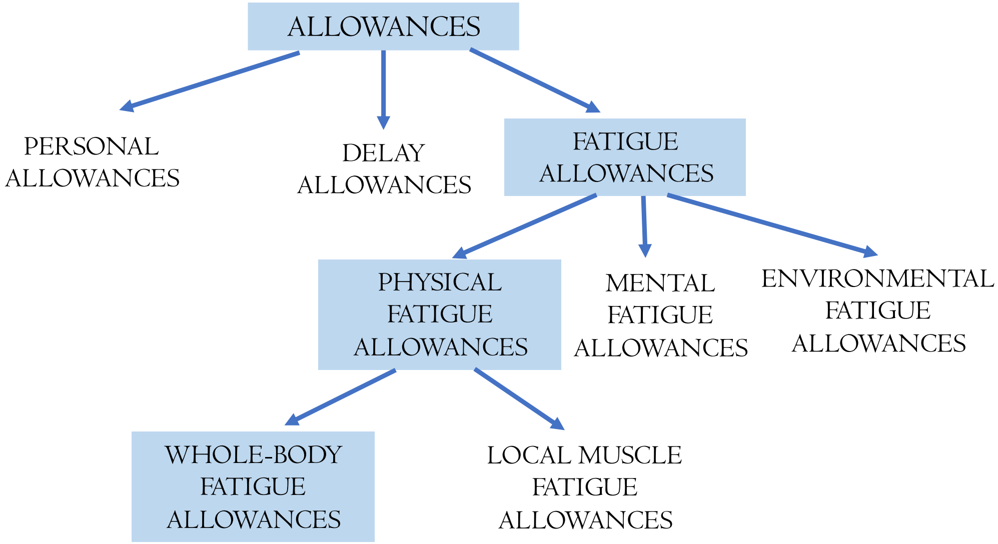


Figure 1.5 Existing allowances for giving operators time to recover

In fact, for "heavy" work such as manual material handling activities, it is fatigued the cardio-vascular system, which has five responses to the exercise: the heart rate, the stroke volume, the artery vein differential, the blood distribution and the anaerobic metabolism. On the other side the muscular fatigue is not due to lack of energy or of oxygen supply (Konz, 1998a). The kind of work that lead to muscular fatigue is the static one, which can lead to musculoskeletal disorders due to the overstress on a predetermined group of muscles.

There is not so much literature focused on the consideration of human factors in manual material handling activities through proper estimation of whole-body fatigue allowances. Instead more attention has been paid to local muscle ones.

1.6 Research framework

According to the topics presented in this first chapter, the following PhD thesis aims at developing the literature focused on the consideration of human factors in manual material handling activities answering to the following research question:

RQ1: In which ways can be better considered the impact of human factors in manual material handling activities?

In relation to this general research question, this thesis is strictly focused on the modelling of the general body fatigue experienced by the operators in order to develop the existing researches focused on the rest allowances for considering how the assignment of activities to operators can be improved. In fact, till now the literature has very little focused on how the activities should be assigned to operators in order to minimize the recovery time necessary to them and consequently the performance of the whole system. In relation to this, the main research question is the following:

RQ4: How can be modelled the fatigue accumulation of operators for reaching the improvement of the system through the minimization of the total recovery time of operators?

In order to reach this contribution of the literature focused on the workers assignment problem (WAP), it should be addressed one more research question related to how the fatigue level of an operator can be monitored. In fact, as far as manual material handling activities is concerned, there still lacks the kind of device to be used to have a real-time feedback of the physical conditions of the operators. This is useful not only for having an immediate data on the impact of the activity on the operator, but also to understand, without the necessity of modelling the fatigue accumulation, which kinds of operators should be assigned to the activities which request a higher level of physical effort. Related to this, it is necessary to answer to the following research question:

RQ2: How can be obtained a personal assessment of the fatigue experienced by operators?

In addition, one more research question should be answered in order to be able to model properly the fatigue accumulation of operators requested by the research question 4, in relation to the development of the existing rest allowance models in order to consider in the estimation of the recovery time to be given to each operator not only the kind of activity but also the kind of operator who has to perform it. According to this, the following research question should be answered before focusing on the WAP problem considering the recovery time reduction:

RQ3: How can parameters for the operators and for the activities be included in the estimation of the recovery time considering the general body fatigue?

The explained relation between the research questions presented can be seen in Figure 1.7.

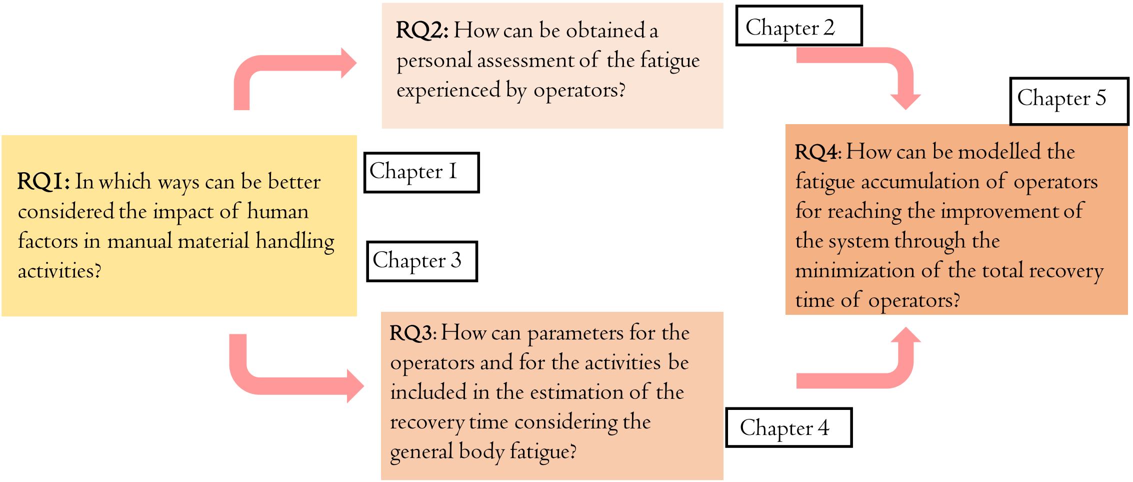


Figure 1.6 Research questions of the PhD thesis

According to these research questions the PhD thesis has been developed in 6 chapters. In chapter 2 it will be presented the kind of device to be used for having a personal assessment of the fatigue experienced by an operator and it will be validated with the existing physiological literature and with tests carried on in a production system. The aim of the following chapter is to answer to the RQ2. In parallel with this chapter, in order to explain the value added of the new rest allowance model presented in chapter 4, in chapter 3 it will be given an overview of the existing rest allowance models putting in evidence the parameters considered in the estimation of the recovery time. Chapter 3 aims at better putting in evidence what lacks in the consideration of human factors in the industrial contexts according to RQ1 focusing on the rest allowance literature. As previously stated, in Chapter 4, after the explanation of what lacks in the rest allowance literature (Chapter 3) and after the feedback obtained by monitoring the fatigue level of operators in industrial context (Chapter 2), it will be presented a new rest allowance model which can consider all the parameters which can influence the level of fatigue of each operator.

According to this new model, it will be developed in chapter 5 by taking into account the fatigue accumulation of operators during the performance of manual material handling activities sequentially. In this chapter the fatigue accumulation will be modelled for permitting the estimation of the average fatigue level in terms of energy expenditure rate of each operator and of the recovery time necessary to them: This permits to improve the literature focused on the workers assignment problem (WAP). Finally, in Chapter 6 the conclusion of the research carried on in this thesis will be drawn and the future steps of research on this topic will be put in evidence. The structure of the chapters with the main topics addressed is presented in Figure 1.8.

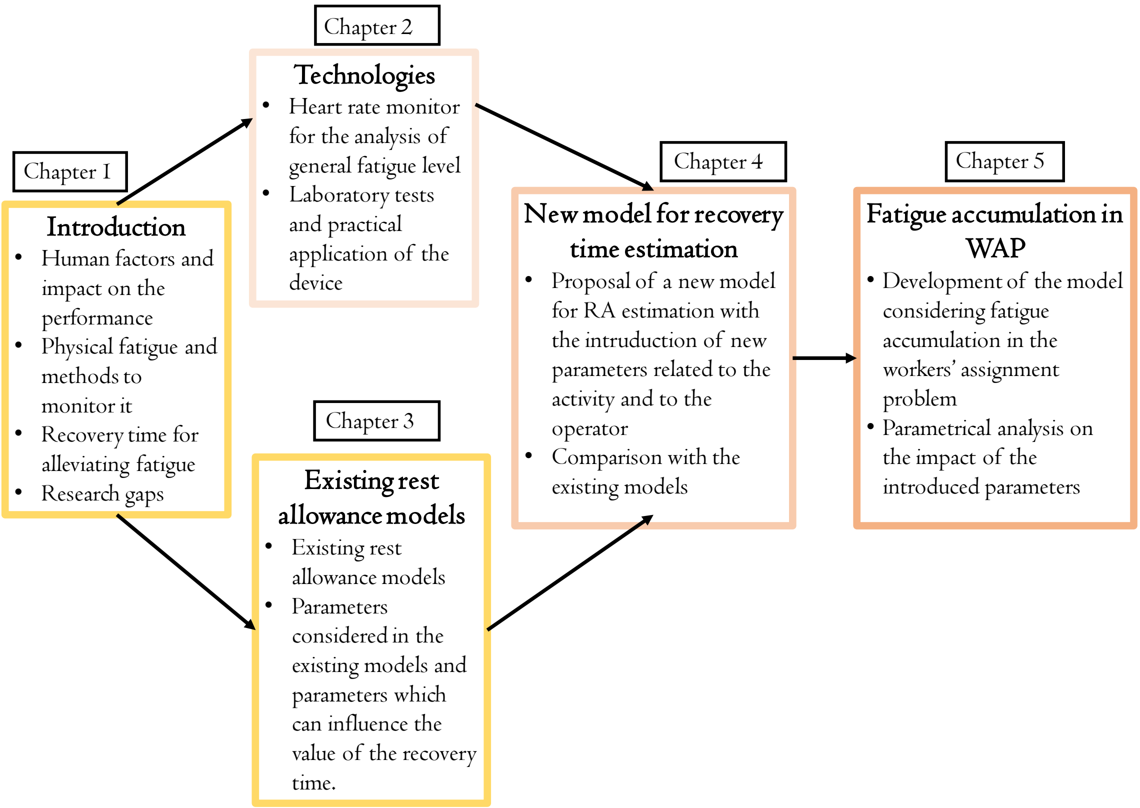


Figure 1.7 Main contents of the chapters

1.7 List of Publications

1.7.1 Papers for chapter 2

Abdous M-A., Finco S., Visentin V. "Workload evaluation of industrial work: existing methods and practical applications." *XXIII Summer School Francesco Turco, 12-14 September 2018.*

Calzavara M., Persona A., Sgarbossa F., Visentin V. "A device to monitor fatigue level in order-picking". *Industrial Management and Data systems.*

1.7.2 Papers for chapter 3

Battini D., Calzavara M., Persona A., Sgarbossa F., Visentin V. "Fatigue and recovery: research opportunities in order picking systems". *The 20th World Congress of the International Federation of Automatic Control, 9-14 July 2017.*

1.7.3 Papers for chapter 4

Calzavara M., Persona A., Sgarbossa F., Visentin V. "Recovery time setting for order picking activities". *XXII Summer School Francesco Turco, 12-15 September 2017.*

Calzavara M., Persona A., Sgarbossa F., Visentin V. "A model for rest allowance estimation to improve operators' performance". *International Journal of Production Research.*

1.7.4 Papers for chapter 5

Calzavara M., Persona A., Sgarbossa F., Visentin V. "Fatigue accumulation in the assignment of manual material handling activities to operators." *The 2018 IFAC Symposium on Information Control Problems in Manufacturing, 11-13 June 2018.*

1.7.5 Papers for chapter 6

Battini D., Calzavara M., Persona A., Sgarbossa F., Visentin V., Zennaro I. "Integrating mocap system and immersive reality for efficient human centred workstation design." *The 2018 IFAC Symposium on Information Control Problems in Manufacturing, 11-13 June 2018.*

Battini D., Persona A., Sgarbossa F., Visentin V. (2016). Including ergonomics aspects into mixed- model assembly line balancing problem. *Advances in physical ergonomics and human factors (pp. 991-1001). Springer, Cham.*

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2. The heart rate monitor

2.1 Importance of monitoring the fatigue level in manual material handling activities

Order picking is defined as the process of retrieving items from their storage locations in a warehouse to fulfill customers' orders (Tompkins et al., 2010). Usually, this activity is carried out by operators rather than machines (Grosse et al., 2015). In fact, in Napolitano (2012) and De Koster et al. (2007) it is confirmed that manual order picking warehouses are the dominant type consisting in about 80% of all the order picking warehouses. Order picking is not only labor-intensive, but also it implies more than 50% of the operating costs of a warehouse (Frazelle, 2002; Tompkins et al., 2010). Considering that the time taken to perform this activity can be high, and that it is not defined as an activity with the same added value as a usual production process, the aim for warehouse picking systems design is usually focused on improving their efficiency and their throughput (De Koster et al., 2007). Then, this goal often turns out on reducing the time needed to perform a picking tour (Battini et al., 2015). During this activity, the operator first has to have the time necessary to receive and understand the picking list, defined as the setup time. After that, during the search time and the pick time, he or she identifies the right item to be picked and picks the item from its storage location. Besides this, he or she needs sufficient time to travel from one storage location to the next one. Up to now, the literature has mainly focused on how to improve the overall performance of the system (Gunasekaran et al., 1999; Grosse et al., 2015) by reducing firstly the travelling time and then the setup, picking, and search times (Grosse et al., 2015). Travel time reduction is often related to the choice of the best warehouse design and on the establishment of the best storage assignment or the best routing and batching method (Chackelson et al., 2013; Pan et al., 2014; Yang et al., 2016). In addition, methods and techniques for preventing errors in picking the wrong item or the wrong quantity have also been analysed (Brynzér et al., 1996; Battini et al., 2015).

As stated in Grosse et al. (2015), considering the current increasing of product differentiation and the decreasing in the life cycles, the employment of operators rather than machines is usually preferred by firms for assuring the flexibility in reacting to unexpected changes, especially if these changes require a certain reasoning ability of the operator. Moreover, the presence of humans has an impact not only in the manual warehouses but also in the automatic ones because the presence of operators is fundamental in the picking bays. This implies the need to consider deeply the human factors, as also reported in some recent contributions in the literature (Helander., 2005; Neumann et al., 2010; Stanton et al., 2013). In Helander (2005) human factors and ergonomics are defined in the following way:

"Considering environmental and organizational constraints, the use of knowledge of human abilities and limitations to design the system, organization, job, machine, tool or consumer product so that it is safe, efficient and comfortable to use".

Concerning manual material handling activities, operators can suffer from health problems due not only to bad ergonomic conditions but also to physical fatigue, which is generally defined as a reduction in capacity to perform physical work as a function of preceding physical effort (Gawron et al., 2001). These kinds of problems can lead to a decrease of operators' physical capabilities over a long-term period. Consequently, the human factor could have a relevant impact on the performance of the picking system (Grosse et al., 2015).

Accordingly, some of the recent literature has been focalized on the importance of taking into account human factors in each manual material handling activity, for the improvement of the overall system efficiency (Grosse et al., 2015; Larco et al., 2016). However, little attention has been paid to the kind of fatigue that operators feel during the execution of their daily work. This kind of fatigue is not only physical but also psychological, and both can affect performance (Konz,1998; Zwarts et al., 2008; Rose et al., 2014). Physical fatigue is due to the need to travel from one location to the other and the need to reach and carry items of a predetermined weight (positioned on a shelving or on the ground) to a certain height. These are all activities that imply the use of the cardio-vascular system. This kind of fatigue can be evaluated in an objective way and leads to a reduction in the capacity to generate force, lower performance, and higher reaction times. Physical fatigue can be influenced not only by the activity performed but also by the manner in which the activity is carried out. In fact, it can increase with a speed up of the operator in reaching the item, carrying it to the pallet, and positioning and repositioning it. On the other hand, psychological fatigue is due to the need to understand the location and retrieve the right item.

The purpose of this chapter is to contribute to the filling of the gap in the existing literature related to the investigation of human factors in order picking activities. In particular, it is focused on the understanding of how the accumulation of the physical fatigue of operators can be monitored, considering that picking activities determine the use of the cardio-vascular system. From a managerial viewpoint, the measurement of the heart rate permits to have a continuous monitoring of the level of workload perceived by each operator. Consequently, it is possible to monitor in real time if the workloads are equally distributed among operators and to redefine the job scheduling and job rotation, not only considering the duration of the activity but also integrating the level of fatigue of the operator by considering the value of energy expenditure, that can be obtained from the heart rate of each operator.

2.2 Methods for fatigue analysis in order-picking systems

Considering the impact of human factors in order-picking activities, there is a need to guarantee a predetermined level of operator performance in the short- as well as the long-term. This can be achieved both through reducing the amount of awkward postures (Battini et al., 2011; Battini et al., 2014) and through minimizing the fatigue level (Gawron et al., 2001). The human factor in the industrial environment has been analyzed for preventing musculoskeletal disorders (MSDs), one of the major causes of health problems in operators, especially those performing manual and repetitive tasks (Burgess-Limerick, 2007). With this aim, ergonomic analyses are usually carried out (David, 2005) to evaluate operator conditions in performing a specific task and, as a consequence, to understand what could be the best design of the workplace or the best definition of the tasks to improve not only the operator's health conditions but also the general efficiency. However, in a picker-to-parts system ergonomic analyses can be useful to evaluate the improvement of awkward postures but are not sufficient to understand the effect of this kind of activity on the cardio-vascular system of each operator. Consequently, in this industrial context there is still a lack of an acknowledged method for the measurement of operator physical fatigue.

Table 2.1 shows some of the existing methods that have been identified as useful approaches for the monitoring of the fatigue that an operator feels during and after the performance, together with their advantages and disadvantages. These methods have been selected since they are strictly linked to the physical fatigue that the operators perceive. In fact, a subjective evaluation can be given by self-report questionnaires (Pope et al., 1998), the measurement of the muscular fatigue is obtained in an objective way with the use of the EMG (Cifrek et al., 2009) and finally, the measurement of the overall body fatigue is given by Garg et al.'s model (1978), PMES (Predetermined Motion Energy System) (Battini et Al., 2016) and the monitoring of the oxygen consumption (VO2) and of the heart rate (HR) (Achten et al., 2003).

Self-report questionnaires and interviews are subjective evaluations done directly by operators regarding the significance of the exertion and their personal discomfort in the workplace. Thus, they allow to obtain personal feedback on the effort that an operator feels during the performance and at the end of the activity. The data obtained from these methods can be useful to individuate the most critical activities on which to focus attention. Moreover, they can be used to confirm and validate with personal feedbacks the results obtained from another fatigue analysis. On the other hand, the use of EMG is strictly linked to the concept of Maximum Endurance Time (MET) (Zhang et al., 2014), which represents the maximum time for which a muscle can sustain a load; when an operator reaches the MET, he or she becomes unable to maintain the load and the level of fatigue is 100%. The MET is set from the Maximum Voluntary Contraction (MVC), defined as the maximum force exerted by a muscle when it contracts. Thus, EMG allows to gain feedbacks regarding the condition of the muscle at the beginning and at the end of the activity and, in contrast to self-reported methods, it is objective. However, it cannot determine the accumulation of fatigue during the performance considering the impact of the effort made by the cardio-vascular system as a result. Both self-report methods and EMG have negative aspects: the former because of its subjectivity, while the latter due to the requirement of high investment and the need of a proper preparation. Besides, neither of these two techniques takes into account personal characteristics that distinguish one operator from another and that have an influence on fatigue accumulation. The macro-studies of Garg et al. (1978) are based on the measurement of energy expenditure. This is one of the most well-known measurements used with the aim of knowing how much physical strain is required to perform a task and to monitor the level of fatigue felt by an operator, making it possible to ensure that the job demands do not exceed the worker's capabilities (Bradfield, 1971; Payne et al.,1971). Garg et al. (1978) developed a model for the prediction of the energy expenditure of a wide variety of manual material handling activities by dividing a complex job into different smaller work tasks, considering not only the energy required for the performance of the task but also the energy required for the maintenance of the posture. The positive aspect of this method is that it can take into account the differences between one person and another in terms of age, body weight, and height. Garg et al. (1978)'s model has been simplified in Battini et al. (2016) to obtain a Predetermined Motion Energy System (PMES), which has the same advantages as the model of Garg et al. (1978) but can speed up the estimation of the energy expenditure of a task. Garg et al. (1978)'s model and PMES cannot be put into practice so easily in an industrial context because they are based on the evaluation of every single movement of the operator performing a task.

The approach of VO2 or HR monitoring to predict energy expenditure is different. VO2 monitoring is the most validated method in the literature, because its relationship with the particular activity performed has been demonstrated (Aberg et al., 1967). However, it cannot be applied easily in an industrial context, since the investment is considerable and it implies a certain level of preparation for the use of the instrument. Besides this, the biggest limit is the size of the instrument and the inconvenience of using the mask for taking the measures, which can influence the operator's performance due to stress and difficulties in breathing. On the other hand, a HR monitoring system (Gamelin et al., 2006) is portable and thus less expensive, easy to use and to understand; it does not require specific knowledge, and it does not disturb the operator's activity. Besides this, the measurement of the heart rate for activities which imply the use of the cardio-vascular system is generally correlated with VO2 (Astrand et al., 1954). HR, like VO2 monitoring, allows to give real-time feedback to the operator, who can be conscious of his or her physical condition and, if appropriate, can speed up or slow down the rate of the activity. Another important aspect is that both of these methods recognize the effect that personal characteristics, such as age, weight, VO2 and HR at rest, and training status, can have on fatigue accumulation.

The use of an HR monitor is easier than the measurement of the VO2. The HR monitor can be used by everyone without difficulty and the measurement of HR to monitor fatigue level can be done for different kinds of activities without disturbing the operators. Consequently, an HR monitor, thanks to all these advantages, could be the best device to carry out a fatigue analysis in order picking contexts.

Table 2.1 Methods for the estimation of physical fatigue

METHOD	ADVANTAGES	DISADVANTAGES
SELF-REPORT QUESTIONNARIES	o Inexpensive o Little time to be compiled o Standard format o Easy to use and to understand o Applicable to different situations	o Subjective evaluation of the effort o Personal questions' interpretation
SELF-REPORT INTERVIEWS	• Inexpensive • Little time to be compiled • Standard format • Easy to use and to understand • Applicable to different situations • Face to face comparison • More accurate than questionnaires • Flexibility	• Subjective evaluation of the effort • Personal questions' interpretation • Necessity of a user trial • Demands characteristics to the situation • Time-consuming
DIRECT MEASURE OF EMG	o Usually put on a specific part of the body o Less time consuming o Recording of myoelectric activity of the muscle	o High investment o It is necessary a certain preparation o It does not consider personal characteristics
GARG ET AL. (1978) MODEL	• Standard movements • Link with the energy expenditure • It considers someway personal characteristics	• It requests the monitoring of operator's activities
PMES	o Standard movements o Link with the energy expenditure o It considers someway personal characteristics o Easier to be applied than Garg's model	o It requests the monitoring of operator's activities
ENERGY EXPENDITURE BASED ON VO2 MONITORING	• It permits the continuous monitoring of an aerobic measure • It is validated • It is strictly related to the intensity of the activity • It considers personal characteristics	• High investment • It is necessary a certain preparation • It can influence operator's performance • Not easy to use in an industrial context

ENERGY EXPENDITURE BASED ON HR RATE MONITORING	○ It permits the continuous monitoring of an aerobic measure ○ Not so expensive ○ Easy to use and to understand ○ It considers personal characteristics ○ It assures a real time feedback to the operator ○ Suitable for all applications	○ At beginning is better to correlate this measure with the oxygen consumption ○ Stress can have a little influence on the heart rate at rest

2.2.1 Use of heart rate as a measure of fatigue level

The HR monitor is based on a Bluetooth HR sensor connected to a watch, where the trend of the heart rate and the duration of the activity are visualized. It is commonly used to obtain feedback regarding the training status and to improve the physical form of a person through accurate planning of the next training activities. As stated above, if the aim is to use this kind of device to monitor physical fatigue in picking activities, there is a need to correlate this measure with the VO2 consumption. In fact, VO2 monitoring is the most precise way to find the energy expenditure on a task, because, if a task whose level of work is not light is carried out for a certain duration, there is a change in the quantity of oxygen transported in the blood. Associated with the measurement of the VO2 is the VO2 max, an important concept referring to the maximal oxygen intake that can be measured after prolonged exercise and permitting the evaluation of the physical fitness and the endurance capacity of an individual. This kind of measure can be obtained if the physical effort in terms of rate and duration is sufficient to disturb the aerobic energy system. Regarding the correlation between VO2 and HR, even though Astrand et al. (1954) demonstrate a certain linearity in the correlation between these two measures, there are difficulties in trusting HR monitoring directly without taking into account the correlation with the VO2. In fact, for activities whose level of rate is low, the slope of the relation between VO2 and HR is flat, so slight movements can increase HR while VO2 remains the same (Achten et al., 2003).

Besides this, it is important to know how much this device can effectively monitor the energy expenditure of an individual. Up to now, considerable efforts have been made in the attempt to determine the energy expense of physical work and the strain induced in the individual due to the stress of the workload. The use of the HR for the measure of the energy expenditure has been analysed in the past as well as in more recent literature. Acheson et al. (1980) present evidence that, despite the accuracy of the measurement of the mean, the relation between HR and energy expenditure is not the same for all the activities because there is a certain influence of the following factors: work rate, type of work and posture, temperature, emotion, food, previous work, time of day, and training status. Payne et al. (1971) also show that personal characteristics can have an influence. In fact, they demonstrate the relation between HR and energy expenditure by dividing the subjects of interest into groups according to their age, sex, and state of training. Despite this, Bradfield (1971) reaffirms the need to start to analyse this relation, after the regression lines between heart rate and oxygen consumption have been taken into account. The need for individual regression lines determined in the field is also shown in Strath et al. (2000). Besides the preferable use of individual calibration curves, it has been demonstrated that it is better to have different kind of activities in the calibration procedure (Li et al., 1993) in order to obtain the energy expenditure through minute-by-minute recording of the HR (Spurr et al., 1988). Consequently, it is possible to estimate the energy expenditure from the HR, if it is considered that the trend of the HR can be different for two different persons performing the same activity because of individual specificities (Maxfield et al., 1971), but the accuracy can be improved if some adjustments for age, gender, body mass, and training status are considered (Keytel at al., 2005). Generally, the validity, stability, and functionality of the HR monitor are evaluated in Léger et al. (1988), where, with the aim of assuring the validity of this kind of device, this is compared with the ECG, and a high coefficient of correlation between the two kind of measures is found. After that, its stability is considered, through the utilization of several geometrical devices, and it is also shown that the instrument is generically functional, and the only difficulty is finding the best one to fit the users' needs. The difference in the activity performed or in the personal characteristics has an influence not only on the prediction of the energy expenditure but also on the variability of the HR itself. In fact, the variability in HR, like that of blood pressure, differs depending on whether it is induced by static or dynamic activities (Gonzàlez-Camarena et al., 2000): considering similar workloads, static activities lead to lower heart rate, higher blood pressure, and higher perception of the effort. Besides this, considering the same kind of effort, the HR trend is different between men and women (Jensen-Urstad et al., 1997). As a consequence, for healthy subjects, gender has an important influence on the trend of the heart rate, but another physiological aspect that has to be taken into account is age. Despite this variability in the heart rate, Pichot et al. (2000) put in evidence why the analysis of the HR can be useful for the monitoring and optimization of physical performance and why the HR variability is better than the HR at rest for considering physical fatigue accumulation. The importance of the HR variability, the effects of training, the main applications of the instrument, and the environmental factors affecting the HR are studied in Achten et al. (2003), where the use of HR, despite its limitations, is recognized as a validated method. The practical use of this device for fatigue accumulation in picking systems are shown in the next section.

2.3 Application of the heart rate monitor device

This section consists in an application of the HR monitor both in a laboratory context and in a real industrial context for the evaluation of its effectiveness. Firstly, it is validated the use of the heart rate monitor in the field by correlating the measurements of both heart rate and the oxygen. After that, it is shown, by applying the heart rate monitor in an industrial context, how the trend of fatigue and recovery can be evaluated for the specific operator. Finally, it is compared the effect of different intensities on the trend of the fatigue for a specific operator and, on the other side, the impact of personal characteristics by considering the intensity and the duration of the activity as constants but changing the kind of operator that has to perform it. Accordingly, the results and the utility of this device to carry out a fatigue analysis will be analysed.

2.3.1 Laboratory tests for setting the correlation between VO2 and HR

As a first step, the correlation between the VO2 consumption and the HR is investigated to validate the use of the heart rate monitor in the order picking context. In fact, as explained in the previous sections, this correlation can differ with the change in the activity performed and from one person to another. According to this, some laboratory tests in collaboration with the physiological department of the University of Padova have been carried on in order to understand if for manual material handling activities such as order picking there is an high coefficient of correlation between the two measures.

The measurement of the VO2 is obtained with an open circuit spirometry, that consists of a spirometer connected to a recording device to account for the O2 removed by the spirometer and the CO2 produced and collected by an absorbing material. On the other hand, the measurement of the HR is carried out with an HR monitor called Polar V800 (Gamelin et al., 2006), which consists of a Bluetooth HR sensor connected with a watch, where the duration of the activity and the HR can be visualized during the performance.

The picking activity simulation was performed by three different persons in a laboratory. Each person had to perform the same picking activity with three different real intensities (4, 8, and 12 items per minute), carried out one after the other for the same duration. In fact, each activity is performed for 10 minutes and between one rate and the following one there was a resting period of two minutes. The total time considered is, respectively, 30 minutes of working and 6 minutes of resting period. It was considered a total activity duration of 30 minutes because this is indicated as the duration of reference for the estimation of the correlation between VO2 and HR (Spurr et al., 1988). The intensities taken into account are considered to be realistic, since they are usually observed in real industrial contexts. In this laboratory test, the order-picking activity is simulated by moving a plastic bin with a weight of 8 kg from a lower level to a higher one and vice versa. The three different persons involved in the performance of the activity have to wear HR rate monitors and oxygen masks together. For the three individuals, the correlation coefficient obtained is higher than 0.7 as can be seen in Figure 2.1. Consequently, for picking activities of medium rate, such as those considered, and for operators with different ages, weights, and levels of VO2 and HR during rest and training, the monitoring of HR can be a good way of measuring the fatigue level.

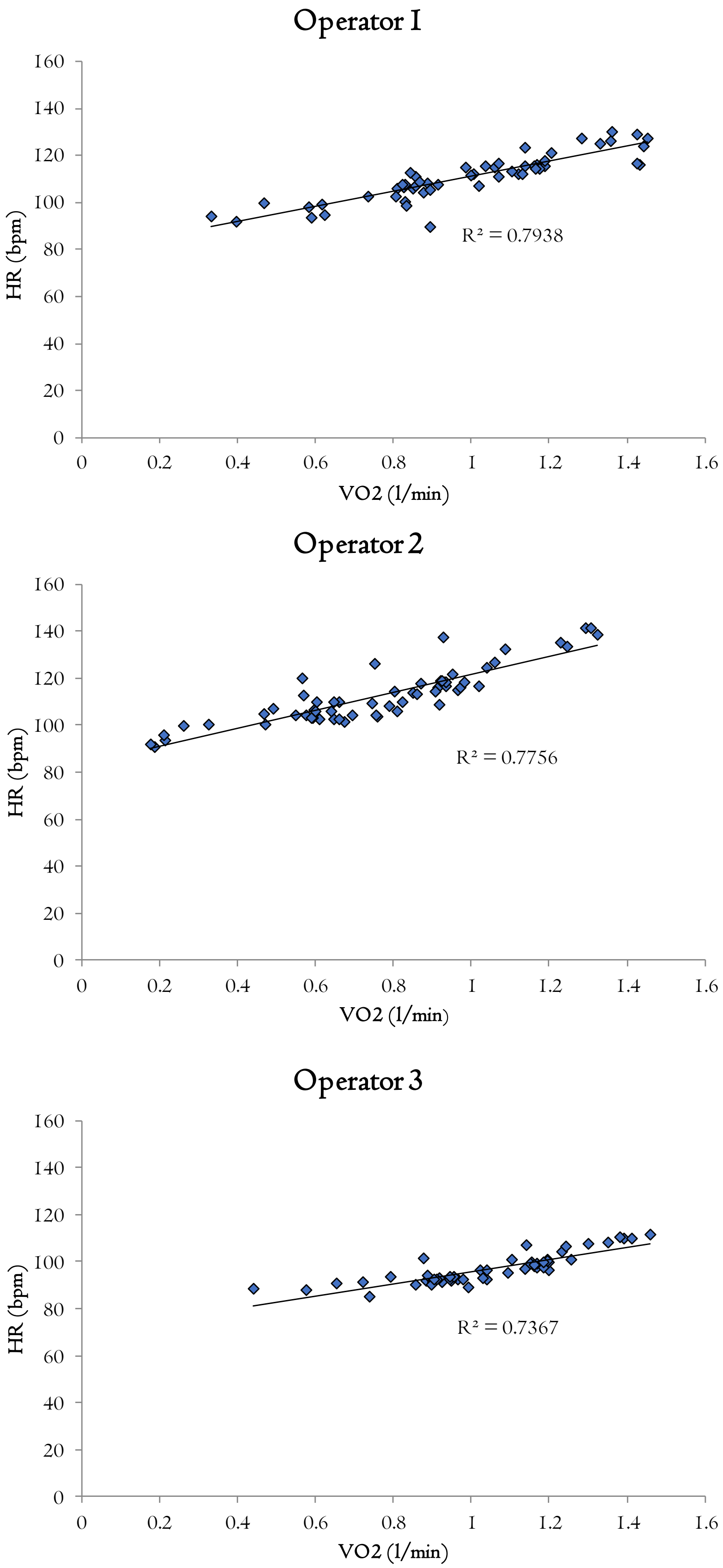


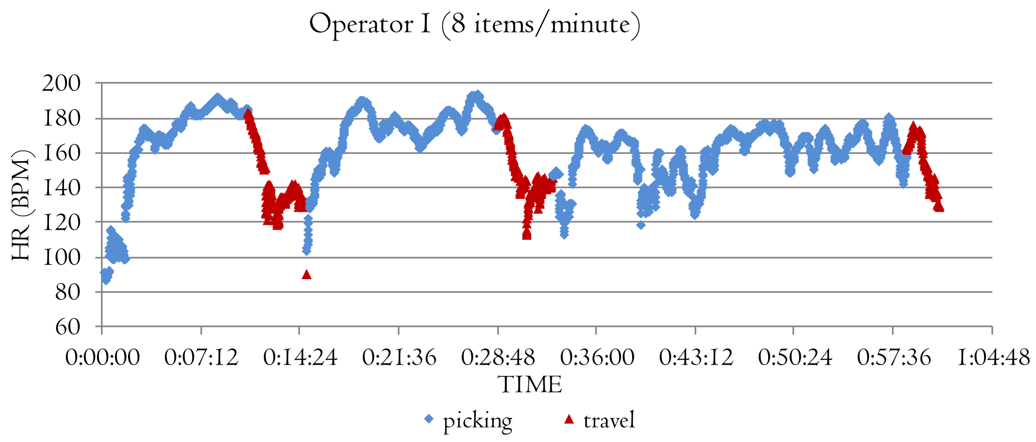
Figure 2.1 Results of the laboratory tests

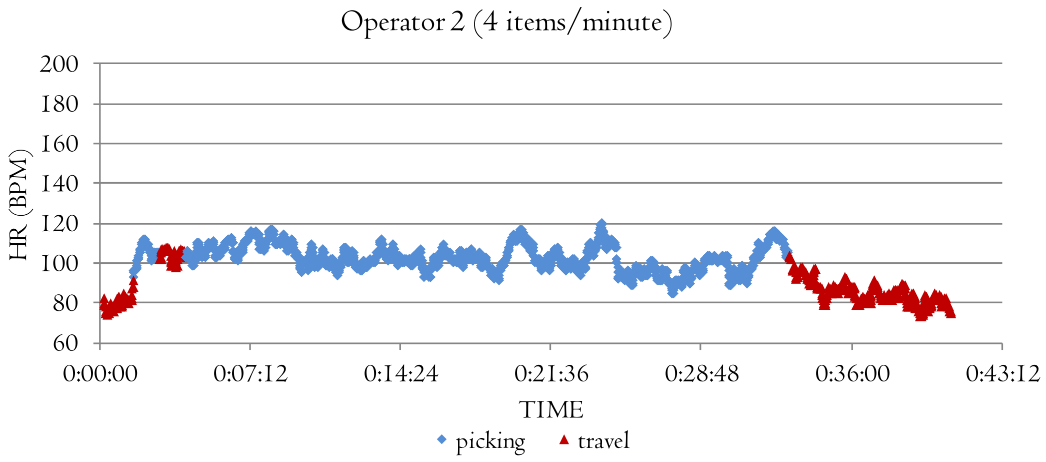
2.3.2 Monitoring of the HR of operators in a real industrial context

After the setting of the correlation between HR and VO2 in the laboratory tests, the HR monitor was put into practice in a real industrial context without the use of an oxygen mask to evaluate if the trend of fatigue accumulation and recovery alleviation could be put in evidence using this device. During the day, the analysis was performed on three different operators who had to carry out their daily picking activities. They had to pick the items indicated by their pick-to-voice system and each operator had to complete two pallets, either only with high rotation items, all located on the ground, or only with low rotation items, placed on a shelf. The difference between the two types of picking is that the first one is faster, with an average picking rate of 8 items or 12 items per minute, while the second one has a lower rate, with an average of 4 items per minute. The time needed by the operator comprises the setup, searching, picking, and travel times (Tompkins et al., 2010). In the analysis presented in this paper, the generic travel time includes also the time for searching and for setting up, in order to carry out a macro-analysis. As far as operators is concerned, they differ in terms of personal characteristics (age, weight, height, VO2 at rest, HR at rest and training level). The first operator, performing a picking intensity of 8 items/minute is 25 years old, a weight of 70 kilograms, a height of 1.70 meters, a value of VO2 and HR at rest of respectively 0.6 l/min and 80 bpm. The second and the third operators, performing respectively a picking intensity of 4 and 3 items/minute, have similar personal characteristics: they are 30 years old, they have a body weight of 80 kilograms and a height of 1.80 meters. As far as VO2 at rest and HR is concerned, the second one has 0.36 l/min and 60 bpm and the third one 0.5 l/min and 70 bpm.

2.3.3 Results of the tests and insights on the use of data obtained with the heart rate monitor

By matching the data of the HR monitor with the data of the video recording of the operators' activities it was possible to identify the alternation of the two phases of picking and travel. As shown in Figure 2.2, the three different operators have different trends of HR, therefore, it can be concluded that they must have different energy expenditures from one another in performing their daily work because, as explained in the paragraphs above, HR is strictly linked to energy expenditure (Spurr et al., 1988).


Operator 1 (8 items/minute)


Operator 2 (4 items/minute)

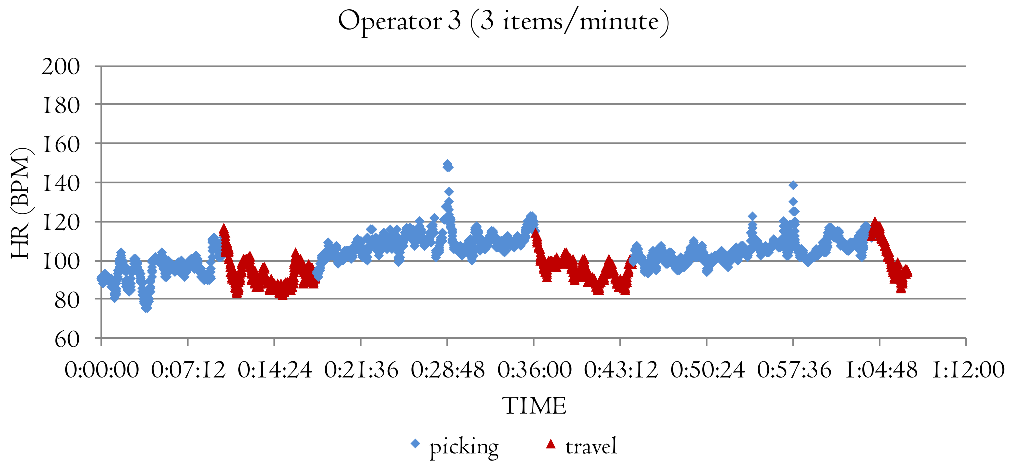

Operator 3 (3 items/minute)

Figure 2.2 HR trends for picking activities performed in an industrial context with three different operators.

Moreover, the rate of the activity has an influence in determining the maximum heart rate reached, since considering a rate of 3 or 4 items/minute and 8 items/minute the maximum heart rate is respectively around 110 and 180 beats per minute. In addition to this, for two similar intensities such as 3 and 4 items/minute the two different operators reached respectively 120 and 110 beats per minute as maximum heart rate: despite a lower rate the first operator reached a higher value of maximum heart rate. Consequently, the energy expenditure of an operator, which can be obtained by using this kind of device, can be due not only to the activity performed but also to the personal characteristics of the operator.

In addition, considering the same operator who performs the same picking activity with three different rates consequently, it can be seen in Figure 2.3 that the maximum heart rate reached is different between one activity and the other.

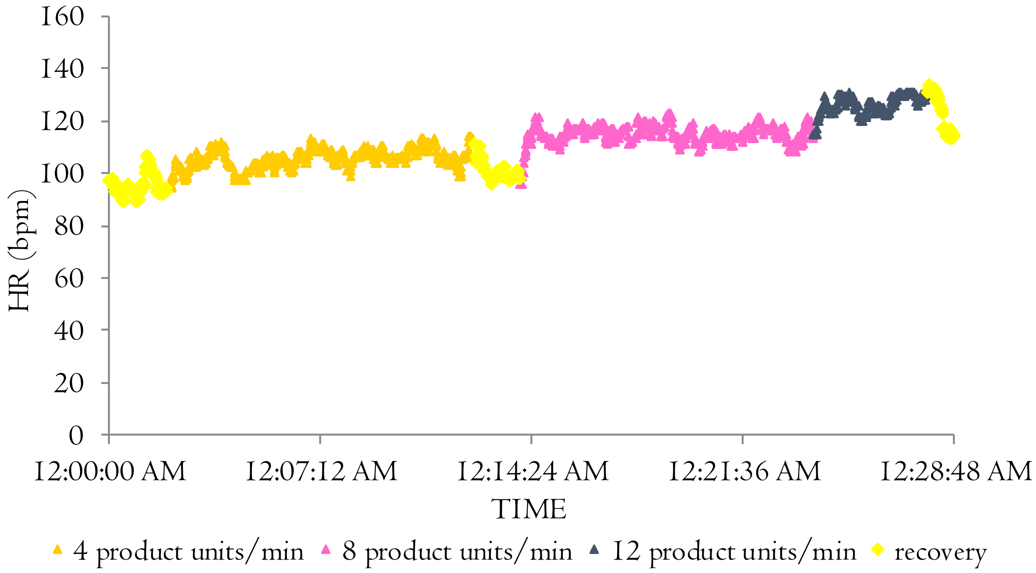


Figure 2.3 Changing of the maximum heart rate with different picking rates

Moreover, the use of this device permits to collect important data related to the physical conditions of the operators. In fact, by obtaining the average heart rate of the activity performed, defined has HR_{ex}, and by knowing the heart rate at rest HR_{rest} and the maximum heart rate HR_{max}, it is possible to obtain the percentage of heart rate deserve, which indicates if the operator is working in aerobic or anaerobic condition (Borresen et al., 2009). This kind of measure can be obtained with the following formulation by Karvonen et al. (1988):

$$\%\, heart\ rate\ deserve = \frac{(HR_{ex} - HR_{rest}) * 100}{HR_{max} - HR_{rest}} \qquad (1)$$

The threshold of $\%\ heart\ rate\ deserve$ which distinguishes between the aerobic condition and the anaerobic one is 80%. Above this value, the operator is in an anaerobic condition, at which he can stay only for a limited period, since this leads to the accumulation of lactic acid, indicating a higher level of physical fatigue (Karvonen et al., 1988).

2.4 Impact of the kind of activity and of the physiological factors on the heart rate trend

As seen in the section above, the factors that can have an influence on the trend of the HR are the personal characteristics and the rate and duration of the activity. In order to evaluate the effect of these variables independently from one another, a generic picking activity has been replicated in the laboratory. The tests were carried out with two different persons, operators 1 and 2, respectively of 35 and 26 years old, with a value of VO2 at rest of 0.6 and 0.4 l/min, a weight of 80 and 60 kilograms and a height of 1.80 and 1.70 meters. They had to wear a heart rate monitor and to lift the same weight of 8 kg inside a plastic picking bin from a lower level to a higher one and vice versa. The left side of Figure 2.4, related to the first test, compares the trends of the HR obtained for operator 1 changing the intensity and the duration. As can be seen, keeping the same rate of 8 items per minute while changing the duration from 10 to 30 minutes, there was a change in the mean HR obtained for the specific activity. On the other hand, when the duration was fixed and the rate varied from 8 to 12 items/minute, the maximum HR reached was higher. It can be derived that both rate and duration affect the fatigue level of the operator, but this effect can be different from one person to another.

For evaluating whether this kind of instrument can also be used for the analysis of the impact of personal characteristics on the accumulation of fatigue, the right side of Figure 2.4, related to the second test, compares the HR trends of operators 1 and

2, considering the same duration of 10 minutes and changing the rate. A certain difference between the two trends of HR for the two operators can be seen. So, it can be concluded that personal characteristics also have an impact, that can be revealed using the HR monitor.

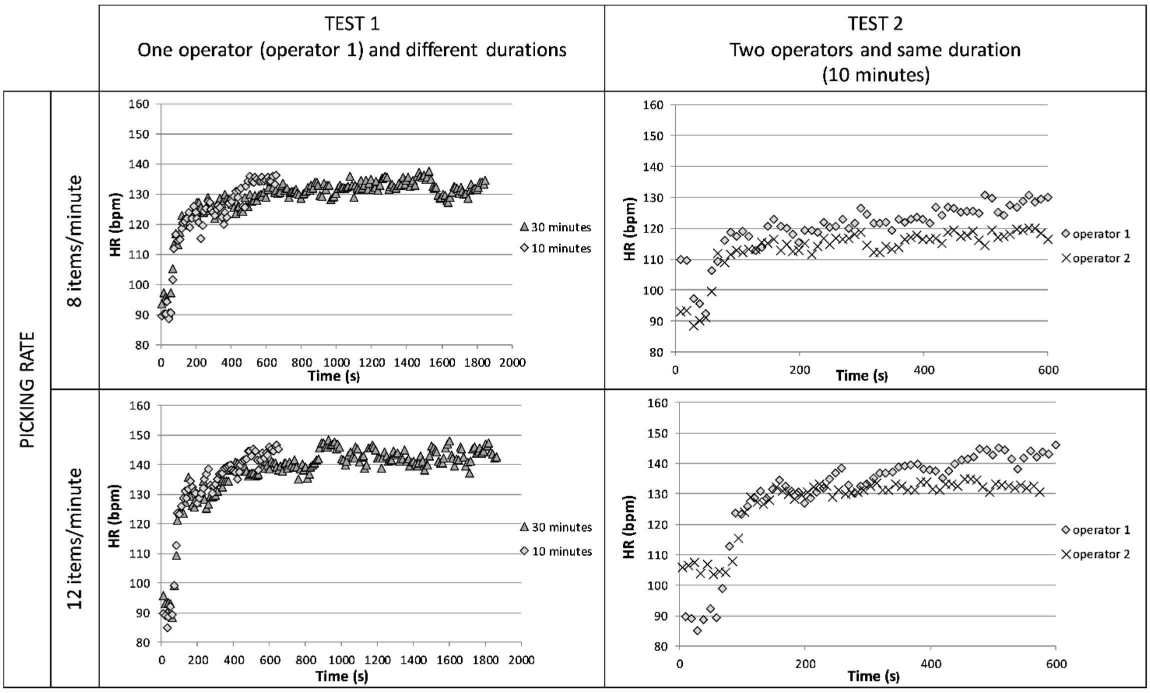


Figure 2.4 HR trend for the same operator and different rates and durations (test 1) and HR trend of different operators with different rates and same duration (test 2).

2.5 Use of the heart rate data for managing the operators

2.5.1 Use of the heart rate for decision making in an industrial context

In the industrial context where the heart rate monitor has been applied such data of the heart rate have been useful for the understanding the impact of different activities on the operator and for the setting of the best design of the workplace. In fact, there has been the presence of two different kinds of activities: the picking of high rotating and the picking of low rotating items (see Figure 2.5). The first one is performed by positioning the pallets of these high rotating items on the ground and the operator has to pick the item directly from the pallet. This way of picking permits to have a higher picking rate. On the other side, the second one is based on the picking from the shelf.

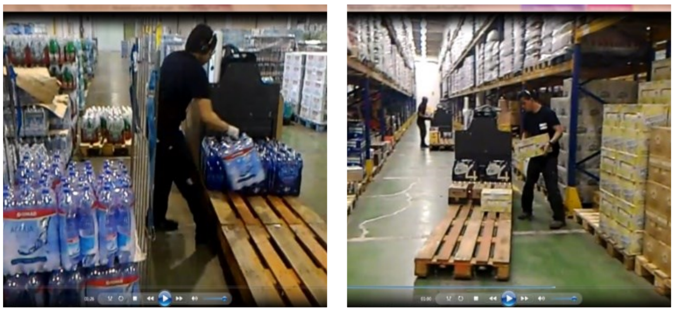


Figure 2.5 Picking of high rotating items (on the left) and of low rotating items (on the right)

For the picking from the shelf the operator is lower in picking the item of interest. Moreover, the items positioned on the ground for the food company considered, are the ones with a higher value of mean weight such as stock keeping unit of water.

Subsequently, the performance of these tests, based on the recording of the heart rate for different operators considering the picking on the ground, helped to understand which are the operators more suitable to this kind of activity. The ones, who during the performance of the activity reached a value of the maximum heart rate higher than the others are the ones which preferably should perform the picking from the shelf because, due to their physical characteristics such as training status, they become fatigued faster. In relation to this, the simple application of this device can give suggestions regarding where the operators should be applied.

But, this is not the only feedback that such device can give to a practitioner. In fact, it can be detected the influence of the weight of the items picked. In relation to this, if it has been decided the zone in which the operator should work (the zones are the ones related to high rotating and low rotating items), it can also be performed a general evaluation of the order in which the items should be picked in relation to their weight. In fact, with the increasing of the weight, keeping the rate of the activity constant, there is an increase of the heart rate. Subsequently, it may be advisable giving to the operators an alternation between the items of higher weight and the ones of a lower one in order to keep the heart rate below a certain established value and allowing them to have a partial recovery during the picking of the lower weight items. According to this, in the industrial context taking into account the feedback on the maximum heart rate reached during the performance of the items positioned on the ground and the feedback on the effect of items picked in term of weight on the heart rate helped to decide in which zone the operator should work and in which order is better to pick the considered items in order to avoid a too high level of fatigue.

2.5.2 Use of the heart rate in combination with the dynamometer for workload evaluation

In this experiment, it is conducted tests with a dynamometer to assess the force related to 3 activities: pushing, pulling carts and carrying items. The aims of this experiment are to assess the forces and the level of forces and to compare the dynamometer results to the results obtained by the heart rate monitor, Borg scale CR10 (Category ratio 10) (Borg 1990) and the Percent Maximum Voluntary Contraction %MVC. Pushing, pulling, and carrying an item are common tasks in several sectors in industry and services. Activity such as warehousing involves pushing, pulling, and carrying. The aim of this part is to introduce methods to evaluate the load of pushing, pulling, and carrying in order to evaluate the risks. The results that can be obtained with this experimental method could be used to design work and to compare the real load to the maximum load suggested in the literature, such as (Snook et al., 1991). Another way to assess the physical exertion is Borg scale; it is a subjective evaluation on a scale to evaluate the difficulty of the exertion and the work.

- Pulling: In this experiment, it is used a dynamometer to assess the force and a heart rate monitor to assess the heart rate. It is executed pushing and pulling of carts and carrying an item for 5 m from a height of 1.5m and the activity is repeated for several cycles. The subject of this experimental part is a man of 1.80 m high and a weight of 80 kg considered in the 50% percentile of worker population. Two different forces are included in each pulling (pushing) activity according to Snook et al. (1991). To get the cart in motion, the force is called initial force (kg) and the force to keep the cart in motion is called the sustained force (kg). It is reported report the evolution of load (kg) and the evolution of heart rate (HR) in Figure 2.6.

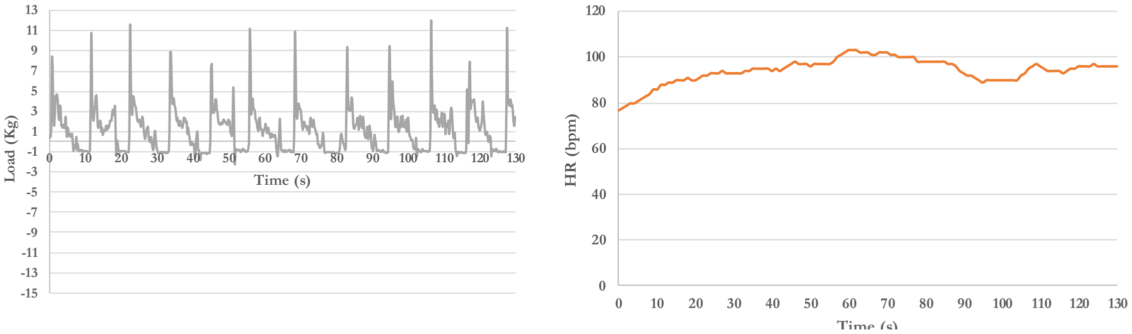


Figure 2.6 Monitoring of HR in bpm and of the Load in kg during the pulling of a cart

From Figure 2.6, it can be observed a periodic pattern with a pic of force at the beginning of the cycle. As observed in the survey by Garg et al. (2014), pushing and pulling tasks require a higher initial force at the beginning of the effort. The heart rate monitor (HRM) shows that during the effort, the subject heart rate is high, however, the heart rate does not show any pattern of forces and hence, we cannot distinguish the pic of initial force with the HR.

- Pushing: The subject pulls a full cart for 5m each cycle from a 1.4 m height. We report the evolution of load (kg) and the evolution of heart rate (bpm) in Figure 2.7.

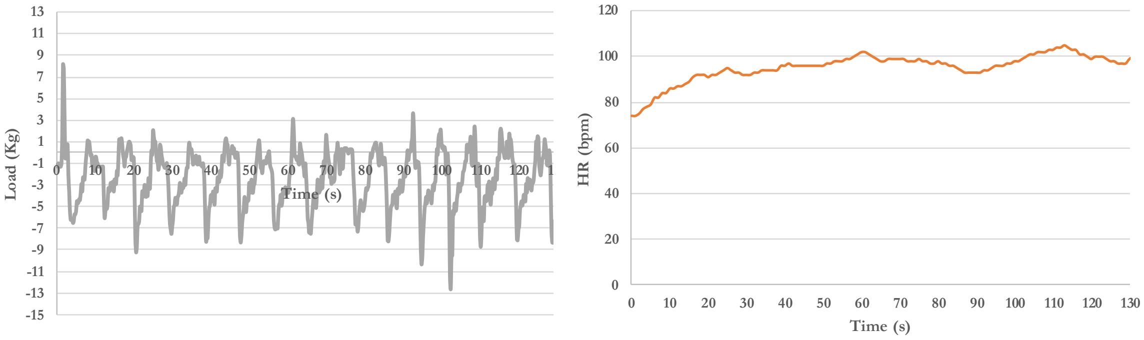


Figure 2.7 Monitoring of HR in bpm and of the Load in kg during the pushing of a cart

The evolution of the load and the heart rate conclusions are similar to the ones of the pulling activity. The pic of force is higher at the beginning and the load is negative because of the positive sense of the dynamometer, in pushing, we get a negative value. The heart rate is high along the exertion and reported as bpm along the activity.

- Carrying: For 200 s, the subject carries an item for a distance of 5 m. In carrying, the load is considered as static along the exertion and the load can be measured with the static assumption, the activity and its intensity could exceed the load limit of a worker. The results related to the carrying activity are shown in Figure 2.8.

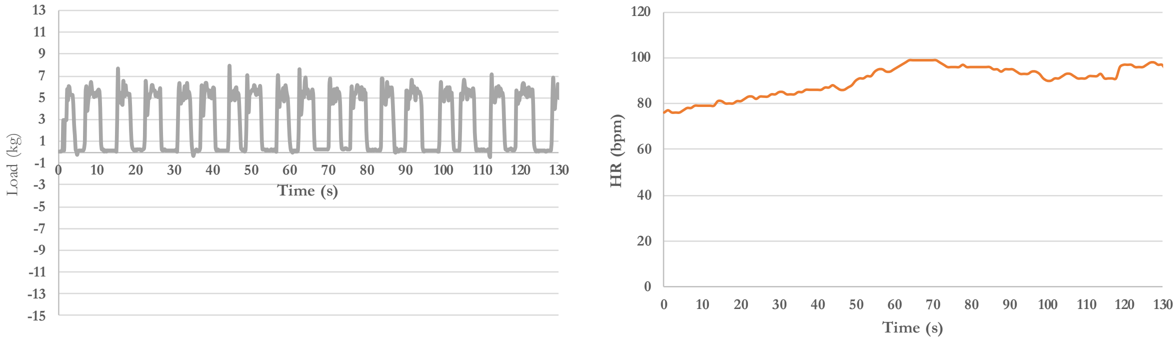


Figure 2.8 Monitoring of HR in bpm and of the Load in kg during the carrying of an item

It is important to compare the result of the load in carrying with limit such as those defined by Ciriello et al. (1990), this comparison is reported as %MVC in Table 2.2. In Table 2.2 different evaluation criteria of load, with Borg scale CR10, when we measure the subjective evaluation of load reported by the subject that exerts the effort. The dynamometer value is reported as the rounded mean value, calculated with the data from all cycle when the force in measured. The mean value is reported in (kg) and for the two phases of pushing and pulling, and only one value in carrying, when we suppose that the effort is static along the exertion. For (%MVC) it is compared the value obtained with the mean dynamometer value with the maximum acceptable forces from Ciriello et al. (1990) and express it as a percentage value, the maximum acceptable forces from Ciriello et al. (1990) are considered as 100% value. Hence, we express the mean value obtained with the dynamometer and express it in percentage.

Table 2.2 Force exertion estimation with different criteria

	Borg Scale		Mean rounded dynamometer value (kg)		%MVC		Mean HR (bpm)
	Initial Force (CR10)	Sustained Force (CR10)	Initial Force (kg)	Sustained Force (kg)	Initial Force (%)	Sustained Force (%)	
Pulling	5	4	10	5	62	50	88
Pushing	5	4	9	5	40	38	90
Carrying	3		6		35		92

In Table 2.2 it is shown the mean value of heart rate (bpm) for pulling, pushing and carrying along the exertion. In general, from this experiment, the perceived effort evaluated with Borg scale corresponds to the %MVC, overall, the Borg scale estimation is close to the real man value measured with the dynamometer. Several studies from the literature showed the correlation between the perceived effort of Borg Scale and a measure of exerted force (Hampton et al., 2014) and some studies consider Borg scale with EMG to evaluate the effort. Assessing %MVC directly with EMG is difficult, especially in the design stage of the workstation. Using either of these methods such as Borg scale is a substitute for direct assessment and may be useful in the design stage. It is particularly interesting note that the heart rate median value tends to increase from pulling analysis to the carrying one even if the dynamometer mean value and the %MVC tend to decrease. This counterintuitive phenomenon could be linked to the frequency on which the activities have been done in the same period of time, in fact, as we can see in Figure 2.8 the frequency of the carrying activity is higher than the one linked to the pulling and pushing activity. However, additional tests could be useful to confirm this aspect.

2.6 Conclusions on the results obtained

An HR monitor, as shown in the reported experimental application, can be the right instrument for the analysis of fatigue in order-picking systems. In fact, since for picking activities of medium rate there is a high coefficient of correlation between VO2 and HR, HR is a reliable measure. Besides this, the use of the HR monitor allows to consider the personal characteristics of the operators, an important factor for the beginning of a fatigue analysis, as well as being easy to use and to understand and not requiring a high investment. Consequently, this device puts in evidence the personalization of a proper fatigue analysis. In fact, it has been demonstrated that changes in rate and duration of the activity or in the kind of operator performing the activity lead to different values of HR and thus different energy expenditures and fatigue levels, which have an impact on the physical capabilities of operators and, thus, lead to decrease in performance. Accordingly, the heart rate is useful to be put in practice in an industrial context because it permits to obtain customized information on the operator in real-time and to understand when the operator is overfatigued. In fact, the data of the heart rate monitor can be utilized, first of all, to have a feedback of a person's well-being since it is possible to understand in real-time if the operator is in the phase of recovery alleviation or fatigue accumulation. In this second case, by using Karvonen et al.' formulation (Karvonen et al., 1988) it is possible to know if the operator is in an anaerobic condition, implying an accumulation of lactic acid on the muscles. Furthermore, the values of heart rate can be used to obtain the value of the mean energy expenditure of the activity performed (Li et al., 1993). Consequently, it is possible to improve the scheduling of the activities to be given to each operator for the reduction of the recovery time and the improvement of the performance of the manual order picking warehouse.

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3. Existing rest allowance models

3.1 Introduction

Fatigue is not so easy to be estimated, since it can affect the cardio-vascular system by manual material handling tasks, the skeletal-muscular system by awkward postures and the brain by information overload. As stated by Konz (1998a, 1998b), there is the necessity to consider how to prevent fatigue and the different ways to reduce it.

The different ways for the reduction of fatigue level can be the improvement of the scheduling of the tasks assigned to the operators, the reduction of information overload of the operators or the promotion of dynamic muscular work instead of static muscular work. On the other side, fatigue can be reduced by trying to use frequent short breaks rather than few long breaks, alternating the body part used during the task and increasing the recovery/work ratio (Konz, 1998a). Once the level of cumulated fatigue is established, it can be used to evaluate how much recovery is necessary to the operator for reaching the physical condition at rest.

Regarding this, allowance is defined as any extra time that has to be added to the time necessary to perform the activity, in order to take into account the operator physical needs and any other industrial necessity. In particular, relaxation allowances (RA) are the time added to basic time in order to give the worker the possibility to recover from psychological and physiological fatigue. Related to this, generally in the setting of the value of rest allowance the variable fatigue of each operator is not considered (Figure 3.1).

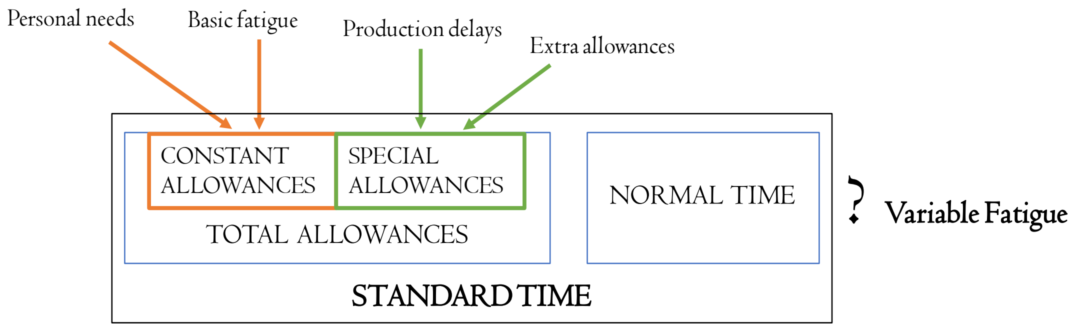


Figure 3.1 Rest allowances for the setting of the standard time

The only way to reduce fatigue effects is to assure rest breaks for the complete recovery of the body parts. A smaller reduction can be recognised also by the decreasing of the working rate or by giving the worker the possibility to walk while performing the task.

Relaxation allowances can be divided into two categories (Price, 1990): fixed and variable allowances. Constant allowance consists of the time given to satisfy personal needs of the worker, such as drinking or washing (normally 5% of basic time for men and 7% for women) and the time given for the need to recover from fatigue and to remove monotony (4% of basic time for operators whose work is light with normal movements and good working conditions). Special allowances are added to fixed allowances considering additional physical or mental work for adverse working conditions. The concept of rest allowance has a certain importance in manual material handling activities, because it can be used to estimate how much time it has to be given to an operator for the full recovery and it influences the performance.

3.2 Importance of the concept of rest allowance

As put in evidence in Neumann and Dul (2010) and in Figure 3.2, the way in which production is managed has effects on the system and on the humans. But, on the other side, the impact on the operators in terms of health, physical workload, quality of life and safety can decrease the performance of the system if they are not correctly managed. In fact, the operator and system effects contribute to the direct and indirect costs (Figure 3.2).

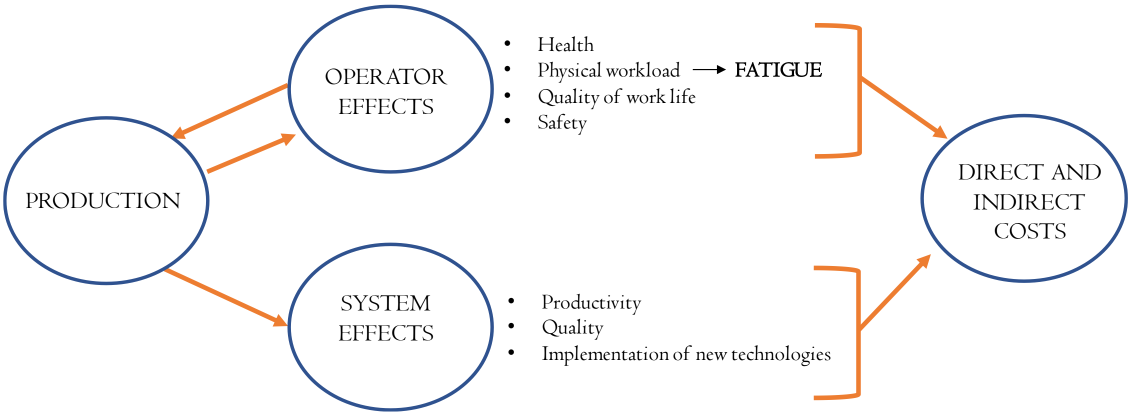


Figure 3.2 Connection of operator and system effects

According to the impact of the operator's fatigue on the production system, the attempt to model the trend of the recovery time in a dual-resource constrained system (machines and workers are the output constraints) is put in practice in Jaber and Neumann (2010), through a mixed-integer linear programming model considering one operator performing n tasks. In this model the objective function includes the productivity and the fatigue index, subjected to time constraints. Through this analysis it has been demonstrated that the system performs best if there is a partial recover after each task and if there is the possibility to alternate different tasks. In addition, it needs to be taken into account that the fatigue experienced by an operator can be also mental in addition to the physical one.

While the analysis of Jaber and Neumann (2010) is focused on the physical aspects of the fatigue theme, the psychological aspect has been explored in Jaber, Givi and Neumann (2013). In fact, the necessity of having flexible workers capable of doing different tasks can be useful to deal with changes in product or machine breakdowns and to prevent the workers from having musculoskeletal disorders. On the other side, it increases the probability of a worker to forget how to do a specific task. In Jaber, Givi and Neumann (2013) the fatigue-recovery model is integrated with the learning-forgetting curve in order to analyse the trade-off between the recovery time and the probability of forgetting. It was shown that having fatigued workers has impacts on the system performance, such as the loss of the experience on the job of the workers: therefore, investing in training programs can improve the overall efficiency.

Considering the impact of the human factors on the overall system, the new trend is to develop new approaches for predicting injury risks immediately in the design stage, integrating both fatigue-recovery model and human learning-forgetting curve through simulation (Dode et al., 2016). In fact, it has been demonstrated that the system performance is influenced by the accumulation of muscular fatigue, by the time necessary for the partial or full recovery and by the learning curve of the worker taken into account. These factors can not only have an effect on the output of the system but also on its quality. Consequently, it has become even more important to develop a model able to consider human factor in the design stage, taking into account the human and his interaction with the instruments of the workplace and generally with the layout of the working area. Up to now, most of the existing literature has focused on the concept of RA relying on MVC for static fatigue analysis, while in picking systems there is the need to consider dynamic fatigue. This can be achieved by integrating the energy expenditure of the activity performed with the necessary RA.

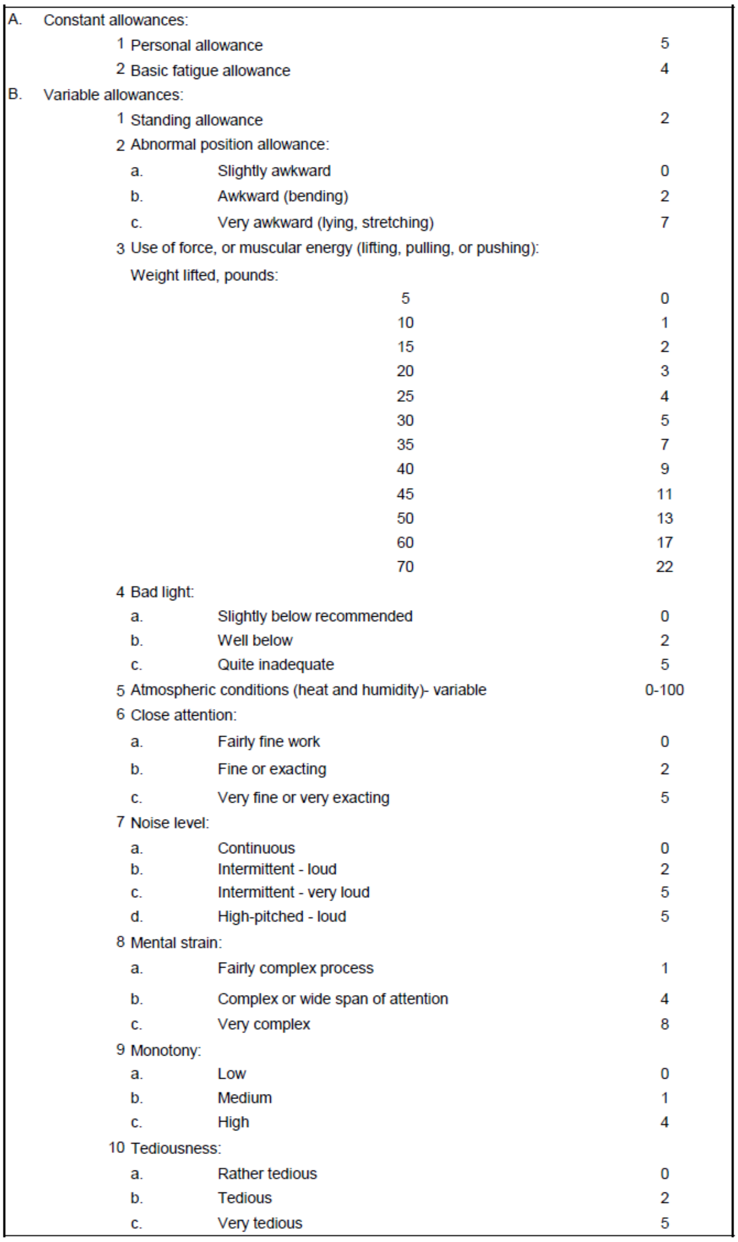
3.3 Rest allowance in time and methods theory

As defined by the International Labour Organisation (ILO) (1986) in the time and methods theory for setting the standard time of an activity each task is divided into work elements, for each work element is assigned a normal time in relation to the standard performance of a worker and finally it is applied an allowance to the normal time to compute the standard time of a task.

Even if the kind of activity can have different effects on the level of fatigue reached depending on the kind of operator who has to carry on the activity, generally the setting of the fatigue level linked to each activity and consequently of the allowance depends on the analyst who has to judge the activity in order to give to it a standard time. Subsequently, in the estimation of the time required to carry on an activity or every kind of operation, it is considered a fully qualified, trained operator who works at standard pace and exerting average effort. As can be seen in Figure 3.3, in addition to the standard value of allowance given to consider the physiological needs and the basic level of fatigue, generally it is considered a predetermined value of allowance also for the use of force in lifting, pulling and pushing activities. This value of allowance is strictly linked to the weight lifted and no attention is paid to the influence of this weight to the specific operator or how the intensity of activity, intended as the frequency at which the task of pulling, pushing or carrying is repeated in the considered timing, can affect the fatigue of the operator. The influence of atmospheric conditions and of the mental effort requested by the task or the influence of the tediousness of the task are considered as added allowances to the ones related the use of force.

Even though, the conditions of the workplace in terms of environmental conditions such temperature, humidity or design of the workplace can influence the level of physical fatigue experienced by the operator. For example, in relation to the heart rate, which can be a measure to monitor the general body fatigue, there can be a higher value of heart rate considering the same activity but a higher temperature of the workplace in which the operator performs the activity. In addition, the evaluation of the level of effort linked to the activity is given by the analysis who has to evaluate the activity, no personal evaluation is given by the operator neither is someway monitored his/her level of fatigue to have a feedback regarding their personal conditions during the performance.

Consequently, all the workers are treated in the same way, without considering their specificities and the impact on the predetermined activity is set by an observer which is the analyst.



A.	Constant allowances:			
	1	Personal allowance		5
	2	Basic fatigue allowance		4
B.	Variable allowances:			
	1	Standing allowance		2
	2	Abnormal position allowance:		
		a.	Slightly awkward	0
		b.	Awkward (bending)	2
		c.	Very awkward (lying, stretching)	7
	3	Use of force, or muscular energy (lifting, pulling, or pushing):		
		Weight lifted, pounds:		
			5	0
			10	1
			15	2
			20	3
			25	4
			30	5
			35	7
			40	9
			45	11
			50	13
			60	17
			70	22
	4	Bad light:		
		a.	Slightly below recommended	0
		b.	Well below	2
		c.	Quite inadequate	5
	5	Atmospheric conditions (heat and humidity)- variable		0-100
	6	Close attention:		
		a.	Fairly fine work	0
		b.	Fine or exacting	2
		c.	Very fine or very exacting	5
	7	Noise level:		
		a.	Continuous	0
		b.	Intermittent - loud	2
		c.	Intermittent - very loud	5
		d.	High-pitched - loud	5
	8	Mental strain:		
		a.	Fairly complex process	1
		b.	Complex or wide span of attention	4
		c.	Very complex	8
	9	Monotony:		
		a.	Low	0
		b.	Medium	1
		c.	High	4
	10	Tediousness:		
		a.	Rather tedious	0
		b.	Tedious	2
		c.	Very tedious	5

Figure 3.3 Standard allowances considered in ILO tables

3.4 Existing rest allowances models

The existing rest allowance models are focused on the muscular fatigue and on the general body one, by taking into account respectively the condition of the muscle after a certain effort and the effect on the energy expenditure of a certain activity. These formulations try to consider more the objective impact of the activity on the operator in the respect to the standard allowances considered in the ILO tables, even if the effect of the personal characteristics of the operator is still not considered.

3.4.1 Muscular fatigue

Relying on the concept of rest allowance, expressed as a percentage of holding time, different models in the literature have been validated (El ahrache and Imbeau, 2009) as can be seen in Table 3.1.

Table 3.1 Existing RA formulations for muscular fatigue

MODEL	FORMULATIONS FOR RA
Rohmert (1973)	$RA = 18 * (fMET)^{1.4} * (fMVC - 0.15)^{0.5} * 100$
Milner (1986)	$RA = 0.164 * \left[4.61 + ln\left(\frac{1}{100 - (fMET)^{-1}}\right)\right]^{-1} * 100$
Rose (1992)	$RA = 3 * MET^{-1.52} * 100$
Bystrom and Fransson-Hall (1994)	$RA = \left[\frac{(\%MVC)}{15} - 1\right] * 100$

In all these formulations the terms used are the MET and the MVC expressed also by indicating a percentage of MET or of MVC: fMET or fMVC. The Maximum Endurance Time (MET) is considered as the maximum time that a muscle can sustain a load during an isometric contraction and generally it is evaluated as a percentage of the Maximum Voluntary Contraction (MVC). It is considered that the operator reaches the value of MET when the level of fatigue is 100% and he/she becomes unable to sustain the load.

In Rohmert's formulation (1973) the two main terms used for the definition of rest allowance are the MET, expressed as a percentage of MET (fMET), and the intensity of the activity, expressed as a percentage of MVC (there is no fatigue if the %MVC is below the 15%). In the models of Milner (1986) and Rose et al. (1992), the only determinant term for the specification of the RA is for the first one the fMET and for the second one the MET. Neither of them considers the intensity of the exertion. On the contrary, in Bystrom and Fransson Hall (1994) the RA is calculated with the %MVC, without the term %MHT.

In relation to these models, a comparison between these different rest allowances models for muscular fatigue has been carried on in El ahrache and Imbeau (2009) and it has been shown a considerable difference between the models if they are applied on a sample of real-world workstations. In addition, there exists several models for the estimation of the MET as shown in Table 3.2.

Table 3.2 Existing MET formulations

MODEL	FORMULATIONS FOR MET
Rohmert (1960)	$MET = -1.5 + \frac{2.1}{fMVC} - \frac{0.6}{fMVC^2} + \frac{0.1}{fMVC^2}$
Sato et al. (1984)	$MET = 0.382 * (fMVC - 0.04)^{-1.44}$
Manenica (1986)	$MET = 14.88 * e^{-4.48\,fMVC}$
Sjogaard (1986)	$MET = 0.2997 * fMVC^{-2.14}$
Rose (1992)	$MET = 7.96 * e^{-4.16fMVC}$
Ma et al. (2009)	$MET = -\frac{\ln(fMVC)}{kfMVC}$

All these formulations are based on the value of MVC, but the estimation of the MET value can be different and subsequently the value of RA which is derived by the MET is different.

In addition, although these rest allowances models are useful to evaluate the time necessary to the operator for his full recovery in case of muscular fatigue, they do not analyse the trend of the recovery time during this calculated rest allowance. This analysis can be useful because, in an industrial context, often there is not the possibility to give the operator all the time he needs to return to the physical condition at rest.

Moreover, as said in Rose et al. (2014) the recovery time is not so easy to be taken into account in a proper way, because it can be influenced by different variables such as loading time, time given for the recovery and variability of the tasks performed. In Rose et al.'s analysis (2014) it has been demonstrated that fatigue exists, since after a predefined loading time the maximum force is lower.

Moreover, when the operator restarts his work after a certain recovery time (not all the time necessary for the full recovery), it can be noticed not only a decreased endurance time, but also an increase in the recovery time necessary and in the fatigue level during the second phase of loading. Besides this, a certain relationship between the recovery time and the load level has been found. In addition, in the formulations of MET of the general models put in evidence in Table 3.2 it is not considered the external variables which can influence the individual.

3.4.2 General body fatigue

According to the literature the only existing model for the determination of rest allowance estimation basing on the energy expenditure rate of the activity is the one of Price (1990).

Here, the energy expenditure rate of the working period and of the rest period, defined respectively as mean working rate (MWR) and resting rate (RR), are related to the acceptable work level (AWL). This last term is set at 300 W considering the maximum oxygen intake, as indicated by Astrand and Ryhming (1954).

The equation developed by Price (1990) has been adapted by Battini et al. (2017) for manual material handling activities, by transforming the terms expressed in Watt into kcal/min, where $\dot{E}_W$ is the working energy expenditure rate and $\dot{E}_R$ is the resting energy expenditure rate:

$$RA = \frac{MWR-300}{300-RR} = \frac{\dot{E}_W-4.3}{4.3-\dot{E}_R} \quad (1)$$

By multiplying the value of rest allowance (RA) by the working time t_W it can be obtained the duration of the recovery.

In this formulation it is associated to the activity a mean value of energy expenditure without considering the impact that the activity can have on the specific individual. In fact, it can be that different individuals reached different values of mean energy expenditure rate during the performance.

3.5 Factors which can impact on the value of rest allowance

In the models put in evidence in the paragraphs 3.3 and 3.4 the parameters considered for the setting of the value of rest allowance do not include the physiological factors related to the individual and the environmental factors related to the workplace which can influence the physical fatigue of the individual. In fact, for the muscular fatigue it is taken into account the Maximum Endurance Time and the Maximum Voluntary Contraction and for the general body fatigue the Mean Energy Expenditure of the activity and the energy expenditure at rest. The influence of the physiological or environmental factors and their impact on the value of rest allowance is not considered.

3.5.1 Environmental factors

Considering the link between the energy expenditure rate and the heart rate of the individual (Achten and Jeukendrup, 2003) it has been put in evidence the environmental variables which influences more the heart rate and consequently the value of energy expenditure rate.

The influence of hot and cold environment on evaluation of the exercise bout has been studied for long in the literature demonstrating that there is an increase in the heart rate in case of hot conditions. In fact, it has been identified that one of the possible factor which can increase the value of the heart rate is the core temperature, which cannot be decrease with the several ways the body put in practice for losing heat (conduction, convection, evaporation, radiation). Moreover, it has been put in evidence a direct linear relationship with the mixed venous blood temperature and with the activation of muscle thermo-reflexes.

Another environmental factor which can influence is the altitude. According to Achten and Jeukendrup (2003) the increase of the altitude causes an increase in the heart rate.

3.5.2 Physiological factors

Some of the physiological factors put in evidence are the age and gender of an operator. Their effect on the heart rate has been studied by the literature. In Jensen et al. (1997) it is measured the effect of age and gender on heart rate variability basing on ECG recordings. The results show that in healthy subjects the age is an important determinant of heart rate variability and a lesser degree is attributed to the gender.

Moreover, in Keytel et al. (2005) it is analysed the effect of body composition and training on the relationship between heart rate and the energy expenditure rate and it is put in evidence that there is an influence of the weight of the individual and of the training status and it has shown that this influence should be taken into account.

In addition, in Achten and Jeukendrup (2003) it is explained that a rise in the value of heart rate can be explained to the rise of the body temperature, to the body water loss and to the peripheral vasodilatation. Consequently, it is put in evidence that the HR is positively correlated to the level of dehydration.

In relation to the importance of such physiological factors in the value of energy expenditure rate of an activity, there exists also less recent literature (Bradfield et al., 1971) which affirms the need of considering these variables in the consideration of the value of heart rate which is obtained by monitoring an individual which performs an activity with a medium-high level of intensity. Subsequently, there is the need of having individual regression lines for each individual in order to estimate the personal level of fatigue of each operator.

3.6 Conclusion on the development of the RA literature

Considering the tables generally used for the setting of the time needed to the operators for recovery and the existing models based both on muscular and general body fatigue, there is the need of better taking into account the factors which can increase or decrease the time necessary to each operator. In case of manual material handling activities, the focus is on the general body fatigue that as stated in the previous chapters can be monitored with the heart rate. According to this, as put in evidence in Figure 3.4, the consideration of the impact of the physiological and environmental factors on the value of heart rate and consequently on the value of energy expenditure rate, can helped to have an estimation of rest allowance nearer to the reality in terms of physical fatigue effectively experienced by the operator. The consideration of these factors can enhance to consider the variable fatigue in the setting of rest allowance value and consequently of the standard time. This lacks in the existing literature as put in evidence in Figure 3.1. Related to this, this need is more important for manual material handling activities. Till now only few models have tried to estimate the value of the recovery basing on the value of the energy expenditure rate (Eliezer, 1982; Price, 1990). In the next chapters it will be considered the value of RA set by Price (Price, 1990) which is a little bit different from the one set by Eliezer (Eliezer, 1982).

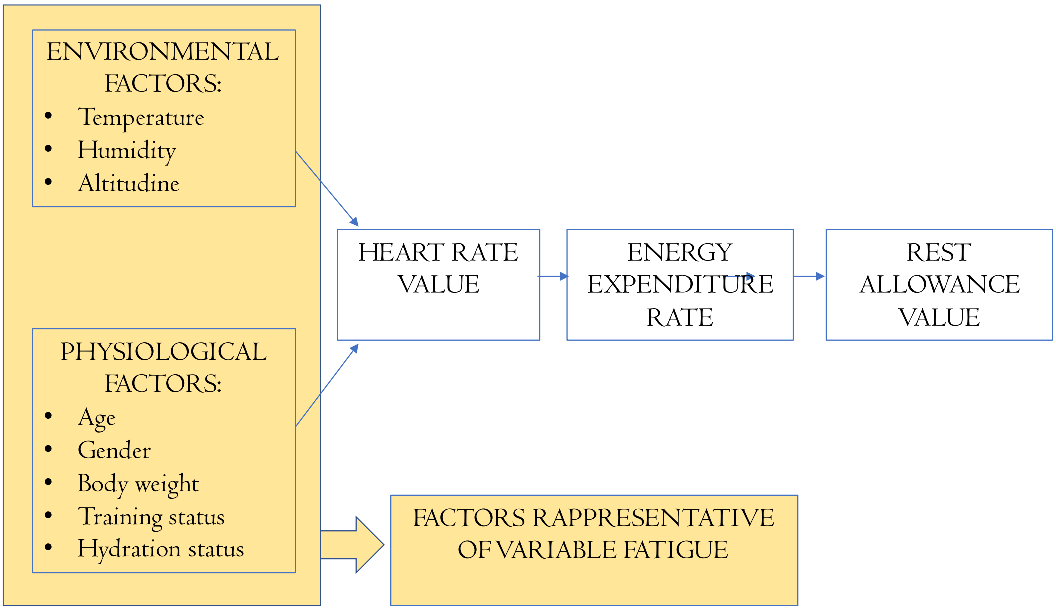


Figure 3.4 How to consider physiological and environmental factors on the estimation of rest allowance value

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4. New rest allowance model

4.1 Introduction

According to the chapters before it has become important to integrate the conditions of operators such as fatigue and stress, discomfort, safety, job satisfaction and errors, into traditional decision support models when designing and managing production systems (Wogalter, Hancock and Dempsey, 1998; Karwowski, 2005; Lodree, Geiger and Jiang, 2009; Grosse, Glock and Neumann, 2017).

In this chapter, the operators' wellbeing and their productivity have been evaluated by the analysis of their fatigue and recovery levels. This analysis permits to improve the traditional time study theory. In fact, as explained in Konz (1998a, 1998b), the standard time of an activity is calculated by summing the normal time obtained from time studies and the rest allowances.

Fatigue is defined in Grandjean (1979) as the loss of efficiency and disinclination for any kind of effort and it is divided into mental and physical fatigue. They are respectively related to the overstimulation of the brain or to a reduction in the capacity to perform physical work as a function of preceding physical effort. The physical fatigue can be related to the general body fatigue or to the fatigue of a specific muscle an operator experiences during the execution of a task. Its accumulation is due to the activities performed, in terms of actual force required for the task and duration (Gawron, French and Funke, 2001; Rose et al., 2014). Moreover, there could be the influence of ergonomic conditions in terms of awkward postures of the part of the body used or of the fatigue accumulated from previous efforts (Rashedi and Nussbaum, 2017; Sonne and Potvin, 2015; Ma et al., 2009). In addition to this, the physical fatigue can lead both to a higher reaction time and a lower capacity of generating force (Konz, 1998a; Konz, 1998b) and normally it is not evaluated with real time monitoring systems (Ma et al., 2009; Jaber, Givi and Neumann, 2013).

The physical fatigue can be assessed using direct measurement systems of the muscles' activities (Zhang et al., 2014) or, for the general body fatigue, it can be correlated to the heart rate or to the energy expenditure rate (Li, Deurenberg and Hautvast, 1993). However, the assessment methods using these two rates are easier to apply in an industrial environment compared to the measurement of muscles' activities.

Consequently, it has become necessary to integrate the analysis of the awkward postures with the fatigue accumulation analysis and to include both these aspects into traditional decision support models in production systems, such as the scheduling of activities for the different operators. This can be obtained by assigning the activities to the operators, without causing excessive fatigue accumulation, taking into consideration the workers' physiological factors. These evaluations can help the practitioners, which despite their efforts to reduce ergonomic risks, are generally still focused on reaching the maximum efficiency of the used resources and the immediate profitability, without considering the influence of physical fatigue (Grosse et al., 2015; Dode et al., 2016).

According to the need of considering the fatigue of operators in production systems, some literature has defined how the fatigue can be alleviated by giving the operator a certain time for recovery. Different analytical models have been developed to estimate the time necessary to have an adequate recovery from accumulated fatigue, called 'Rest Allowance' (RA) (Price, 1990; El Ahrache and Imbeau, 2009).

Next section will show that, since these models consider the general body fatigue experienced by an operator performing manual activities constant over time, they did not include the actual exponential fatigue accumulation and recovery alleviation into the rest allowance estimation. As already stated, this exponential trend of fatigue and recovery is due to the physiological factors of each operator, which are, as indicated in Achten and Jeukendrup (2003): level of training, age, body weight, and hydration status.

The aim of this chapter is to develop an analytical formulation to calculate the rest allowance considering the actual exponential behaviour of the fatigue and the recovery functions. Moreover, differing from the literature, the general body fatigue is modelled based on an energy expenditure rate estimated by heart rate monitoring. The fatigue and the recovery functions can be adapted to each operator thanks to the introduction of two parameters, which include the impact of the physiological factors. The use of the heart rate monitoring system permits to estimate these two parameters a priori for each operator and, then, to derive the actual energy expenditure rates for the analysed activities. Therefore, the rest allowance formulation can be personalized for each operator in a more accurate way.

Such a model allows practitioners to have an accurate assessment of the task execution total time, including also the rest allowance. In this way, it is possible not only to prevent the operator becoming overfatigued, but also to improve the performance of the overall system, through a more proper assignment of activities to the operators.

4.2 Importance of this new model in an industrial context

The performance of a production system with many manual activities, is strongly related to the execution time of the jobs of the operators. In the well-known time study theory (Macey, 2010), the analysts assess the workers' actual pace and their fatigue level to estimate a more accurate total execution time, as sum of standard time and rest allowance. Even though the time study theory has tried to consider the differences between individuals by giving a rate to the speed at which each operator works (Macey, 2010), the estimation of the rest allowance remains qualitative, since the influence of physiological factors of operators is not taken into account through proper mathematical formulations.

Most of the existing rest allowance models are based on the estimation of the recovery time of the operator based on the MVC (Maximum Voluntary

Contraction) or MET (Maximum Endurance Time), which are related, respectively, to the relative effort of the muscle contraction and to the time a muscle can sustain a load or a specific posture before reaching its maximum capability as explained in the chapter before.

Related to muscular fatigue, some recent literature has tried to consider the influence of external load, workload history (Xia and Law, 2008) and individual differences in predicting the value of MET (Ma et al., 2009). Ma et al. (2015) has integrated the time-related task parameters and individual attributes in the recovery model. They have identified, as factors influencing the recovery, the ones they called inter-individual factors, such as age, gender, training, fatiguing operation and recovery mode and the inter-muscle group factors, such as the composition and coordination of muscle fibers and the anatomical structure of the individual.

Despite the several existing models related to muscular fatigue, in a production system it is not easy to continuously monitor muscles; therefore, it would be better to find an easier way to evaluate the operator's level of fatigue.

As far as manual activities are concerned, such as order picking, loading or unloading of machines and every manual carrying of material from one location to another, the whole body is involved. It has been shown that, if the activity involves the overall body and influences the cardiovascular system, the fatigue level can be evaluated by using the energy expenditure rate and, consequently, the value of rest allowance can be determined (Price, 1990).

The model developed by Price (1990) sets the value of RA for manual activities based on the energy expenditure rate function of the operator's general body fatigue. Price (1990) considers that the operators immediately reach the maximum energy expenditure rate $\dot{E}_W$ at the beginning of the activity. Then, at the end of the task execution, they immediately have the typical resting energy expenditure rate $\dot{E}_R$ (see Figure 4.1).

A possible way to obtain the value of energy expenditure rate expressed in kcal/min can be through the measurement of the oxygen consumption, which has a high coefficient of correlation with the heart rate (Christensen et al., 1983). Consequently, the measurement of the energy expenditure rate in a production system could be done by using a heart rate monitor rather than by measuring the fatigue accumulation on the muscle based on MVC, MET or similar (Maxfield, 1971; Li, Deurenberg and Hautvast, 1993; Achten and Jeukendrup, 2003; Rusko et al., 2003).

Moreover, the Excess Post-Exercise Oxygen Consumption (EPOC) is one of the most comprehensive methods for monitoring fatigue accumulation after a predetermined exercise. Analyzing the trend of fatigue and recovery, a more accurate model is exponential (Rusko et al., 2003; Rusko, 2004; Seppanen, 2005). This exponential trend of fatigue accumulation has been shown also in Ma et al. (2009), in Jaber and Neumann (2010), in Zhang et al. (2014) and in Givi, Jaber and Neumann (2015) in relation to the muscular fatigue.

As shown in Ye and Pan (2015), the complete recovery time for high intensity activities is strictly correlated with the body mass index, the perceived functional ability, the physical activity rating and the maximum heart rate reached by the individual during the activity.

Summarizing, the literature analysis shows the need of mathematical models based on the energy expenditure rate which include the exponential trend of fatigue and recovery. Moreover, the models have to consider the kind of activity and the operator's physiological factors. Accordingly, these models can support the estimation of the task execution times, with a more accurate rest allowance assessment.

In the next sections, analytical models are introduced based on the exponential trend of fatigue and recovery in terms of energy expenditure rate. Then, these models are included in the rest allowance estimation. Moreover, the physiological factors of the operators are considered through the introduction of two parameters; some simple laboratory tests show how to determine them.

4.3 Models for recovery time estimation based on energy expenditure rate

The physical fatigue and the performance of the operators are strictly related to the effort they have to achieve during their working time. Different activities have different effects on the specific operator, depending on the rate and on the duration of the task to perform.

In addition, the actual exponential behaviour of the fatigue and the recovery functions could be different for each operator because of the physiological factors, which are specific of each individual. Consequently, the recovery time may differ from operator to operator. As explained in Konz (1998a; 1998b) it is important for operators to rest before the level of fatigue becomes too high.

This aspect has a direct effect on the performance of a production system featuring manual activities, such as order picking, loading and unloading of a work station, manual assembly tasks, carrying and moving loads. An example related to the consideration of rest allowance in production systems design and management concerns the assignment of activities to operators. In defining the total execution time to perform an activity, it should be considered how long the operators must rest in relation to the intensity and duration of the activity performed.

As discussed in the previous section, several analytical models have been developed based on different fatigue and recovery assessment methods. In the following, the proposed model is focused on the energy expenditure rate. First, the model developed by Price (1990) is briefly presented, then a new rest allowance formulation based on exponential fatigue and recovery models is introduced, in which the strong assumptions made by Price (1990) are relaxed.

4.3.1 Exponential fatigue and recovery trend based on energy expenditure rate

Price's assumptions consider a fixed value of the energy expenditure rate $\dot{E}_W$ during the execution of the analysed activity for t_W, and, after the operator has completed the task, the energy expenditure rate immediately reaches the resting value $\dot{E}_R$ as can be seen in Equation (1) and in Figure 4.1:

$$RA = \frac{MWR-300}{300-RR} = \frac{\dot{E}_W-4.3}{4.3-\dot{E}_R} \tag{1}$$

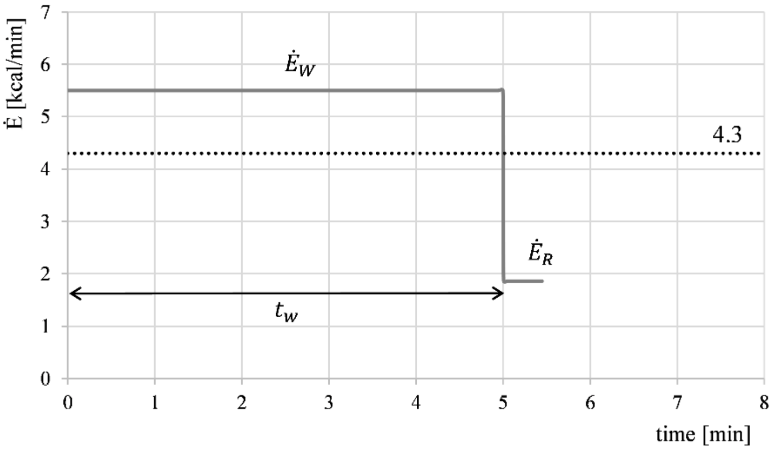

Figure 4.1 Trend of the Energy expenditure rate E˙ [kcal/min] as a function of time, according to Price's model (1990).

Even though, many studies demonstrated that the energy expenditure rate during job execution is not constant and that an additional time to reach the resting energy expenditure rate is needed (Ye and Pan, 2015).

As far as physical fatigue is concerned, Konz (1998a, 1998b) gives evidence of how general body fatigue can affect the cardiovascular system and how different jobs can have different combinations of fatigue, with an exponential increasing function over time.

In addition, he considers how the recovery function depends on the accumulation of fatigue in the muscle and how this decreases exponentially with time, considering the conditions of the muscle at rest. These aspects have been put into evidence also by more recent literature (Rusko et al., 2003; Rusko, 2004; Seppänen, 2005; Dode et al., 2016).

Jaber and Neumann (2010) and Jaber, Givi and Neumann (2013) developed an equation to show the exponential function of fatigue and recovery level based on the Maximum Endurance Time (MET).

As already explained, since in a production system it could be easier to have a feedback regarding the cardiovascular system, here fatigue and recovery functions based on energy expenditure rate are introduced. In fact, by using the heart rate monitoring (Calzavara et al., 2017; Calzavara et al., 2018), the energy expenditure rate can be estimated using the equation introduced by Spurr et al. (1988). However, it has to be assumed that the intensity is sufficiently high to disturb the cardio-vascular system, such as in manual activities in order picking systems, workplaces, internal material handling operations as loading or unloading of work centers (Garg, Chaffin and Herrin, 1978). Knowing the value of the maximum working energy expenditure rate $\dot{E}_W$ and the energy expenditure rate set at rest $\dot{E}_R$, which can differ from one operator to another, it is possible to model fatigue $F(\mathrm{t})$ and recovery $R(\tau)$ as follows:

$$F(\mathrm{t}) = \dot{E}_W + \left(\dot{E}_R - \dot{E}_W\right) \cdot e^{-\lambda \mathrm{t}} \tag{2}$$

$$R(\tau) = F(t_W) \cdot e^{-\mu\tau} \tag{3}$$

where t is the duration of the working activity and τ is the recovery time necessary for the operator to recuperate from the accumulated fatigue. The value of t ranges between 0 and t_W which is the total duration of the activity. In these equations physiological factors, are considered by including the parameters λ and μ, already introduced in Jaber, Givi and Neumann (2013), that are, respectively, the factor of fatigue accumulation and the one of recovery alleviation. Moreover, in equation (2) as in equation (3) the energy expenditure rate of the activity is considered.

As far as fatigue is concerned, as it can be seen in Equation (2) and in Figure 4.2, the operator does not start the fatigue accumulation from 0, but from the energy expenditure rate at rest $\dot{E}_R$. Moreover, there is an exponential trend till the reaching of the maximum energy expenditure rate $\dot{E}_W$ during the task execution time t . This maximum limit of $\dot{E}$ is strictly linked to the intensity of the activity performed and to the physiological factors of the operator. The equation (1) proposed is different from the one of Jaber, Givi and Neumann (2013). In Jaber, Givi and Neumann (2013), the fatigue function is 0 in case of negligible fatigue and 1 when the operator reaches the maximum allowance value of fatigue. In equation (1) the fatigue function is equal to $\dot{E}_R$ in case of negligible fatigue and is equal to the maximum energy expenditure rate when the operator reaches the maximum allowance value of fatigue. As far as recovery is concerned, at the end of the activity, when the operator is at $\dot{E}_W$, the recovery starts and the energy expenditure rate decreases exponentially till the reaching of $\dot{E}_R$. The time needed to reach $\dot{E}_R$ is τ_r (Figure 4.2). Subsequently the value of τ in equation (3) ranges between t_W and t_W plus τ_r .

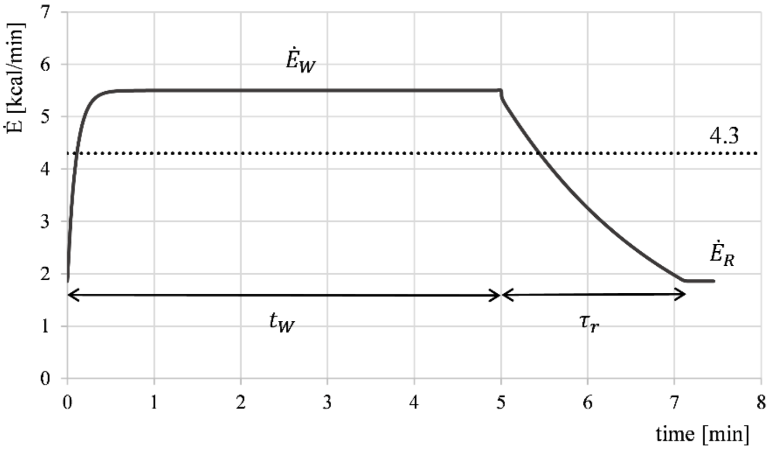

Figure 4.2 Trend of the Energy expenditure rate E˙ [kcal/min] as a function of time, considering an exponential trend during fatigue and recovery.

In the following formulations, it is considered $\dot{E}_R$=1.86 kcal/min, which is an average value also indicated in Price (1990) and Battini et al. (2017) as a good estimation for energy expenditure at rest. However, since the value of $\dot{E}_R$ can slightly differ according to the individual, it would be possible to set a different value for it.

By setting $R(\tau)$=1.86 kcal/min in Equation (3), it is possible to obtain τ_r, the time in which the recovery function $R(\tau)$ reaches the average energy expenditure rate at rest 1.86 kcal/min:

$$\tau_r = \frac{\ln F(t_W) - \ln \dot{E}_R}{\mu} \tag{4}$$

The exponential behaviour of these functions (Equations 2 and 3) has been already demonstrated in previous researches (Konz, 1998a, 1998b; Rusko et al., 2003; Rusko, 2004; Seppänen, 2005); however, it becomes important to understand how to estimate the parameters λ and μ directly from data collected in real cases, as shown in the following.

4.3.1.1 Estimation of λ and μ parameters using and heart rate monitoring system

Simple laboratory tests have been carried out to show how to estimate the values of λ and μ. These parameters have been already introduced by previous researches (Jaber, Givi and Neumann, 2013; Givi, Jaber and Neumann, 2015); however, these studies are based on muscular fatigue and they do not give any specification on how to practically obtain λ and μ.

Based on these tests, it is explained how to set the parameters λ and μ starting from the measured heart rate, showing that they are affected by physiological factors and performed activities.

Since the approximation of λ and μ is not so easy because the trend of the heart rate has a certain variability, the aim of this section is not to find an exact model but to have a good estimation of the real trend of the heart rate, and consequently, of the energy expenditure rate, by using λ and μ.

To estimate the values of these two parameters similar tests can be replicated also in a production system, through the following step by step procedure:

1) As a first step, it is necessary to record data in the field for the specific activity (e.g. a picking activity) by making the operator wearing the heart rate monitor during the activity and during the rest. It can be used only the heart rate monitor if the correlation coefficient with the heart rate for the specific operator is known; otherwise, a further test for its estimation, through oxygen consumption measurement, is needed (Åstrand and Ryhming, 1954; Li, Deurenberg and Hautvast, 1993; Calzavara et al., 2018).

2) For having a specific estimation of λ and μ it can be used the mean squared error (MSE) to measure the average of the squares of the differences between the estimator and what is estimated. By setting the minimization of the MSE between the data recorded with the heart rate monitor and the trend of fatigue and recovery of the model it is possible to obtain the values of λ and μ which can better represent the real data

3) After the setting of the values of λ and μ for the specific activity it is possible to consider the same values also if the intensity of the activity changes (e.g. the operator changes from a picking activity of 8 items/minute to a picking activity of 12 items/minute).

4) If the kind of activity differs (e.g. the activity does not regard picking but assembly) it is necessary to perform another real test with the heart rate monitor and, hence, repeat steps 1, 2 and 3.

According to this procedure, in the performed tests picking activities of different intensities have been repeated by two operators, who were wearing a heart rate monitoring system and an oxygen mask during the performance of their working activity and during their resting period.

This allowed the setting of the correlation index between the heart rate (HR) and the oxygen consumption (VO2) for the specific operator, which permits to validate the use of the heart rate monitor for manual activities (Christensen et al, 1983; Calzavara et al., 2018). The value of this index, together with the values obtained from the heart rate, are used to estimate the value of energy expenditure rate ($\dot{E}$) using the equation of Spurr et al. (1988); by multiplying the conversion factor 0.239 it is obtained the value in kcal/min instead of kJ/min:

$$\dot{E} = (m \cdot fH + b) \cdot 20.48 \cdot 0.239 \qquad (5)$$

where m is the slope, b is the intercept of the correlation line between the oxygen consumption and the HR and fH is the value of the measured heart rate.

According to step 2 of the presented procedure, for the setting of the parameters λ and μ the real trends for fatigue and recovery, obtained in a laboratory test for two operators performing a picking activity with an intensity of 12 items per minute, have been matched to the fatigue and recovery trends obtained by using the model (Equations 2 and 3) with different hypothetical values of λ and μ. In this laboratory test, each operator had to pick an 8-kilograms item positioned on a 1-metre-high shelf and place it on a pallet positioned on the ground at the established rate of 12 items per minute for 30 minutes. The item weight, the height of the shelf and the picking rate have been replicated in the test environment according to what has been detected in a production system. By matching the real trends for fatigue and recovery obtained in this laboratory test (the test values of Figure 4.3) with the different trends which can be obtained by using the model (Equations 2 and 3) assigning different values of λ and μ, it is possible to understand which are the values of λ and μ that best fit the characteristics of the two operators at the predetermined rate. Figure 4.3 shows the trend of $\dot{E}$ during activity performance and during rest for two different operators (operator 1 and 2) performing the test. It is reported the comparison of the test values and of the mathematical model ones, as well as the derived values of λ and μ. As it has been underlined before, the value of the two parameters λ and μ could change from one operator to another; however, the values indicated in Figure 4.3 can be used for reference.

As explained in the step 3 of the procedure, once the values of λ and μ for the operator performing the specific activity are known, they can be used even if the intensity of the monitored activity changes.

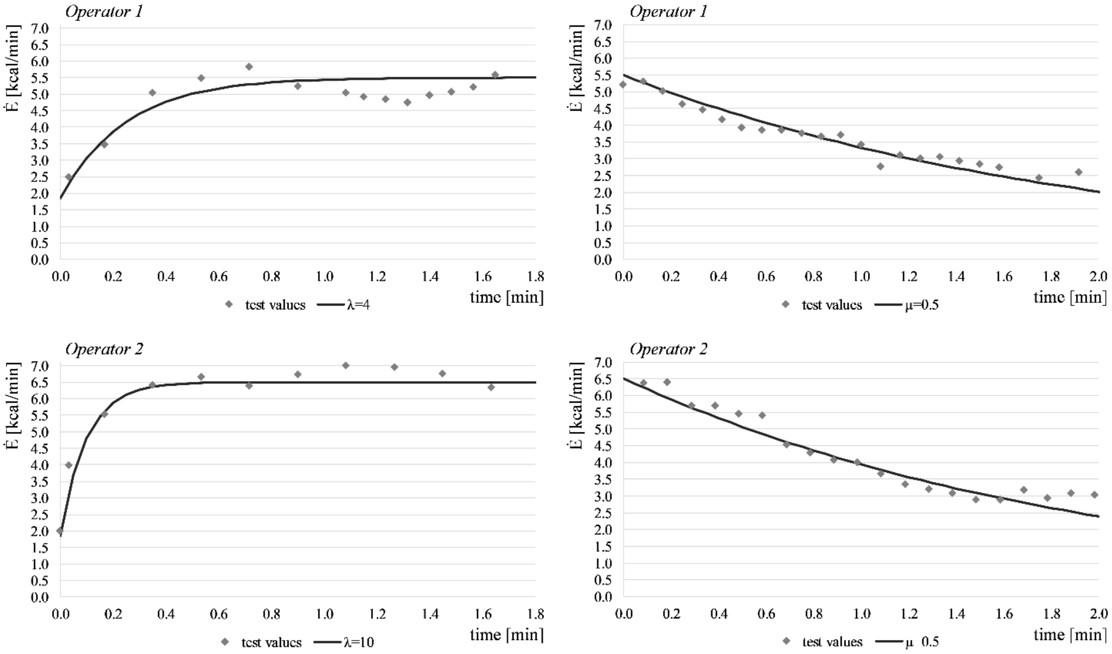

Figure 4.3 Setting of the values of λ and μ by applying the model to the data recorded in the field (indicated as test values) for a picking activity of 12 items/minute for two different operators.

As can be seen in Figure 4.3, a possible value of λ for the operators 1 and 2 could be, respectively, 4 and 10. As far as μ is concerned, the reference value is 0.5 for both operators. The value of these two parameters changes depending on the operator performing the activity and influences the energy expenditure rate increase during fatigue and its decrease during recovery, as can be seen in Figure 4.4. A higher value of λ means a fast fatigue accumulation, whereas a higher value of μ means a slow recovery. Consequently, to carry on an estimation of the $RA^{\lambda,\mu}$ value it is essential to evaluate the λ and μ values for a specific operator for the considered activity.

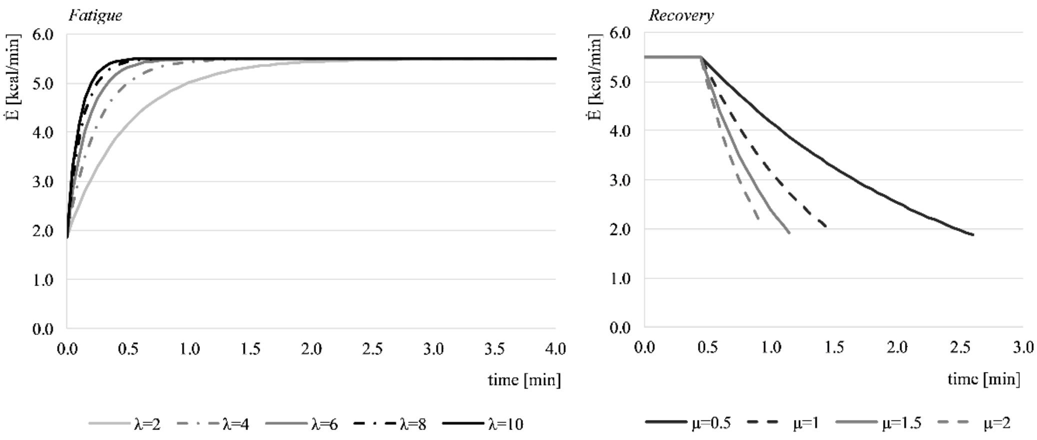

Figure 4.4 4 Influence of the parameters λ and μ on the trends of fatigue and recovery stated by the model.

4.4 Rest allowance based on exponential fatigue and recovery function

In this section, a new equation for rest allowance estimation is introduced, extending Equation (I) and considering the exponential fatigue and recovery functions.

Figure 4.5 shows the fatigue and recovery trends for the rest allowance according to Price's model RA^{P} on the left and the new model $RA^{\lambda,\mu}$ on the right.

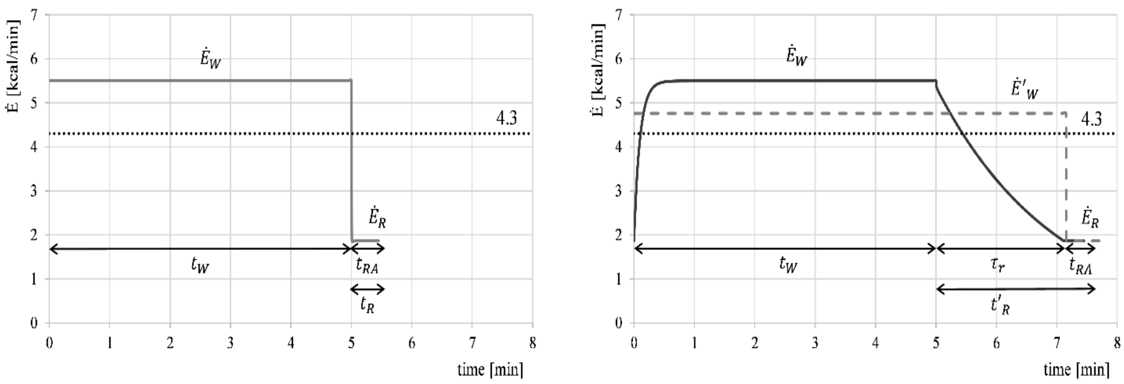

Figure 4.5 Comparison of Price's model (left) and the new model (right) for the estimation of RA, considering different values of mean energy expenditure rate and of recovery time.

RA^P is calculated considering a fixed energy expenditure rate $\dot{E}_W$ during the task execution and an instantaneous $\dot{E}_R$ after that (as can be seen also in Figure 4.5):

$$RA^P = \frac{t_R}{t_W} = \frac{t_{RA}}{t_W} \tag{6}$$

in which, t_R, time needed for the operator to recover, is equal to t_{RA} since the operator reaches immediately $\dot{E}_R$.

The new rest allowance is called $RA^{\lambda,\mu}$, since it depends on the parameters λ and μ of the exponential fatigue and recovery functions and is defined as:

$$RA^{\lambda,\mu} = \frac{t'_R}{t_W} \tag{7}$$

where t'_R is the real time necessary for a full recovery, obtained by summing two different terms:

$$t'_R = \tau_r + \ t_{RA} = \tau_r + RA \cdot (t_W + \tau_r) \tag{8}$$

The first term, τ_r, is related to the exponential recovery function applying Equation (4), while the second term t_{RA} is related to the rest allowance RA, as defined by

Equation (1) and considering a mean value of energy expenditure rate calculated on the total time $t_W + \tau_r$, $\dot{E}'_W$ (Figure 4.5):

$$RA = \begin{cases} \frac{\dot{E}'_W - 4.3}{4.3 - \dot{E}_R} & if\ \dot{E}'_W \ > 4.3 \\ 0 & otherwise \end{cases} \tag{9}$$

The value of $\dot{E}'_W$ is obtained by integrating $F(t_W)$ and $R(\tau)$:

$$\dot{E}'_W = \frac{\int_0^{t_W} F(t_W) + \int_{t_W}^{t_W+\tau_r} R(\tau)}{t_W + \tau_r} \tag{10}$$

where

$$\int_0^{t_W} F(t_W) = \dot{E}_W \cdot t_W + \left(\dot{E}_R - \dot{E}_W\right) \cdot \frac{e^{-\lambda t_W}}{-\lambda} + \frac{(\dot{E}_R - \dot{E}_W)}{\lambda} \tag{11}$$

$$\int_{t_W}^{t_W+\tau_r} R(\tau) = \frac{F(t_W)}{-\mu} \cdot e^{-\mu t_W} \cdot \left(e^{(-\ln F(t_W) + \ln(\dot{E}_R)} - 1\right) \tag{12}$$

This new value of $RA^{\lambda,\mu}$ could be different from the RA^P value. In fact, $RA^{\lambda,\mu}$ considers the real time necessary for a full recovery t'_R instead of t_R.

In the next section, a comparison between the two values $RA^{\lambda,\mu}$ and RA^P is carried out to understand the influence of λ, μ, $\dot{E}_W$ and t_W on $RA^{\lambda,\mu}$, and in which cases this value cannot approximate the RA^P. In this analysis, the value of $RA^{\lambda,\mu}$ is calculated through the application of the model for different values of λ and μ and for activities with different intensity. After that, this value is compared to RA^P to understand when these two models differ more.

4.5 Comparison between $RA^{\lambda,\mu}$ and RA^P

The comparison between the two rest allowance models is based on the different values of λ and μ, which are related to the physiological factors of the operator, and to the kind of activity. In the following analysis, the considered values λ and μ have been obtained by real operators, performing picking activities at different intensities.

The energy expenditure rate estimated by using the heart rate monitoring have been equal to 4.5, 5.5 and 6.5 kcal/min. These values are similar to the ones obtained in previous researches (Garg, Chaffin and Herrin, 1978; Calzavara et al., 2017; Calzavara et al., 2018).

The following analysis aims to demonstrate in which cases $RA^{\lambda,\mu}$ differs from the one resulting from the application of Equation (6) (Price, 1990). Different values of λ and μ, and of $\dot{E}_W$ and t_W have been assumed. The results of the analysis are shown in Figures 4.6 and 4.7.

Figure 4.6 shows the value of $RA^{\lambda,\mu}$: it can be noted that it increases with the increase of λ and the decrease of μ, because the slope of the fatigue function increases and the slope of the recovery function decreases. In addition, both $\dot{E}_W$ and t_W influence the value of $RA^{\lambda,\mu}$: the increase in both $\dot{E}_W$ and t_W implies an increase in the value of the $RA^{\lambda,\mu}$.

On the other hand, the value of RA^P for 4.5, 5.5 and 6.5 kcal/min, is 10%, 50% and 90% of the time of the activity performed, respectively, and this value does not change if the time of the activity decreases or increases.

It can also be seen that, for the chosen values of λ and μ, the parameter which most influences the value of $RA^{\lambda,\mu}$ is μ, because the change from one value of μ to another causes a major increase in the value of $RA^{\lambda,\mu}$ rather than the change in the value of λ.

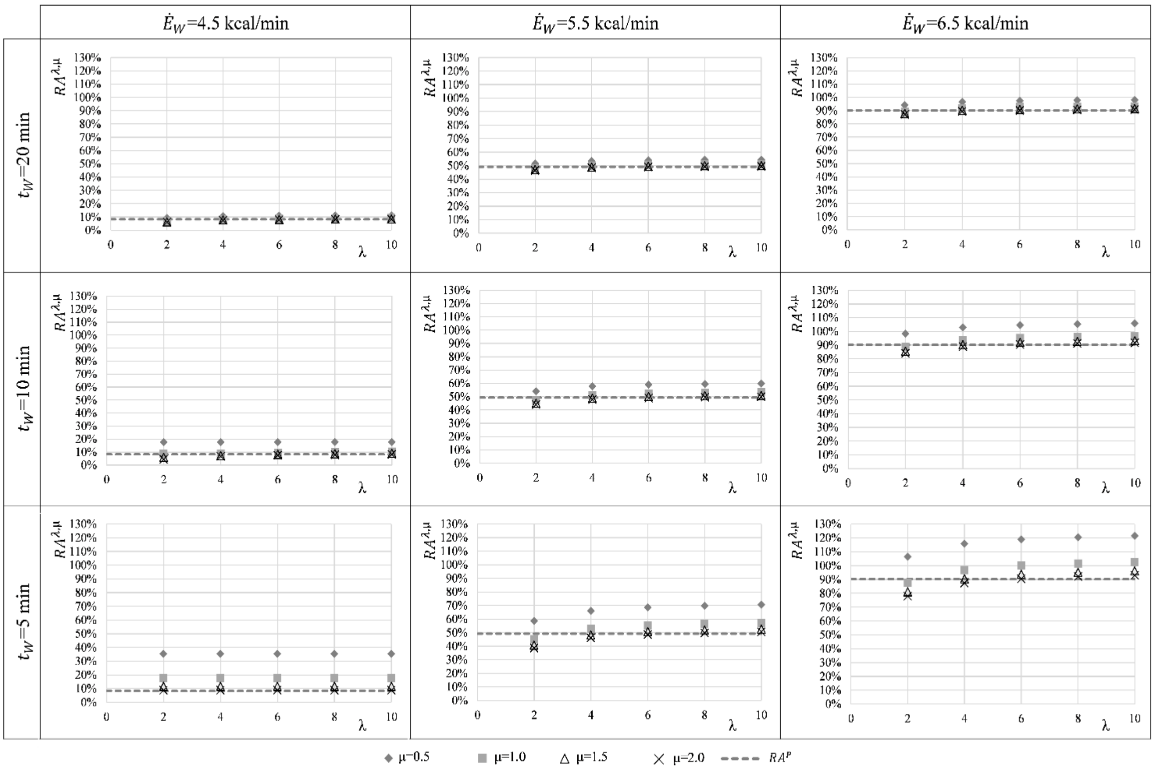

Figure 4.6 Evaluation of $RA^{\lambda,\mu}$ and of RA^P changing the duration of the activity (5, 10, 20 min), the maximum energy expenditure rate of the activity (5.5, 6.5 kcal/min), λ (2, 4, 6, 8, 10) and μ (0.5, 1, 1.5, 2).

As far as Figure 4.7 is concerned, the ratio between $RA^{\lambda,\mu}$ and RA^P provides evidence of the cases in which the value of $RA^{\lambda,\mu}$ is similar to RA^P, which is calculated without considering t_W, λ and μ. As can be seen in Figure 4.7, the value of $RA^{\lambda,\mu}$ can be approximated to RA^P by increasing both $\dot{E}_W$ and t_W.

The main difference between the $RA^{\lambda,\mu}$ and RA^P is for a value of $\dot{E}_W$ of 4.5 kcal/min and of t_W of 5 minutes. In this case, the value of RA^P is 0 because of a value of $\dot{E}'_W$ below 4.3 kcal/min, but, on the other hand, the influence of τ_r determines a value of $RA^{\lambda,\mu}$ that is considerably higher than RA^P.

In addition to this, with a fixed low value of $\dot{E}_W$ such as 5.5 kcal/min, it can be noticed that the difference increases with the decrease in the time of the activity: if the activity is carried on for a short time, the influence of the $\dot{E}_W$ on the value of the $\dot{E}'_W$ is lower. Consequently, it is more probable to have a value of $RA^{\lambda,\mu}$ different from RA^P, not only if the $\dot{E}_W$ is low, but also if the duration of the activity is short.

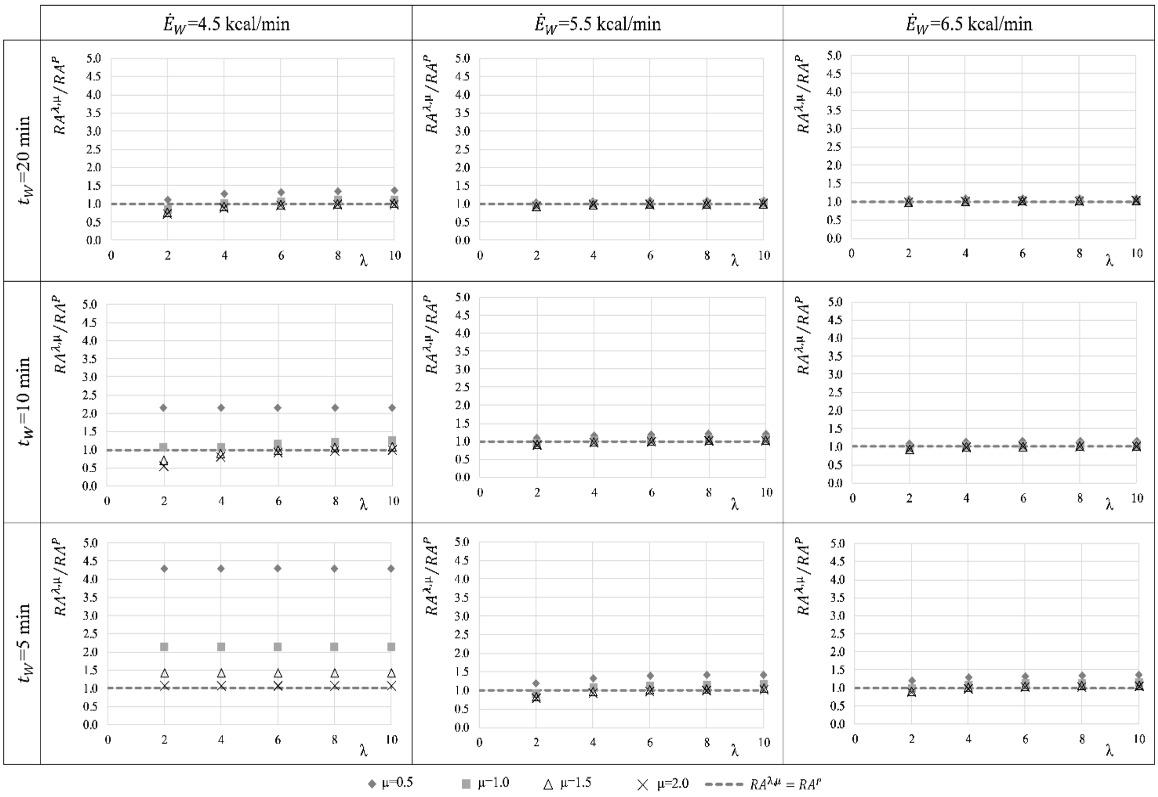

Figure 4.7 Comparison of $RA^{\lambda,\mu}$ and RA^P by considering the value of $RA^{\lambda,\mu}/RA^P$, changing the duration of the activity (5, 10, 20 min), the maximum energy expenditure rate of the activity (4.5, 5.5, 6.5 kcal/min), λ (2, 4, 6, 8, 10) and μ (0.5, 1, 1.5)

4.6 Application of the model

This section presents an application of the model explained previously. The model is applied in a picking context where it is necessary to determine which activities have to be given to each operator. Twenty activities are taken into account, which need to be assigned to 3 different operators.

As far as operators are concerned, there are three different values of λ and μ. The values taken into account for λ and μ are the following: for the first operator, 10 and 0.5; for the second, 2 and 2; and for the third, 6 and 1, respectively. It is assumed that the intensity of each activity (in terms of energy expenditure rate and duration) is known. In addition, knowing the kind of activity to be performed, the value of the rest allowance can be obtained by using the model, if each operator has to carry out that particular activity. These initial data regarding activities and operators can be seen in Table 4.1. In this table it is considered that the operators reach the same value of energy expenditure rate for the activity considered and that they differ only for their values of λ and μ, also if as stated before, they can reach different values of energy expenditure rates according to their physical characteristics. In this case it is considered λ and μ as variables because the aim is to understand if, also in this case, can be obtained an improvement in term of time reduction through the scheduling.

The scheduling of activities is performed by considering the three operators working in parallel, and McNaughton's algorithm is used to schedule activities for different operators in order to minimize schedule length (McNaughton, 1959), considering that each operator has to rest after the performance of each activity.

For the implementation of this algorithm four different measures are considered for ordering the activities: task time, workload, task time plus RA^P, and task time plus $RA^{\lambda,\mu}$ for each activity. The final aim of the case study is to provide evidence that if the $RA^{\lambda,\mu}$ is used in the early stage of the assignment of the activities to the operators then the makespan decreases. In this situation, the makespan is intended to be the maximum time necessary to carry out all the picking orders with three operators working in parallel.

Table 4.1 List of the considered activities, with $\dot{E}_W$, t_W and respective Rest Allowances.

Activity	$\dot{E}_W$ (kcal/min)	t_W (min)	RA_{OP1}	RA_{OP2}	RA_{OP3}	RA^P
1	3.0	5	0.191	0.048	0.096	0
2	3.5	5	0.253	0.063	0.126	0
3	4.0	5	0.306	0.077	0.153	0
4	4.5	5	0.353	0.088	0.177	0.082
5	5.0	5	0.453	0.191	0.330	0.287
6	5.5	5	0.705	0.386	0.552	0.492
7	6.0	5	0.959	0.583	0.776	0.697
8	3.0	10	0.096	0.024	0.048	0
9	3.5	10	0.126	0.032	0.063	0
10	4.0	10	0.153	0.038	0.077	0
11	4.5	10	0.177	0.044	0.095	0.082
12	5.0	10	0.370	0.239	0.308	0.287
13	5.5	10	0.598	0.439	0.522	0.492
14	6.0	10	0.828	0.640	0.736	0.697
15	3.0	20	0.048	0.012	0.024	0
16	3.5	20	0.063	0.016	0.032	0
17	4.0	20	0.077	0.019	0.038	0
18	4.5	20	0.113	0.060	0.089	0.082
19	5.0	20	0.329	0.263	0.298	0.287
20	5.5	20	0.545	0.465	0.507	0.492

4.6.1 Scheduling of the activities and results

The data necessary to put McNaughton's algorithm (1959) into practice are the characteristics of the activity: the energy expenditure rate and the execution time. In fact, when there is the need to give to different operators a certain amount of activities, it is important to know how the minimization of the makespan in the first phase of assignment can be reached. First of all, in this case study, the time of each activity for scheduling the operators' activities is considered, without taking into account the energy expenditure rate. After that, activities are ordered in the following way. First, the three activities with a higher time value are considered. These three activities are assigned one by one to each of the three operators. Then, the next activity is given to the operator who has the lowest value of time for the first activity assigned, and if the time is the same, the activity is assigned to the operator who performs better, because he has a lower value of λ and a higher value of μ. Then the procedure is continued using the same reasoning, by considering the time of each activity in descending order and looking at the time the operators accumulate with the assignment of activities. In this way, it is possible to have a scheduling solution for the 20 picking activities, and by summing up the time for all the activities assigned to an operator, the total time necessary for the operator to carry out all the activities assigned can be calculated. For each activity assigned to an operator it is necessary to consider the time of the activity and the time that is needed for the operator's recovery after the performance of the activity. Consequently, the comprehensive time of the activity is calculated by summing up the duration of the activity and the time necessary for the operator's recovery, obtained by multiplying the activity duration by the $RA^{\lambda,\mu}$ for an operator with predetermined values of λ and μ. Consequently, the time for the activity is calculated after the scheduling has been established because it is known which operator will perform each activity.

Figure 4.8 presents the four different scheduling solutions, called respectively "Scheduling with time", "Scheduling with workload", "Scheduling with time and RA^{P}", "Scheduling with time and $RA^{\lambda,\mu}$".

For each solution, in the upper part (called A) there are the activities assigned to each operator. Then, in the bottom part (indicated with B), the time of each activity is reported, with the recovery time if needed. Moreover, the comprehensive time (summing up the time of the activity and $RA^{\lambda,\mu}$) and subsequently the makespan are shown.

Scheduling with time

A	Activity number							
OP1	20	17	14	11	8	3		
OP2	19	16	13	10	7	5	2	
OP3	18	15	12	9	6	4	1	
B	**Time [min]**							**Total**
OP1	30.90	21.53	18.28	11.77	10.96	6.53		99.97
OP2	25.26	20.32	14.39	10.38	7.91	5.95	5.32	89.53
OP3	21.77	20.48	13.08	10.63	7.76	5.88	5.48	85.09

Scheduling with workload

A	Activity number								
OP1	20	15	13	12	9	7	5	1	
OP2	19	16	8	3	2				
OP3	18	17	14	11	10	6	4		
B	**Time [min]**								**Total**
OP1	30.90	20.96	15.98	13.70	11.26	9.80	7.27	5.96	115.83
OP2	25.26	20.32	10.24	5.38	5.32				66.51
OP3	21.77	20.77	17.36	10.95	10.77	7.76	5.88		95.27

Scheduling with time and RA^P

A	Activity number							
OP1	20	15	12	9	6	3	1	
OP2	19	16	13	10	7	5		
OP3	18	17	14	11	8	4	2	
B	**Time [min]**							**Total**
OP1	30.90	20.96	13.70	11.26	8.52	6.53	5.96	97.84
OP2	25.26	20.32	14.39	10.38	7.91	5.95		84.22
OP3	21.77	20.77	17.36	10.95	10.48	5.88	5.63	92.85

Scheduling with time and $RA^{\lambda,\mu}$

A	Activity number								
OP1	20	15	12	9	6	3			
OP2	19	16	13	10	8	4	2		
OP3	18	17	14	11	7	5	1		
B	**Time [min]**								**Total**
OP1	30.90	20.96	13.70	11.26	8.52	6.53			91.88
OP2	25.26	20.32	14.39	10.38	10.24	5.44	5.32		86.03
OP3	21.77	20.77	17.36	10.95	8.88	6.65	5.48		91.86

Figure 4.8 Makespan comparison of different scheduling strategies (time, workload, time and RA^P, time and $RA^{\lambda,\mu}$) for the assignment of 20 activities to 3 operators, reporting the activity numbers assigned to the operators (A) and the respective times (B).

The makespan, which is the higher value of total time among the operators, has been calculated for each scheduling solution. In all solutions, the physiological factors of each operator, in terms of λ and μ, are considered to calculate the total execution time ($t_W + t'_R$) after the scheduling has been established.

In the case of scheduling based on descending time for the activity (Scheduling with time), the makespan is 99.97 minutes.

The same logic is used by considering, to order the activities, the workload of each activity (Scheduling with workload). The workload of each activity is obtained by multiplying the duration of the activity by its energy expenditure rate. Also in this case, the activities are ordered in descending order, but the term of reference is the workload. In this case, as it is shown in Figure 4.8, the value of the makespan is 115.83 minutes, higher than the previous case.

If the execution time plus RA^{P} is considered for each activity (Scheduling with time and RA^{P}), the makespan is 97.84 minutes.

In the last scenario (Scheduling with time and $RA^{\lambda,\mu}$) the operators' physiological factors are considered in the first stage of activity assignment. First, the activities are ordered considering the duration of the activity plus the $RA^{\lambda,\mu}$. Then, the first three activities are assigned to the operators. As a second step, the time of the first activity is calculated by summing up the duration of the activity with the recovery time obtained knowing the value of $RA^{\lambda,\mu}$. After that, the next activity is given to the operator who first finishes the first activity assigned in terms of time, and the new value of time plus $RA^{\lambda,\mu}$ is calculated after this second assignment to the operator. This procedure is followed for all the 20 activities. In this scheduling solution, the makespan obtained is 91.88 minutes, even lower than the one calculated using only the duration, only work, or with duration plus RA^{P}.

Looking at these results, in the case of an operator who recovers after every activity, it is better to consider the time plus the $RA^{\lambda,\mu}$ in the early stage of activity assignment because, in this way, the makespan is minimized and it reaches the best schedule in terms of time. In fact, if only the time of the activity is considered, no attention is given to the energy expenditure rate requested by the activity in kcal/min, nor to the kind of operator who has to perform the activity. On the other hand, if, in addition to the duration, the RA^{P} is considered, the makespan is reduced because RA^{P} is set by knowing the energy expenditure rate of the activity, so the first attempt should also consider the requested energy expenditure rate as well as the duration of the activity. Finally, by looking at the $RA^{\lambda,\mu}$ at the early stage of assignment, not only are the duration and energy expenditure rate of the activity considered, but also the physiological factors of the operators in terms of fatigue accumulation and recovery.

4.6.2 Applicability and limitations of the model

The model presented then applied to an example in the previous section can be used for all the activities that can be classified as manual activities, and that require the use of the whole body. This can be easily applied because the value of the energy expenditure rate can be obtained without difficulty by making the operator wear a heart rate monitor. In addition, once the values of λ and μ are set for the specific operator, they are valid for every kind of activity that the operator performs with the same energy expenditure rate.

As far as the limitations are concerned, the model cannot be applied for activities where there could be, during the performance of repetitive activities, the continuous use of the same groups of muscles causing muscular fatigue. In these cases, the use of this model based on energy expenditure rate can lead to erroneous conclusions in relation to the assignment of activities to operators. In fact, the operators can be given a certain number of activities that will not be considered risky because of low values of energy expenditure rate but, that, on the other side, can cause musculoskeletal disorders due to the continuous use of the same group of muscles. To enlarge the use of this model to activities where there can be high values of muscular fatigue, it is necessary to analyze in depth the relation between the energy expenditure rate and the parameters MVC and MET, introducing some additional terms in the model.

4.7 Conclusions on the results obtained

In this chapter, a model for fatigue evaluation and rest allowance estimation is developed and analysed, also by putting it into practice using a numerical example. The contribution of this model is to consider how the rate, the duration of the activity and the physiological factors of the operator can affect the accumulation of fatigue and the recovery time, for activities where the whole body is used and where there is an influence on the cardiovascular system because there is a modification in the operator's heart rate. Through the developed mathematical model, it is possible to estimate the recovery time of each specific operator, by considering the influence of the parameters of fatigue accumulation and recovery alleviation, respectively λ and μ. Moreover, it is considered the kind of activity performed which determine the value of the maximum energy expenditure rate reached by the operator. In relation to this, the existing models based on muscular fatigue (Jaber and Neumann, 2010; Givi, Jaber and Neumann, 2015) are based on the MVC, which is a measure difficult to be obtained easily in an industrial context and to be applied by a practitioner, and they do not give information about how to estimate the value of λ and μ and how to apply these values for the analysis of fatigue and recovery of each operator. The estimation of RA considering human factors and energy expenditure rate for manual material handling activities lacks in the existing literature. In fact, in this chapter it is shown how this model differs from the existing model of Price (1990) modified by Battini et al. (2017). In addition, through a numerical example, it is put in evidence how the application of this model in the early stages of activities assignment to operators working in parallel permits to improve the performance of the system by reducing the makespan.

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5. Fatigue accumulation in the WAP

5.1 Introduction

One of the main problems with which companies have to face in the management of human resources is the workers assignment problem (Ammar, Pierreval and Elkosentini; 2013). In fact, for the companies where the use of human resources is fundamental for performing production activities, the allocation of different kinds of activities to operators can influence the performance of the overall production system. Normally this is preferably considered for assembling or production activities rather than material handling activities such as carrying, picking, loading or unloading of machines or pushing or pulling activities. As far as assembling or production activities is concerned, the assignment of activities to operators it is evaluated for, first of all, matching their capabilities to ease the respect of the requested cycle time. In addition, for such repetitive tasks, it is considered the ergonomic risk factors in the assignment for reducing the probability of facing injuries or a reduction of workers' physical capabilities. Less attention is paid in the workers assignment problem for the physical fatigue perceived by the operators. In fact, most of the existing literature related to the consideration of human factors on the workers assignment problem has been focused on the proposals of algorithms for minimizing the risk of musculoskeletal disorders in the workplace and the accumulated work load for body parts (Song et al., 2016) instead of minimizing the level of fatigue. The physical fatigue an operator experiences is the muscular and general body one. The first is related to the continuous stress of the same group of muscles during repetitive activities and the second one is related to the movement of all the body during the performance of the activity. For the reduction of the fatigue level of operators the literature has been focused on the estimation on the time necessary to the operator for recovering after the efforts performed previously. This recovery time is called rest allowance. Its value is evaluated by considering respectively, for the muscular fatigue, the value of the Maximum Voluntary Contraction (MVC) and of Maximum Endurance Time (MET) and for the general body fatigue the value of energy expenditure. Even though several models existed for the estimation of RA by considering muscular fatigue, for general body fatigue there exists very few. The only one existed (Price, 1990), has been developed in chapter 4 by considering the real trend of fatigue and recovery of operators performing material handling activities (Calzavara et al., 2018a; Calzavara et al., 2018b). The fatigue has been considered in existing heuristics for the assignment of multi-skilled workers subjected to fatigue to different kinds of machines only for the reduction of the mean flowtime avoiding congestion, not for the reduction of the overall recovery time of the operators (Ferjani et al, 2017). The recovery time has been taken into account in Othman, Gouw and Bhuiyan (2012) through a multi-objective integer programming model which takes into account the muscular fatigue of operators. Subsequently, the aim of this chapter is to develop a model which can consider how fatigue accumulates for operators performing a predetermined number of activities and can give information regarding in which order these activities should be assigned for minimizing the total recovery time. This model aims to be applied to operators who carry on manual material handling activities involving the whole body and causing general body fatigue on them.

5.2 Existing models for considering fatigue into the workers' assignment problem

The literature focused on the workers assignment problem has faced in addition to the problems of the workers flexibility, the evaluation of their movements and possibilities of collaboration and of the impact of the static or dynamic assignment and of the operators' training level (Ammar, Pierreval and Elkosentini; 2013). In fact, the human resources together with the machines are the constraints of a production system. For such dual resource constrained systems, the scheduling of the operators' activities is important because they need to move across different machines or workstations in according to their capabilities (Xu, Xu and Xie, 2011; Givi, Jaber and Neumann, 2015a). The presence of human resources is still considerable, but the existing literature remains focused on maximising the use of these resources through the reduction of the travelled distances and the minimization of the make-span of each machine without considering the human factors and the physical fatigue of each operator (Suer and Dagli, 2005). In fact, generally, the aim is to maximise the output rate of the production system without considering the impact on the human resources. The workforce planning and allocation is considered in the decisions model for minimizing the whole labour costs given a certain production rate (Gronalt and Hartl, 2003).

Even though, in the literature review of Neumann and Dul (2010) it has been put in evidence the relation between the human factors and the system performance and how the management of human factors leads to improve labour efficiency and consequently to the reduction of labour costs. Related to this, some recent literature, has tried to consider the work overload in the managing of the production activities to be given to the operators (Aroui, Alpan and Frein, 2017) by taking into account the sequencing of activities for minimizing the work overload. In addition, some papers have been focused on the balancing of assembly lines by considering not only the duration of the tasks but also their relative energy expenditure rate, which is representative of the physical fatigue of an operator (Battini et al., 2016).

During the performance of a predetermined activity an operator perceive fatigue which can be physical or mental and with different intensities (Gawron, French and Funke, 2001). The physical one can be muscular or general body fatigue. The muscular fatigue is related to the continuous stress of the same group of muscle and it is measured with MVC and MET. In the literature exists different models which aim at estimating the value of MET in relation to the group of muscles and of their position in the body (El ahrache, Imbeau and Farbos, 2005). Basing on the value of MVC several static and dynamic models have been developed during years for describing the fatigue accumulation on muscles and some of these have also included the influence of the external load, of the workload history and of the individual differences (Xia and Law, 2008; Ma et al., 2009; Perez et al., 2014) showing an increase of fatigue during loading and its decreasing during recovery (Rose et al., 2014). They have also been put into practice for male and female operators (Zhang et al, 2014). This increasing trend of fatigue during the performance of the activity and the decreasing one during recovery has been put in evidence also for general body fatigue related to the energy expenditure rate of the operators (Calzavara et al., 2018a; Calzavara et al, 2018b). Moreover, these exponential fatigue and recovery trend are influenced by parameters linked to the operator (Jaber, Givi and Neumann, 2013). In addition to the exponential trend of fatigue during the performance of a task it has been put in evidence that the fatigue accumulates if it is not given to the operator time for recovery (Perez et al., 2014). This fatigue accumulation can lead to fatigue-related quality effects and productivity changes (Dode et al., 2016).

As put in evidence in Rashedi and Nussbaum (2017) the analysis of fatigue accumulation in relation to muscular fatigue is not easy because it can be affected by many factors. There could be a dependency of muscle recovery with the history of fatiguing muscle contractions, the cycle time or the exertion level. The analysis of such factors can help the prediction of the localized muscle fatigue. On the other side, for general body fatigue the influence of the physiological factors of operators, of the intensity of the activity and of the duration of the activity is considered in Calzavara et al. (2018b). As explained in Carroll, Taylor and Gandevia (2016) the mechanism of recovery after a certain number of activities which cause fatigue accumulation is strictly related to the characteristics of the exercise bout, if it is disturbed the central or peripheral neuromuscular fatigue. Even though it is recognised in the literature that the only way to permit to the operator to return to the physical condition at rest is to give to him/her the time to recovery from the efforts performed. There exist different ways for making the operator recovering such as work breaks, the maximization of the recovery rate or the increasing of the recovery/work ratio (Konz, 1998a;1998b). In addition to this, there could be the influence of environmental factors such as the climate, the noise and the illumination of the workplace. In El Ahrache and Imbeau (2009) it is put in evidence different rest allowance models related to static muscular work which aim at estimating the value of recovery knowing different parameters of muscle condition such as the MVC or the MHT, which is the maximum time a muscle can sustain a load. For general body fatigue it has been proposed a model for estimating the recovery time considering the energy expenditure rate from heart rate (HR) (Calzavara et al., 2018b). The validity of the model is also confirmed by existing literature focused on the complete recovery time prediction model taking into account the body mass index, the perceived functional ability and the physical activity rating (Ye and Pan, 2015). The use of rest allowance model based on energy expenditure rate for estimating the standard time of manual task taking into account the overall assignment of working tasks to a workstation has been considered by recent literature and companies (Caragnano and Lavatelli, 2012).

As far as workers' assignment problem with fatigue accumulation is concerned, the effect of task variation is evaluated in Luger et al. (2014) and positive effects were put in evidence only for tasks of high muscular demand, but it is also explained the need for the focusing of future researches on this topic. In fact, there is the need of considering more in the assignment of activities to operators the way in which fatigue accumulates and how a predetermined assignment can influence the time the operator has to recover. The existing literature have analysed the influence of the force time-history for tasks with the same duty cycle and average forces (Sonne and Potvin, 2015), have put in evidence that the preceding efforts play a role in fatigue accumulation (Sonne et al., 2015) and have proposed algorithms for solving multi-tasking scheduling problems with a rate-modifying activity (Lodree and Geiger, 2010; Zhu, Zheng and Chu, 2015). Even though, they have focused on muscular fatigue not on general body one. In Ma et al. (2015) a recovery model based on local muscle fatigue is proposed for determining the work-rest cycle of an operator knowing his/her recovery rate. In Othman, Gouw and Bhuiyan it has been proposed a multi objective integer linear programming model considering in the workforce scheduling also the minimization of the recovery time and of the average fatigue level of operators but without considering the worker heterogeneity as far as physiological factors in concerned. The attention of fatigue in the assignment of activities to multi-skilled workers is paid also in Ferjani et al. (2017) where a dynamic assignment heuristic is proposed. Here, it is evaluated an increasing of the processing time of an activity due to the fatigue which has been accumulated but the attention is focused on muscular fatigue and there lacks the consideration of the differences between individuals such as in Jaber and Neumann (2010). In relation to the best assignment of activities to operators is concerned, in Givi, Jaber and Neumann (2015b) an experimental analysis is carried on for showing the scheduling which leads to a lowest value of worker fatigue and the effect of an additional break on the optimal schedule. Considering the existing literature presented in this Section there lacks the analysis of the worker assignment problem for material handling activities causing general body fatigue (measured with the energy expenditure rate) on operators taking into account the differences between individuals, the influence of the kind of activity and the effect of giving to operators additional breaks before the end of the workload. Subsequently the aim of the following chapter will be the filling of this gap of the literature focused on the scheduling of operators' activities considering human factors.

5.3 New model for estimating the RA value considering fatigue accumulation

The mathematical model that will be proposed in this Section is based on manual material handling activities where the value of energy expenditure rate can be obtained with the monitoring of the heart rate. The aim of this model is to evaluate the fatigue accumulation and its impact on the recovery time of an operator considering the physiological factors which differ one operator from the other and the maximum energy expenditure rate and the duration of each activity. The final aim is to give a mathematical model to practitioners which want to define the activities to be given to operators minimizing the recovery time necessary to each of these.

5.3.1 Data considered in the model: energy expenditure from the heart rate

Existing physiological literature assessed the link between the heart rate and the energy expenditure rate of the individual. In Spurr et al. (1988) the total daily energy expenditure and the energy expenditure in activity is estimated with the heart rate and these results are compared with the ones obtained with the whole-body indirect calorimetry. There it is demonstrated that the two methods do not differ much between them. In addition, it is given a formulation for the estimation of the energy expenditure rate in kj/min knowing the value of heart rate recorded during the performance of the activity. A further development of the estimation of energy expenditure rate from heart rate in Li et al. (1993) demonstrates that physiological factors such as body weight, training status and age in addition to environmental factors such as temperature and humidity and to the kind and intensity of the activity can affect the relationship between heart rate and energy expenditure. The effects of these factors have been taken into account in the prediction equation for energy expenditure rate of Keytel et al. (2005). In this study it is shown that the value of energy expenditure rate can be obtained for individuals different between each other in terms of age and fitness without the necessity of having an individual calibration for activities of high and moderate intensity. The accuracy of the estimation can be improved using, in addition of a heart rate monitor, an accelerometer (Kuo et al, 2018). Even though, in the proposed model so much precision is not required, and the energy expenditure rate of reference is the one derived from the formulation of Spurr et al. (1988). As far as the monitoring of the heart rate during material handling activities is concerned, a recent research (Calzavara et al., 2018a) shown that for that kind of activities there is a high coefficient of correlation of HR (heart rate) and VO2 (oxygen consumption) and that the HR can revealed the changes of the kind of activity performed and of its intensity in real time. Subsequently from the data recording in an industrial context, for operators performing these kinds of activities, the heart rate and the subsequently the value of energy expenditure rate can be obtained easily, and these data can be representative of the fatigue the operator is experiencing taking into account how an activity can impact differently on different individuals. The model that will be presented in this section has been developed basing on the values of HR recorded in the field (Calzavara et al., 2018a) where the value of energy expenditure rate is calculated with the formulation of Spurr et al. (1988).

5.3.2 Data considered in the model: rest allowance estimation with the physiological factors

The model presented in the next Section aims at being a further development of the one presented by Calzavara et al. (2018b) and in the chapter before considering how the fatigue accumulates if a proper rest to the operator after each activity is not given (Calzavara et al., 2018b). As explained in Calzavara et al. (2018b), the existing literature focused on the reduction of operator's fatigue try to estimate the value of RA (Rest Allowance) to be given to each operator to recover after the performance of a specific activity. This recovery time can be estimated basing on the value of MVC (Maximum Voluntary Contraction) for muscular fatigue or of energy expenditure rate for general body fatigue. Considering that material handling activities involved the whole body the energy expenditure rate (which can be obtained with the HR) is the best way of evaluating the time the operator has to recover (Calzavara et al., 2018b). Through that model it is possible to consider the physiological factors of each operator and how these values of fatigue accumulation and recovery alleviation affect the changing of the value of RA in comparison to existing models where the values of these parameters are not considered such as the one of Price (1990). As put in evidence in the chapter before (Calzavara et al., 2018b) the value of RA estimated taking into account these parameters differ more from the existing ones if the duration and the energy expenditure rate of the activity decreases. In addition, the value of the parameter of recovery alleviation affects more this difference in comparison to the parameter of fatigue accumulation. In the next Section the model will be further developed in order to consider how the value of rest allowance can be estimated if an operator need to perform a certain number of consecutive activities of different energy expenditure rate, which is expressed in kcal/min.

5.3.3 Mathematical model

The proposed model aims at considering how fatigue accumulates for each kind of operator, which performs a certain number of activities, each of these with a certain energy expenditure rate and duration. As explained in Calzavara et al. (2017, 2018b) the fatigue accumulation during an activity can be modelled as follows:

$$F(t_W)_i = \dot{E}_{W_i} + \left(\dot{E}_R - \dot{E}_{W_i}\right) \cdot e^{-\lambda t_{W_i}} \tag{1}$$

In fact, the fatigue of activity i increases exponentially till the reaching of the maximum energy expenditure $\dot{E}_{W_i}$, which is the maximum value of energy expenditure rate obtained during the performance of the activity by the specific operator. It needs to be considered that this value can change between one operator and the other because an activity can cause different levels of fatigue depending on the operators' characteristics. In fact, during the performance of an activity different operators reach different values of maximum heart rate rate and consequently of energy expenditure rate.

The parameter λ is the parameter of fatigue accumulation, which considers the differences between individuals in reaching the maximum energy expenditure rate

(Calzavara et al., 2018b). On the other side, the recovery function (equation 2) for the activity i is $R(\tau)_i$. It starts at the maximum energy expenditure rate and decreases according to the parameter of recovery alleviation μ during Ʈ, which is the time necessary to the operator for reaching the energy expenditure rate at rest, which as indicated by Price (1990) is equal to 1.86 kcal/min.

$$R(\tau)_i = F(t_W)_i \cdot e^{-\mu\tau} \qquad (2)$$

Basing on equation 1 it can be evaluated how fatigue accumulates if it is not given to the operator a recovery.

As can be seen in equation 3 if the activity which follows activity i, which is called $i+1$, has a value of energy expenditure rate higher than the one reached at the end of activity i (as can be seen in Figure 5.1, A) than the fatigue function of activity $i+1$ starts at the maximum energy expenditure rate of activity i and increases with λ till the reaching of the maximum energy expenditure rate of activity $i+1$ which is $\dot{E}_{W_{i+1}}$.

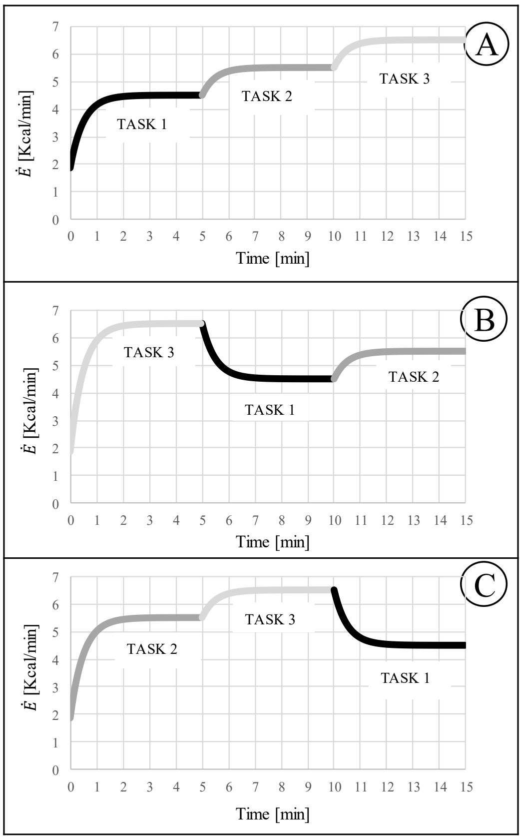


Figure 5.1 Accumulation of fatigue changing the order of 3 different activities.

Instead, if the activity $i+1$ has a value of maximum energy expenditure rate lower than the one of activity i, for the operator there is a kind of recovery so the fatigue function $F(t_W)_{i+1}$ starts at the maximum energy expenditure rate of activity i and decreases till the reaching of the $\dot{E}_{W_{i+1}}$ according to the parameter μ (Figure 5.1, B and C).

$$F(t_W)_{i+1} = \begin{cases} \dot{E}_{W_{i+1}} + \left(F(t_W)_i - \dot{E}_{W_{i+1}}\right) \cdot e^{-\lambda t_{W_{i+1}}} \\ \qquad\qquad\qquad\qquad if\ \ \dot{E}_{W_{i+1}} \geq F(t_W)_i \\ \\ \dot{E}_{W_{i+1}} + \left(F(t_W)_i - \dot{E}_{Wi+1}\right) \cdot e^{-\mu t_{W_{i+1}}} \\ \qquad\qquad\qquad\qquad if\ \ \dot{E}_{W_{i+1}} < F(t_W)_i \end{cases} \tag{3}$$

As far as the recovery function is concerned, it does not change with the fatigue accumulation, but it should be considered when the recovery is given to the operator in order to put inside equation 2 the respective value of maximum energy expenditure rate of the considered activity. Once the trend of fatigue and recovery are modelled with respectively equation (3) and (2) there is the need of setting the recovery time for the specific operator. According to Battini et al. (2017) the rest allowance can be defined as in equation 4. Subsequently the percentage of the working time the operator has to recover is strictly linked to energy expenditure rate of the activity. If the energy expenditure rate is below 4.3 kcal/min the operator does not need to recover.

$$RA = \begin{cases} \frac{\dot{E}_W - 4.3}{4.3 - \dot{E}_R} & if\ \dot{E}_W > 4.3 \\ 0 & otherwise \end{cases} \tag{4}$$

For using equation (4) it is necessary to set the mean energy expenditure rate considering a certain number of activities carried on sequentially as can be seen in Figure 5.2.

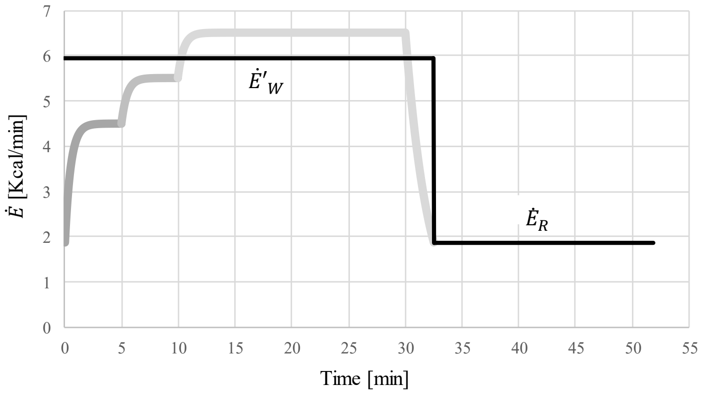


Figure 5.2 Setting of $\dot{E}'_W$ considering the exponential trend of fatigue and recovery.

The value of the mean energy expenditure can be obtained, as shown in equation 5, by integrating the fatigue and recovery function and by dividing this value to the sum of working time and of the time for reaching the energy expenditure rate at rest τ_r. In equation 5 it should be considered whether the rest is given after every activity or only after the k^{th} activity. It needs to be put into evidence that the operator is considered at rest only when he reaches the value of energy expenditure rate at rest. Subsequently also during τ the operator is not recovering as considered in equation 5.

$$\dot{E}'_W = \begin{cases} \dfrac{\sum_{i=1}^{n}\int_0^{t_{W_i}} F(t_W)_i + \int_{t_{W_i}}^{t_{W_i}+\tau_{r_i}} R(\tau)_i}{\sum_{i=1}^{n} t_{W_i}+\tau_{r_i}} \\ if\ rest\ after\ every\ activity \\ \\ \dfrac{\sum_{i=1}^{n}\int_0^{t_{W_i}} F(t_W)_i + \sum_k \int_{t_{W_k}}^{t_{W_k}+\tau_{r_k}} R(\tau)_k}{\sum_{i=1}^{n} t_{W_i}+\sum_k \tau_{r_k}} \\ if\ \ rest\ after\ k^{th}\ activity \end{cases} \tag{5}$$

The fatigue accumulation is obtained by integrating the fatigue function during t_W . For the first activity it can be expressed as in equation 6 because the operator starts at the energy expenditure at rest and accumulates fatigue till the reaching of the maximum energy expenditure rate of the activity. Subsequently, for the first activity the only physiological factor taken into account is λ.

$$\int_0^{t_{W_1}} F(t_W)_1 = \dot{E}_{W_1} \cdot t_{W_1} + \left(\dot{E}_R - \dot{E}_{W_1}\right) \cdot \frac{e^{-\lambda t_{W_1}}}{-\lambda} + \frac{(\dot{E}_R - \dot{E}_{W_1})}{\lambda} \tag{6}$$

For the activities which follows, the physiological factor of reference for the evaluation of the fatigue accumulation can be whether λ or μ depending on the value of the maximum energy expenditure rate of the considered activity in relation to the previous one. As can be seen in equation 7 if this value is lower than the previous activity the physiological factor considered is μ, otherwise is λ.

$$\int_0^{t_{W_i}} F(t_W)_i = \begin{cases} \dot{E}_{W_i} \cdot t_{W_i} + \left(F(t_W)_{i-1} - \dot{E}_{W\mathrm{i}}\right) \cdot \dfrac{e^{-\lambda t_{W_i}}}{-\lambda} + \dfrac{\left(F(t_W)_{i-1} - \dot{E}_{W_i}\right)}{\lambda} \\ \qquad\qquad if\ \ \dot{E}_{W_i}\ \geq F(t_W)_{i-1} \\ \\ \dot{E}_{W_i} \cdot t_{W_i} + \left(F(t_W)_{i-1} - \dot{E}_{Wi}\right) \cdot \dfrac{e^{-\mu t_{W_i}}}{-\mu} + \dfrac{(F(t_W)_{i-1} - \dot{E}_{W_i})}{\mu} \\ \qquad\qquad if\ \ \dot{E}_{W_i} < F(t_W)_{i-1} \end{cases} \tag{7}$$

Considering that the operator recovers only when he reaches the energy expenditure at rest, it needs to be considered also the fatigue accumulation during τ_R. The fatigue accumulation during the time necessary for reaching 1.86 kcal/min should be evaluated not for all the activities but only for the activities k after which the recovery is given to operator (equation 8).

$$\int_{t_{W_k}}^{t_{W_k}+\tau_{r_k}} R(\tau)_k = \frac{F(t_W)_k}{-\mu} \cdot e^{-\mu t_{W_k}} \cdot \left(e^{(-\ln F(t_W)_k)+\ln(\dot{E}_R)} - 1\right) \qquad (8)$$

As put in evidence in equation 9 the value of τ_{r_k}, which is the time necessary for reaching 1.86 kcal/min, is strictly related to the maximum energy expenditure rate reached during the performance of the activity k and to the parameter of recovery alleviation μ.

$$\tau_{r_k} = \frac{-\ln 1.86 + \ln F(t_W)_k}{\mu} \qquad (9)$$

Subsequently, knowing the sequence of activities and the ones after which a recovery is given to the operators it is possible to evaluate the total time necessary for carrying on the activities and for recovering by considering the working time, the time for reaching the energy expenditure rate at rest and the time necessary for recovering (equation 10)

$$t_{tot} = \sum_{i=1}^{n} t_{W_i} + \sum_k \tau_{r_k} + RA \cdot \left(\sum_{i=1}^{n} t_{W_i} + \sum_k \tau_{r_k}\right) \qquad (10)$$

The following model permits to estimate the total time necessary to the operator for performing a certain number of activities in sequence. In addition, it permits to analyse how to assign the activities to operator for reducing the total recovery time. As far as this is concerned in the following section it will be put in evidence how the physiological factors and the kind of activities to be performed can influence on the recovery time reduction through the optimal assignment of activities to the operators.

5.4 Impact of the parameters on the best allocation of activities

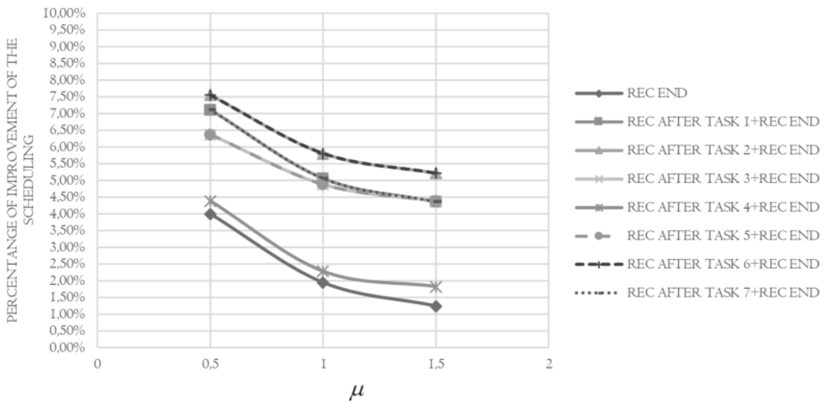
In the following Section it will be evaluated how the physiological factors and the kind of the considered activities can impact on the improvement obtained with the job sequencing in order to give to a practitioner information of how it can be convenient to focus the attention on job sequencing for obtaining a considerable value of recovery time reduction. The influence of these parameters is carried on for different options of recovery considering that it is possible to give to the operator an additional rest in respect to the one given to him at the end of the overall work content. As far as the best sequencing of activities is concerned, the results obtained shown that if the recovery is given only at the end of the whole work content it is better to perform the activities of higher intensity as last. On the other side, if it is possible to give to the operator ad additional rest, these kinds of activities should be performed immediately before this additional rest. This result makes sense because, the additional rest, given after the activities of higher intensities, help reducing the influence of the fatigue accumulated during the performance of these activities on the activities which should be performed after. The best job sequencing changes if the value of energy expenditure of most of the activities is below 4.3 Kcal/min. In this case, to reduce the recovery time it is better to perform the activities with a higher value of energy expenditure rate at the beginning. In fact, during the following activities with a value of energy expenditure rate below 4.3 kcal/min the operator recovers partially reducing the need of recovery at the end of all the activities.

5.4.1 Influence of the physiological factors

The model presented has been put into practice considering a certain number of activities with an overall work content of two hours. In fact, normally, in an industrial context a break is given to the operators after every two hours of work so, during these two hours the operator has not the possibility of recovering and the fatigue accumulates. The activities considered are related to order picking activities, where the average duration for completing an order is equal to 15 minutes. The different possibilities of allocating the activities to operator are simulated in MS excel considering different options of recovery. These different options are related of when the recovery is given to operator. If fact, it should be given only at the end of the 8 activities (each of these with a duration of 15 minutes) or in addition to the recovery at the end an additional recovery can be given to the operator before the end of the whole work content. This additional recovery can be given after one of the activities performed before the last activity. As far as the kind of operators considered the value of λ and μ considered for the application of the model are the ones indicated in Calzavara et al. (2018b). These values are respectively 2, 4, 6, 8, 10 for λ and 0.5, 1, 1.5, 2 for μ.

The first aim of this application is to understand for which kind of operators the improvement of the allocation of activities can determine a higher percentage of improvement in terms of recovery time reduction. Considering activities of different intensities in the range of 3.5 and 7 kcal/min (these are the energy expenditure rate obtained in a real industrial context) each of a duration of 15 minutes and fixing the value of λ the influence of μ can be detected. On the top and on the bottom of Figure 5.3 can be seen respectively, the influence of the value of μ and of λ on the percentage of improvement of the scheduling for each recovery option.

FIXED DATA:
Energy expenditure rate of each activity=3.5-7 kcal/min
Duration of each activity=15 min
λ =6
VARIABLE DATA:
μ= 0.5;1;1.5



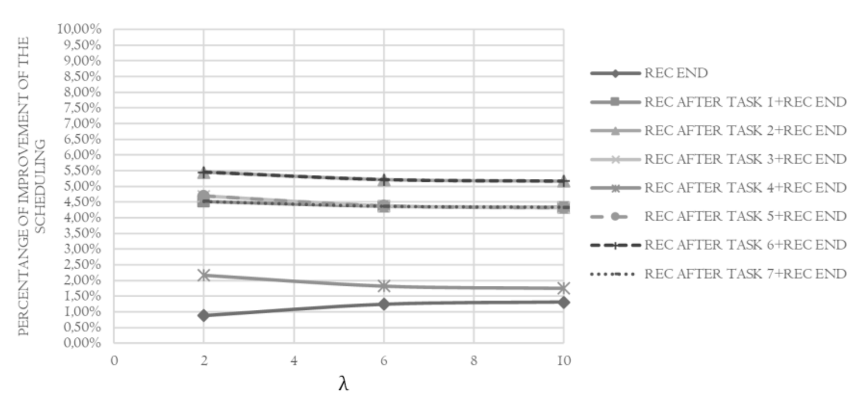
FIXED DATA: Energy expenditure rate of each activity =3.5-7 kcal/min Duration of each activity=15 min μ=1.5 VARIABLE DATA: λ= 2;6;10	

Figure 5.3 Influence of λ and μ on the allocation of the activities

The percentage of improvement of the scheduling is the improvement in terms of time which can be obtained in comparison to the worst scenario if the best allocation of activities to operators is chosen. This percentage of time reduction is considered for each option of recovery as can be seen on the right side of Figure 5.3.

As far as the parameter of fatigue accumulation λ is concerned, its value influences less than μ the improvement which can be obtained by improving the assignment of activities to the operators as can be seen on the bottom of Figure 5.3. Subsequently, considering the values of λ and μ of reference (Calzavara et al., 2018b), there may be more advantages in the reduction of the total recovery time of operators if the value of their parameter of recovery alleviation in low, which means a lighter slope of the curve of recovery causing a longer time in reaching the energy expenditure at rest. A lower value of μ can be characteristic of operators with low level of training.

5.4.2 Influence of the duration of the activities

The percentage of improvement in terms of recovery time reduction by evaluating the best assignment of activities to the operators can be influenced not only by the physiological factors as explained by the paragraph before but also by the kind of activity performed in terms of duration and energy expenditure rate. By considering 8 activities in the range of energy expenditure rate between 3.5 and 7 kcal/min and fixing the value of λ and μ, it can be evaluated with the presented model how the change of the duration of each activity (considering the same duration for each activity) can influenced the improvement obtained with the best allocation of activities to the operators. The duration of the activities considered are 7.5, 15 and 20 minutes. These values were chosen because they have been detected in an industrial context: for the completion of a picking order it is not spend less than 5 minutes and no more of 20 minutes. By changing the duration of the activities also the overall work content changes. It is no more of 120 minutes, but it is respectively for 7.5 and 20 minutes of duration, equal to 60 and 160 minutes.

As can be seen in Figure 5.4, with the increasing of the duration of each activity, the improvement which can be obtained by optimising the allocation of activities decreases for each recovery option. Subsequently a higher reduction of the recovery time can be reached if the duration of the considered activities is short.

FIXED DATA:
Energy expenditure rate of each activity =3.5-7 kcal/min
λ =6
μ =1.5
VARIABLE DATA:
Duration of each activity = 7.5; 15; 20 minutes

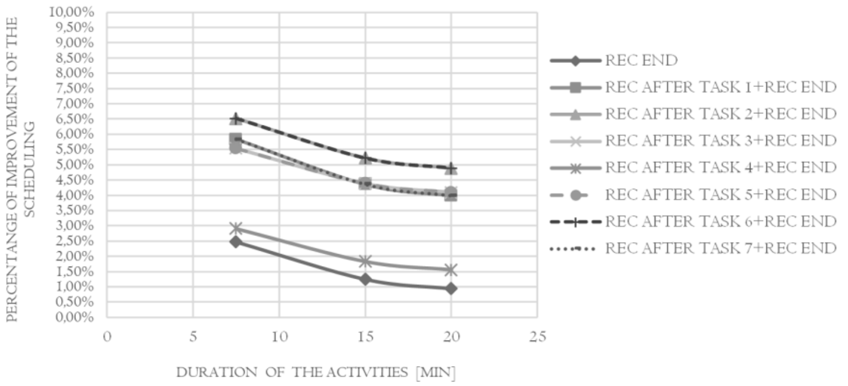


Figure 5.4 Influence of the duration of each activity

In an industrial context, as far as picking orders in concerned, most of the time not all the order to be completed, which correspond to the considered activities, have the same duration, consequently it is necessary to evaluate how the change between one activity and the other can affect the improvement of the assignment of the activities. In Table 5.1 can be seen the energy expenditure rate considered for each activity and the respective duration. For the three scenarios considered the work content is the same and it is equal to 120 minutes but what changes in the scenario B and C is the duration of the two activities with the lowest and with the highest energy expenditure rate in order to understand how the decreasing or decreasing of their value of duration can affect the improvement which can be obtained during the assignment of the activities. In the scenario B, activities 1 and 2, the ones which do not imply recovery because the energy expenditure rate is below 4.3 kcal/min have a value of duration which is half the one considered for activities 7 and 8, which are the ones with the higher values of energy expenditure rate, respectively 6.5 and 7 kcal/min. Whereas, the contrary is considered in scenario C. In Figure 5.5 the results of the application of the model for the 8 activities of Table 5.1 are presented.

Table 5.1 Data of each scenario related to the changing of activities' duration

		Duration [min]		
ACTIVITY	$\dot{E_W}$ [kcal/min]	A	B	C
1	3.5	15	10	20
2	4	15	10	20
3	4.5	15	15	15
4	5	15	15	15
5	5.5	15	15	15
6	6	15	15	15
7	6.5	15	20	10
8	7	15	20	10

FIXED DATA:
Energy expenditure rate of each activity : 3.5-7 kcal/min
λ =6
μ =1.5
Total work content= 120 minutes
VARIABLE DATA:
Duration of each activity (see Table 1)

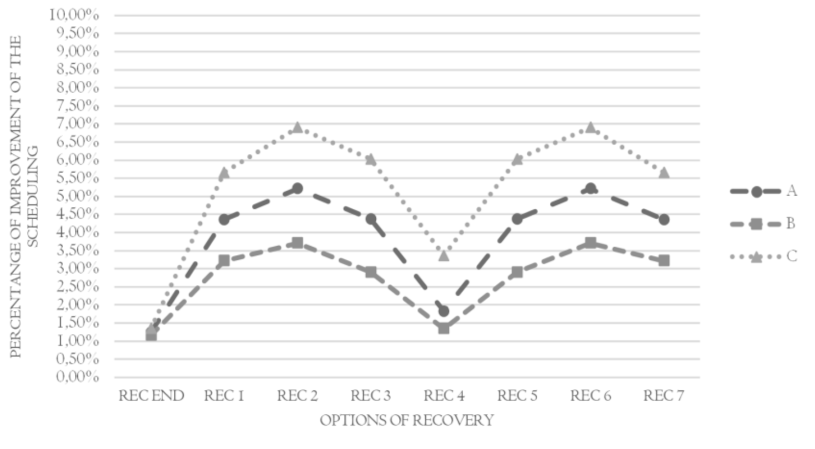


Figure 5.5 Impact of the changing of duration between the activities

In Figure 5.5 it is put in evidence the how the assignment of activities for each option of recovery can be improved in terms of recovery time reduction between the best assignment and the worst one. As can be seen in Figure 5.5 the improvement reduces if the impact of the activities of higher energy expenditure rate increases in terms of duration. In fact, the scenario B has in all the options of recovery the lower percentage of improvement due to the longer duration of activities 7 and 8, each of these of 20 minutes. On the other side, there are more possibilities to have a higher improvement with the optimal assignment of the activities to the operators if the influence in terms of the duration of the activities with lower values of energy expenditure rate increases, such as scenario C. According to this, scenario A, where all the activities have the same duration of 15 minutes, is positioned in the middle.

5.4.3 Influence of the range of the energy expenditure rate of the activities

Considering the impact of the kind of activity, there is the need to consider not only the duration but also the energy expenditure rate of the activity in kcal/min. In fact, considering the range of energy expenditure rate between 3.5 and 7 kcal/min and fixing the duration of 15 minutes of each activity, it can be detected how the number of activities below 4.3 kcal/min can affect the improvement obtained with the best assignment of activities to operators. The scenario of 100% activities below 4.3 kcal/min is not considered because in that case the duration of the recovery to be given to each operator is equal to 0.

Table 5.2 Data of each scenario related to the changing of activities' energy expenditure rate

		% of activities with the energy expenditure rate below 4.3 kcal/min							
Activity	Duration [min]	0%	12.5%	25%	37.5%	50%	62.5%	75%	87.5%
1	15	4.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
2	15	4.85	4.5	4	3.7	3.7	3.7	3.7	3.7
3	15	5.2	4.7	4.5	4.2	3.9	3.9	3.9	3.9
4	15	5.55	5	5	5	4.2	4	4	4
5	15	5.9	5.5	5.5	5.5	5.5	4.2	4.2	4.1
6	15	6.25	6	6	6	6	6	4.3	4.2
7	15	6.6	6.5	6.5	6.5	6.5	6.5	6.5	4.3
8	15	7	7	7	7	7	7	7	7

As can be seen in Table 5.2 there has been considered 8 activities as in previous cases of the paragraph before and all the activities have the same duration of 15 minutes. The aim is to understand how the mix of activities in terms of difference of energy expenditure rate between them can affect the improvement obtained with the best allocation of activities. In Figure 5.6 can be seen the results obtained by applying the model presented to the scenarios put in evidence in Table 5.2.

As shown in Figure 5.6, if all the activities have a value of energy expenditure rate above 4.3 kcal/min the percentage of improvement of recovery time is low and it is pretty much the same for all the recovery options. Subsequently, if all the activities have a value of energy expenditure rate above 4.3 kcal/min and more they are near in terms of energy expenditure rate between one and the other, less recovery time reduction can be obtained with the job sequencing optimization. The improvement of the recovery time reduction increases with the increase of the percentage of activities with a value of energy expenditure rate below 4.3 kcal/min.

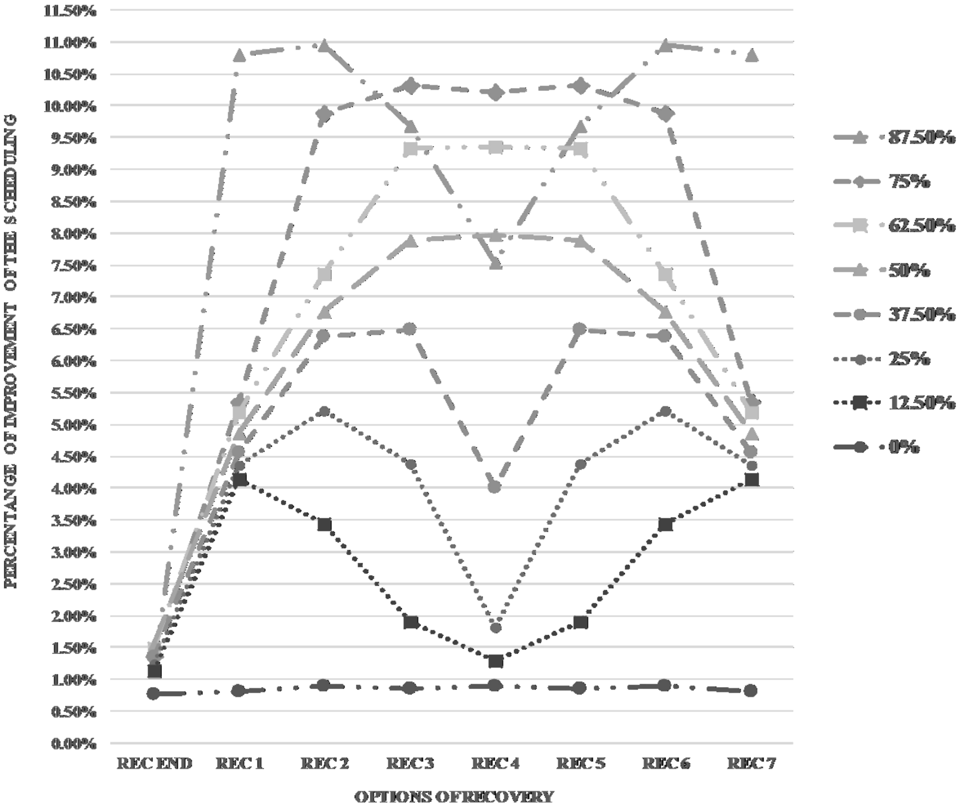


Figure 5.6 Impact of the percentage of activities below 4.3 kcal/min

5.5 Evaluation of giving to the operator an additional rest

5.5.1 Analysis of the percentage of scenarios in which an additional recovery is convenient

The proposed model is this Section is applied to a numerical example. The aim is to understand the best scheduling of operators' activities to reach the minimization of the total time, taking into account also the time the operator needs to recover.

In this sense, 1,000 different scenarios have been created in Ms Office Excel for three different ranges of intensity: between 2 and 4.5 kcal/min, between 3 and 6 kcal/min and between 4 and 8 kcal/min. Each scenario corresponds to a set of activities. The value of the energy expenditure rate of each activity is representative of the reality and the scenarios are generated randomly.

In fact, for each scenario there are 8 activities, which are carried out one after the other. For each activity, the duration is a random value between 5 and 20 minutes and the intensity is a random value in the range of intensity considered. For each scenario is calculated the total recovery time if a rest is given after every activity, only at the end of the 8 activities or if, in addition to the rest at the end, a rest is given between the 8 activities. Considering the case of giving to the operator a rest only at the end, it is calculated the value of the recovery time if the scheduling is optimised (by selecting the lower value of RA for 40320 scheduling combinations of each scenario).

In addition to this, fixing the range of intensity considered, the 1000 scenarios and the 40320 scheduling combinations of each scenario are replicated by changing the characteristics of the operator who has to perform the activities. This has been taken into account by assigning three different values to the parameters of fatigue accumulation λ and recovery alleviation μ: λ=4, 6, or 8 and μ=0.5, 1.5 or 2.5.

These values were obtained using a heart rate monitor in an industrial context. Each activity, characterized by a certain value of intensity and duration, can potentially be assigned to one of the different kinds of operator, who is described by his specific combination of parameters λ and μ.

The mathematical model was applied to reach the final aim of calculating the total recovery time comprehensive of the time for reaching the energy expenditure rate at rest (the term $\sum_k \tau_{r_k}$ of (10)) plus the time the operator needs to recover obtained by calculating the value of the RA (the term $RA \cdot \left(\sum_{i=1}^{n} t_{W_i} + \sum_k \tau_{r_k}\right)$of (10)). The terms of reference introduced for the analysis and indicated in Table 1 are:

- t_{et}: total recovery time if a rest is given after every activity
- t_m: total recovery time if a rest is given between the activities and at the end of all 8 activities
- t_{end}: total recovery time if the rest is given only at the end of all 8 activities
- $t_{end\ opt}$: total recovery time if the rest is given at the end of all 8 activities but with the optimization in the sequencing of the activities
- $\%\ t\ reduction$: percentage of improvement of $t_{end\ opt}$ in comparison to t_{end} in terms of total recovery time reduction

Table 5.3 reports a summary comparison of the results obtained from all the generated scenarios. There can be seen the percentage of the 1000 scenarios evaluated for which are valid the options indicated at the top of the Table 5.3. In particular, for each possible combination of the values of $\dot{E}$, λ and μ it shows the percentage of scenarios that have a higher value of the total times t_{et}, t_m, t_{end}, $t_{end\ opt}$, comparing them two at a time. It is then possible to understand the total number of scenarios for which one solution is more convenient than another in terms of time reduction. Moreover, in the last column it is indicated the percentage of time reduction obtained by optimizing the sequencing of the activities.

For the sets of activities and operators considered in this numerical example, it can be seen that for the activities of low intensity (included in the range 2-4.5 kcal/min), it is preferable to give to the operators the rest at the end of all the activities than giving a rest after every activity or after a set of activities, for all the scenarios. Moreover, it can be obtained a time reduction of around 53% if it is considered to assign the activities in the best order. In this case, the personal characteristics of the operators in terms of λ and μ have little influence. The optimization of the scheduling of activities gives more advantages in terms of time reduction for activities of low intensity rather than activities of medium (range of 3-6 kcal/min) or high intensity (range of 4-8 kcal/min). In fact, the mean percentage of time improvement for activities of low, medium and high intensity is respectively around 53%, 15% and 1.5%. If for activities of low intensity it is better to give the recovery to the operators at the end of all the activities ($t_{et}>t_{end}$ and $t_{et}>t_m$ for all scenarios), for activities of medium intensity (3-6 kcal/min) it is better to give to the operators a rest between the activities besides the rest at the end of all the activities ($t_{end}>t_m$) for more than the 70% of the scenarios. Such a convenience is confirmed for the 100% of the scenarios if the intensity of the considered activities increases (4-8 kcal/min). In addition, there is also an influence of the parameters λ and μ for the activities of medium and high intensity: the increasing of λ and the decreasing of μ implies an increase in the percentage of scenarios where the rest at the end or between the activities (t_{end} and t_m) is advantageous in comparison to the rest after every activity (t_{et}).

This simple numerical example has shown how this model can help in comparing different scheduling alternatives and, therefore, in understanding which is the best one for each operator, also considering whether and when it is better to give him a rest to reduce the total time.

Table 5.3 Comparison of the scenarios with different ranges of intensity, duration of the activities and operators

$\dot{E}$	λ	μ	$t_{et} > t_{end}$	$t_{et} > t_m$	$t_{end} > t_m$	$t_{end} >$ $t_{end\ opt}$	% t $reduction$
2-4.5	2	0.5	100.00%	100.00%	0.00%	100.00%	53.61%
2-4.5	2	1.5	100.00%	100.00%	0.00%	97.90%	53.53%
2-4.5	2	2.5	100.00%	100.00%	0.00%	90.00%	53.53%
2-4.5	4	0.5	100.00%	100.00%	0.00%	100.00%	53.61%
2-4.5	4	1.5	100.00%	100.00%	0.00%	97.90%	53.53%
2-4.5	4	2.5	100.00%	100.00%	0.00%	90.00%	53.53%
2-4.5	6	0.5	100.00%	100.00%	0.00%	100.00%	53.61%
2-4.5	6	1.5	100.00%	100.00%	0.00%	97.90%	53.53%
2-4.5	6	2.5	100.00%	100.00%	0.00%	90.00%	53.53%
3-6	2	0.5	84.00%	100.00%	72.50%	100.00%	19.03%
3-6	2	1.5	36.80%	37.40%	70.90%	99.10%	10.71%
3-6	2	2.5	33.60%	34.00%	70.60%	97.40%	9.78%
3-6	4	0.5	98.30%	100.00%	73.50%	100.00%	20.00%
3-6	4	1.5	36.20%	87.50%	72.40%	99.10%	12.46%
3-6	4	2.5	32.40%	32.80%	72.20%	97.40%	10.12%
3-6	6	0.5	99.10%	100.00%	74.00%	100.00%	20.24%
3-6	6	1.5	72.50%	100.00%	72.70%	99.10%	13.02%
3-6	6	2.5	31.80%	36.50%	72.60%	97.40%	10.81%
4-8	2	0.5	98.70%	100.00%	100.00%	100.00%	2.84%
4-8	2	1.5	0.00%	0.10%	100.00%	100.00%	0.45%
4-8	2	2.5	0.00%	0.10%	100.00%	100.00%	0.22%
4-8	4	0.5	100.00%	100.00%	100.00%	100.00%	3.20%
4-8	4	1.5	53.80%	100.00%	100.00%	100.00%	0.85%
4-8	4	2.5	0.00%	0.10%	100.00%	100.00%	0.35%
4-8	6	0.5	100.00%	100.00%	100.00%	100.00%	3.31%
4-8	6	1.5	98.70%	100.00%	100.00%	100.00%	0.98%
4-8	6	2.5	21.20%	97.80%	100.00%	100.00%	0.49%

5.5.2 Analysis of the improvement obtained with an additional rest

The Section before has evaluated the percentage of improvement that can be reached for each recovery scenario if the best scheduling option is chosen. In addition, the influence of the kind of operator and activity has been put in evidence. Even though, it could be useful for a practitioner the understanding of when an additional rest before the end of the whole work content can be used with the aim of reducing the total recovery time. Subsequently in this Section the presented model has been applied to the kind of activities considered in the Section before. Here, it is carried on the comparison in terms of recovery time reduction between the best scheduling option of the scenario of recovery only at the end of all the activities and the one where an additional rest is given to the operator after one of the activities carried on before the end. Related to this, the percentage of recovery time reduction indicated in Figure 5.7 is intended to be percentage of recovery time reduction if the option of an additional recovery is chosen in respect to the recovery only at the end. Regarding the influence of the physiological factor λ and μ, it can be seen in on the graphs 1 and 2 of Figure 5.7 that an additional rest does not permit to improve the recovery time reduction in comparison the best scheduling considering the rest at the end. As far as activities' characteristics is concerned, it can be evaluated on the graphs 3 and 4, that respectively the duration of the activities and the percentage of activities with an energy expenditure rate below 4.3 kcal/min has not so much influence as the physiological factors.

In the graph 4 of Figure 5.7 it is considered the influence of the changing of the duration of same of the activities taking into account the scenarios presented in Table 5.1. Also, in this case, the changing of scenario does not affect much the improvement that can be achieved with an additional rest. It can be concluded that the additional rest does not improve so much the recovery time reduction and that most of the reduction can be achieved by optimising the assignment of activities to operators considering fixed the position of the recovery. It needs to be taken into account that in the examined case, if the percentage of percentage of activities with an energy expenditure rate below 4.3 is more than the 80% there it is advantageous giving to the operator the rest only at the end of the all the activities.

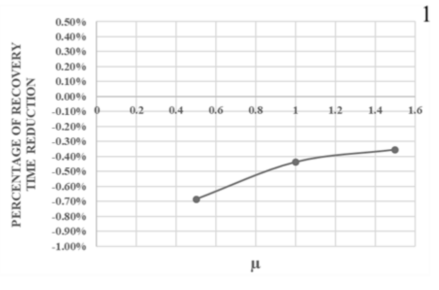
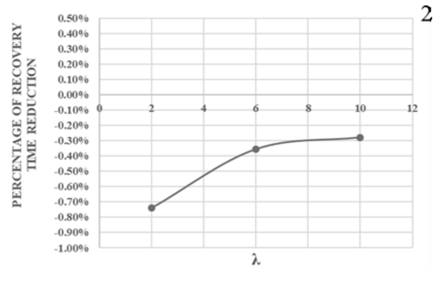
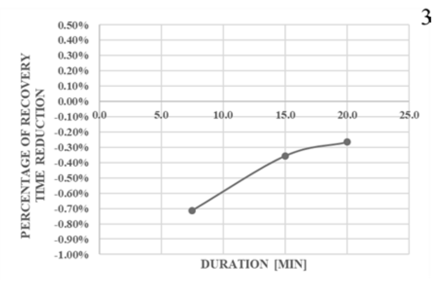
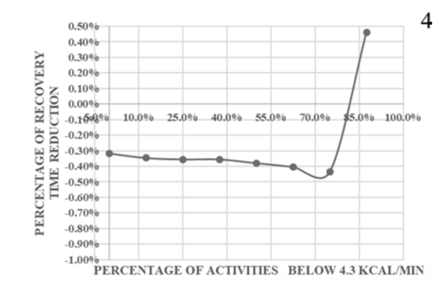
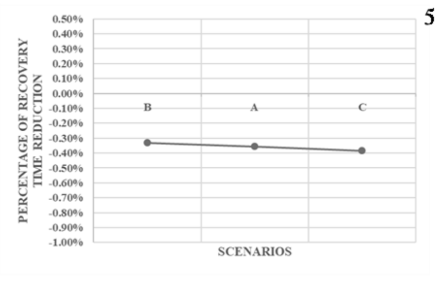
Energy expenditure rate of each activity: 3.5-7 kcal/min **λ =6** **Duration of each activity=15 min**	
Energy expenditure rate of each activity: 3.5-7 kcal/min **μ =1.5** **Duration of each activity=15 min**	
Energy expenditure rate of each activity: 3.5-7 kcal/min **λ =6** **μ =1.5**	
Energy expenditure rate of each activity: 3.5-7 kcal/min **λ =6** **μ =1.5** **Duration of each activity=15 min**	
Energy expenditure rate of each activity: 3.5-7 kcal/min **λ =6** **μ =1.5** **Total work content= 120 minutes**	

Figure 5.7 Impact of the parameters on the advantage of having an additional rest

5.6 Practical grids to be used for managing the activities and the operator in an industrial context

According to the model presented in this chapter, the results which can be used in an industrial context to improve the assignment of activities to the operators are summarized in Table 5.4 and in Table 5.5. Table 5.4 gives a rough indication of the best position of the recovery and of the percentage of time reduction if the best assignment of activities is chosen. The activities considered can have a random value between 5 and 20 minutes in the range of energy expenditure rate indicated in the first column. As indicated in this table, the additional recovery should be taken into account if the rates of the considered activities increase. On the other side there can be more advantage in the optimisation of the assignment if the energy expenditure rate of the activities decreases. Consequently, a practitioner, knowing the value of the energy expenditure rate of the activities can understand if the focus on the assignment of operators' activities can give benefits to the performance of the system in terms of recovery time reduction.

Table 5.4 General indications for managing operators

$\dot{E}$	λ	μ	DURATION [min]	POSITION OF THE REST	% TIME REDUCTION WITH ASSIGNMENT OPTIMIZATION
2-4.5	2	0.5	5-20	END	53.6%
2-4.5	2	1.5	5-20	END	53.5%
2-4.5	2	2.5	5-20	END	53.5%
2-4.5	4	0.5	5-20	END	53.6%
2-4.5	4	1.5	5-20	END	53.5%
2-4.5	4	2.5	5-20	END	53.5%
2-4.5	6	0.5	5-20	END	53.6%
2-4.5	6	1.5	5-20	END	53.5%
2-4.5	6	2.5	5-20	END	53.5%
3-6	2	0.5	5-20	RESULT LINKED TO THE SCENARIO CONSIDERED	19%
3-6	2	1.5	5-20		17.7%
3-6	2	2.5	5-20		9.8%
3-6	4	0.5	5-20		20%
3-6	4	1.5	5-20		12.5%
3-6	4	2.5	5-20		10%
3-6	6	0.5	5-20		20.2%
3-6	6	1.5	5-20		13%
3-6	6	2.5	5-20		10.8%
4-8	2	0.5	5-20	ADDITIONAL REST	2.84%
4-8	2	1.5	5-20	EVERY ACTIVITY	0.45%
4-8	2	2.5	5-20	EVERY ACTIVITY	0.22%
4-8	4	0.5	5-20	ADDITIONAL REST	3.20%
4-8	4	1.5	5-20	ADDITIONAL REST	0.85%
4-8	4	2.5	5-20	EVERY ACTIVITY	0.35%
4-8	6	0.5	5-20	ADDITIONAL REST	3.31%
4-8	6	1.5	5-20	ADDITIONAL REST	0.98%
4-8	6	2.5	5-20	ADDITIONAL REST	0.49%

Even though Table 5.4, it can be harder to understand the improvement which can be obtained with the best assignment of activities and the position of the recovery if the considered activities have an energy expenditure rate which is included in a wider range such as 3.5-7 kcal/min. In such a range there are both activities of high and of low energy expenditure rate. In Table 5.5 can be seen, how the percentage of recovery time reduction changes with the change of $\dot{E}$, of λ and μ, of the duration of the activities and of the percentage of activities with a value of energy expenditure rate below 4.3 kcal/min.

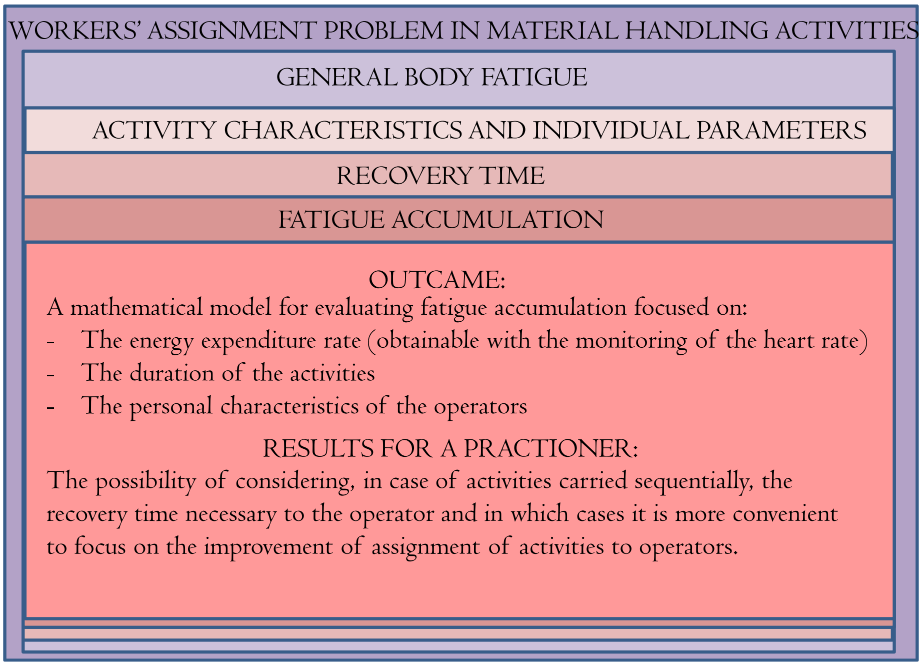
Table 5.5 Specific indications related to the changing of the variables

Additional rest in the middle				DURATION [min]			
				This % of time reduction increases if the duration of the activities with a low value of $\dot{E}$ increases in respect to the ones with a high value of $\dot{E}$			
				7.5	15	20	
$\dot{E}$	λ	μ	% of activities below 4.3 kcal/min	% time reduction with assignment optimization	% time reduction with assignment optimization	% time reduction with assignment optimization	BEST ASSIGNMENT OF ACTIVITIES
3.5-7	2	0.5	0%	4.75%	3.5%	3.25%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	0%	2%	0.75%	0.5%	
3.5-7	2	2.5	0%	2%	0.75%	0.5%	
3.5-7	4	0.5	0%	4.75%	3.5%	3.25%	
3.5-7	4	1.5	0%	2%	0.75%	0.5%	
3.5-7	4	2.5	0%	2%	0.75%	0.5%	
3.5-7	6	0.5	0%	5%	3.75%	3.5%	
3.5-7	6	1.5	0%	2.25%	1%	0.75%	
3.5-7	6	2.5	0%	2.25%	1%	0.75%	
3.5-7	2	0.5	12.5%	5%	3.75%	3.5%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	12.5%	2.25%	1%	0.75%	
3.5-7	2	2.5	12.5%	2.25%	1%	0.75%	
3.5-7	4	0.5	12.5%	5%	3.75%	3.5%	
3.5-7	4	1.5	12.5%	2.25%	1%	0.75%	
3.5-7	4	2.5	12.5%	2.25%	1%	0.75%	
3.5-7	6	0.5	12.5%	5.25%	4%	3.75%	
3.5-7	6	1.5	12.5%	2.5%	1.25%	1%	
3.5-7	6	2.5	12.5%	2.5%	1.25%	1%	
3.5-7	2	0.5	25%	5.5%	4.25%	4%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	25%	2.75%	1.5%	1.25%	
3.5-7	2	2.5	25%	2.75%	1.5%	1.25%	
3.5-7	4	0.5	25%	5.5%	4.25%	4%	
3.5-7	4	1.5	25%	2.75%	1.5%	1.25%	
3.5-7	4	2.5	25%	2.75%	1.5%	1.25%	
3.5-7	6	0.5	25%	5.75%	4.5%	4.25%	
3.5-7	6	1.5	25%	3%	1.75%	1.5%	
3.5-7	6	2.5	25%	3%	1.75%	1.5%	
3.5-7	2	0.5	37.5%	7.75%	6.5%	6.25%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	37.5%	5%	3.75%	3.5%	
3.5-7	2	2.5	37.5%	5%	3.75%	3.5%	
3.5-7	4	0.5	37.5%	7.75%	6.5%	6.25%	
3.5-7	4	1.5	37.5%	5%	3.75%	3.5%	
3.5-7	4	2.5	37.5%	5%	3.75%	3.5%	

3.5-7	6	0.5	37.5%	8%	6.75%	6.5%	
3.5-7	6	1.5	37.5%	5.25%	4%	3.75%	
3.5-7	6	2.5	37.5%	5.25%	4%	3.75%	
3.5-7	2	0.5	50%	11.25%	10%	9.75%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	50%	8.5%	7.25%	7%	
3.5-7	2	2.5	50%	8.5%	7.25%	7%	
3.5-7	4	0.5	50%	11.25%	10%	9.75%	
3.5-7	4	1.5	50%	8.5%	7.25%	7%	
3.5-7	4	2.5	50%	8.5%	7.25%	7%	
3.5-7	6	0.5	50%	11.5%	10.25%	10%	
3.5-7	6	1.5	50%	8.75%	7.5%	7.25%	
3.5-7	6	2.5	50%	8.75%	7.5%	7.25%	
3.5-7	2	0.5	62.5%	13%	11.75%	11.5%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	62.5%	10.25%	9%	8.75%	
3.5-7	2	2.5	62.5%	10.25%	9%	8.75%	
3.5-7	4	0.5	62.5%	13%	11.75%	11.5%	
3.5-7	4	1.5	62.5%	10.25%	9%	8.75%	
3.5-7	4	2.5	62.5%	10.25%	9%	8.75%	
3.5-7	6	0.5	62.5%	13.25%	12%	11.75%	
3.5-7	6	1.5	62.5%	10.5%	9.25%	9%	
3.5-7	6	2.5	62.5%	10.5%	9.25%	9%	
3.5-7	2	0.5	75%	14%	12.75%	12.5%	Activities with a higher $\dot{E}$ should be performed immediately before the two rests
3.5-7	2	1.5	75%	11.25%	10%	9.75%	
3.5-7	2	2.5	75%	11.25%	10%	9.75%	
3.5-7	4	0.5	75%	14%	12.75%	12.5%	
3.5-7	4	1.5	75%	11.25%	10%	9.75%	
3.5-7	4	2.5	75%	11.25%	10%	9.75%	
3.5-7	6	0.5	75%	14.25%	13%	12.75%	
3.5-7	6	1.5	75%	11.5%	10.25%	10%	
3.5-7	6	2.5	75%	11.5%	10.25%	10%	
3.5-7	2	0.5	87.5%	11.25%	10%	9.75%	Activities with a higher $\dot{E}$ should be performed at the very beginning and at the end of the all the activities
3.5-7	2	1.5	87.5%	8.5%	7.25%	7%	
3.5-7	2	2.5	87.5%	8.5%	7.25%	7%	
3.5-7	4	0.5	87.5%	11.25%	10%	9.75%	
3.5-7	4	1.5	87.5%	8.5%	7.25%	7%	
3.5-7	4	2.5	87.5%	8.5%	7.25%	7%	
3.5-7	6	0.5	87.5%	11.5%	10.25%	10%	
3.5-7	6	1.5	87.5%	8.75%	7.5%	7.25%	
3.5-7	6	2.5	87.5%	8.75%	7.5%	7.25%	
3.5-7	2	0.5	100%	0%	0%	0%	The assignment of activities does not affect because no recovery is required
3.5-7	2	1.5	100%	0%	0%	0%	
3.5-7	2	2.5	100%	0%	0%	0%	
3.5-7	4	0.5	100%	0%	0%	0%	
3.5-7	4	1.5	100%	0%	0%	0%	
3.5-7	4	2.5	100%	0%	0%	0%	
3.5-7	6	0.5	100%	0%	0%	0%	
3.5-7	6	1.5	100%	0%	0%	0%	
3.5-7	6	2.5	100%	0%	0%	0%	

5.7 Conclusions on the results obtained

The following chapter proposes a model for setting the value of recovery time considering how fatigue accumulates and the kind of operator. The application of this model has helped to understand the influence of the parameters representing the kind of activity and the kind of operator. Moreover, this model helps to understand the best assignment of activities to operators and how and additional rest, given to the operator before the end of the whole workload, can improve the reduction of the total recovery time. This paper continues the research carried on in chapter 4 regarding the estimation of the recovery time of operators performing material handling activities with the involvement of the whole body. This paper fills the gap in the literature related to the workers' assignment problem considering fatigue and how it can be alleviated through the recovery (Figure 5.8). In addition, it gives to practitioners a model which help them managing human resources in production systems without causing them excessive fatigue levels which can lead on long terms to musculoskeletal disorders.



A mathematical model for evaluating fatigue accumulation focused on:

- The energy expenditure rate (obtainable with the monitoring of the heart rate)
- The duration of the activities
- The personal characteristics of the operators

The possibility of considering, in case of activities carried sequentially, the recovery time necessary to the operator and in which cases it is more convenient to focus on the improvement of assignment of activities to operators.

Figure 5.8 Output of the research on the fatigue accumulation

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6. Conclusions

6.1 Results of the research

According to the main topics presented in the Abstract of the thesis and to the outlines but in evidence at the end of each chapter the main concepts addressed are the ones presented in Figure 6.1.

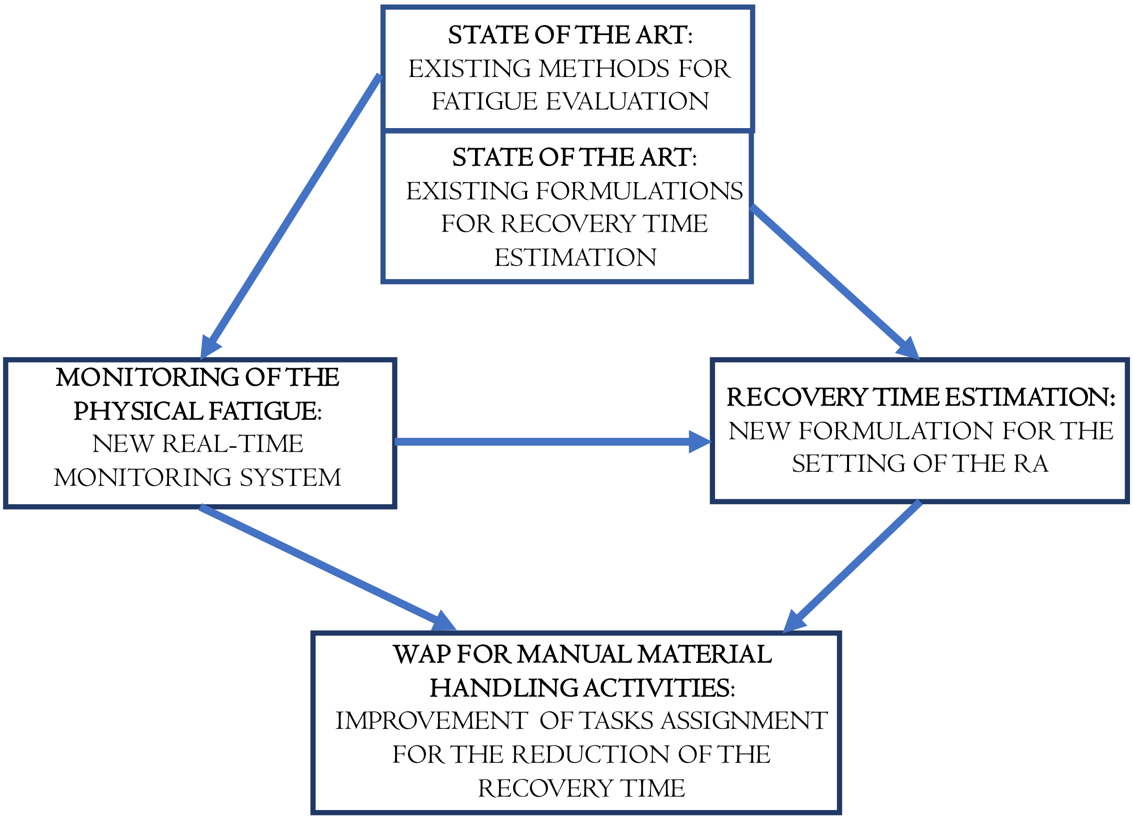

Figure 6.1 PhD Thesis outline

The analysis of the state of the art regarding the existing devices used for monitoring the level of fatigue in Chapter 2 and of the existing formulations for setting the value of the rest allowance considering different parameters in Chapter 3 has helped to understand what lacks in the analysis of human factors related to manual material handling activities.

According to this, in Chapter 2 it is presented and validated a new device to monitor the general body fatigue level for manual material handling activities with its advantages in respect to the existing technologies. Moreover it is put in practice in a real industrial context explaining how its feedbacks has been used to take decisions regarding the managing of the operators.

In addition, the data of the energy expenditure rate obtained thought the real-time monitoring of the heart rate has been used to create a new formulation for the setting of the value of rest allowance in Chapter 4. This formulation can take into account the parameters describing both the activities and the operators in order to take into account more the human factors in manual material handling activities.

Finally, this new rest allowance model and the monitoring of the fatigue level with the use of the heart rate monitor have been used in Chapter 5 for improving the assignment of the activities to the operators considering the minimization of their general body fatigue level and consequently of the time necessary to them to recover from the efforts made. The formulations presented in Chapter 5 are a development of the ones presented in Chapter 4 considering how fatigue is accumulated on the specific operator if a rest after every activity cannot be given.

The modelling of fatigue and recovery carried on in this thesis can give to a practitioner suggestion on the improvement which can be obtained if the assignment is optimised considering different kind of activities and of operators.

In addition, it is given the kind of device to be used to have information regarding the value of energy expenditure rate related to each activity and to value of the personal parameters linked to the operators in order to be able to apply the suggested new formulations. The only use of this device can give a rough indication of how to manage the operators. This assignment in terms of recovery time minimisation can be optimised with the application of the proposed model.

As explained in the Introduction, the proposed formulations can fill the gap of existing literature related to the considerations of the human factors in the workers assignment problem in relation of manual material handling activities where the whole body is used causing the general body fatigue.

6.2 Final considerations on the future developments

As far as future developments of the research presented in this PhD thesis is concerned, as put in evidence in Battini et al. (2018) the monitoring of the general body fatigue level by using a heart rate monitor can be useful also in the design phase of the workplace. In fact, by integrating it with the immersive reality and a motion capture system it can be carried on a complete analysis on the ergonomic and fatigue aspects of the operator.

The system called VR-Ergo Log system (see Figure 6.2) could lead to interesting advantages from a concurrent engineering perspective. The practical use of the system consists in creating a virtual environment, in which the operator is expected to work. Such environment, developed in typical simulation software and integrated with the VIVE™ system, should reflect one or even more possible configurations of the workstation under study. The human operator, by wearing the motion capture suite and the VR headset, is immersed in that virtual reality. Therefore, he can virtually perform all the activities that he normally would do during his job, but without needing a physical prototype of the workstation.

The data collected by the system during the virtual execution of the tasks are useful to evaluate the goodness and the effectiveness of a certain configuration of a workplace under study. This can be done through the determination of a set of specific indicators (KPIs), referring to time, ergonomics and fatigue performance.

This would allow to have a real-time feedback inherent to possible changes that have to be done for improving the performance of the operator in the workstation (e.g. moving objects and relocating products). In fact, as already pointed out in previous researches, during the workplace design phase it is necessary to include not only the technological variables related to the market demand, to the product and to the assembly process but also the environmental variables. These variables are linked to the physiological and psychological wellbeing of the workforce and can be revealed by using a heart rate monitor.

In the following, it is proposed a tentative list of time, ergonomics and fatigue based indices which can be obtained through the employ of the VR-Ergo Log system. Of course, this is not a comprehensive list of all the possible indicators which can be calculated from the output data and that could be considered for the redesign of a workstation. Furthermore, they could also differ according to the working environment and/or to the problem under study.

For example, some KPIs regarding time-performance could be: the total time necessary for performing a specific task; the percentage of time the operator requires for the performance of the value-added activities rather than the non-value-added activities (i.e. picking activities); the percentage of time the operator spends in the golden zone, defined as the area closest to the worker's body, between the waist and the shoulders: more time the operator is in the golden zone more time it is avoided the need of stretching or bending, which can imply serious ergonomic problems. Other ones are: the percentage of time the operator stays in an upright position, indicating how much the operator is employed, during the performance of the task, for kneeling or lowering; the time the operator needs for moving into the workstation, obtained from the horizontal movements of the hips; the percentage of picking errors related to a specific workplace design.

On the other side, for the ergonomic evaluation it could be interesting to estimate in real time the value of RULA, OCRA, OWAS and Lifting Index thanks to the tools developed in Battini et al. (2014). By recording this data, it is also possible to estimate the percentage of time the operator spends at a high value of these indices, then with a negative impact on ergonomics.

Furthermore, through the integration of a heart rate monitor in the system, some indices regarding fatigue level and performance can be evaluated: average HR, useful to indicate the mean energy expenditure rate of an activity for the specific operator (Ceesay et al., 1989); the influence of each task on the fatigue accumulation of the operator, measured through an HR increase (for example due to a high weight to be lifted); the influence of erroneous postures on the fatigue perceived by the operator, measured through an HR increase (awkward postures can increase HR, and a fatigued operator could perform the activity in a wrong way); the needed recovery time, estimated by monitoring the fatigue level; the impact of fatigue on tasks duration, so an increase of the fatigue level can affect the time necessary for performing a task.

The possibility of having an overall view of the impact of a certain workplace setting on the operators using these KPIs, can be of help for defining the priorities of intervention and to understand when (and how) the workstation is ready to be realized in practice. Therefore, the virtual workplace can be modified according to these criticalities and immediately verify with the use of the system. The comparison of the indices permits to estimate the best workplace configuration before it has really built.

The use of such an integrated system such be better developed by future researches with the real application of an industrial context.

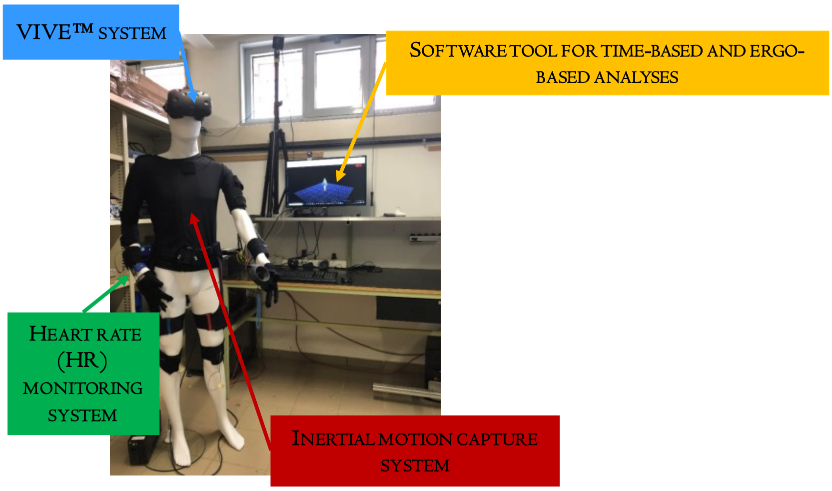

Figure 6.2 Integration of the heart rate monitor in the design phase of the workplace

Moreover, as stated in the chapters of this PhD thesis the estimation of the fatigue level and consequently of the value of the rest allowance, by basing on the energy expenditure rate estimated with a heart rate monitor can be effectively used for manual material handling activities. Even though, more research should be performed for the repetitive activities which influence more the muscular fatigue. In fact, future researches should focus on the validity of the model proposed in this PhD thesis in comparison to the existing models based on MET and MVC for repetitive activities such as the assembly ones which stressed continuously the same part of the body. This can be of utility in order to understand if this method can be used for applications different from manual material handling activities such as in the balancing and sequencing of assembly lines considering human factors (Battini et al., 2016).

6.3 Chapter references

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Table of Figures

Tables