**Università degli Studi di Padova**

School of Engineering
Department of Industrial Engineering
Department of Technology and Management of Industrial Systems
Master of Mechanical Engineering

# THE ROLE OF ERGONOMICS IN LOT SIZING DECISIONS

**Candidate**

**Alberto Antonio Sacco**

**Advisor**

**Prof. Fabio Sgarbossa**

**Co-advisor**

**Prof. Christoph Glock**

Academic year 2015-2016

# Acknowledgements

I would like to remember all the people who have helped me during the research and the writing of this thesis, with suggestions, criticisms and observations, or only being by my side.

Foremost, I would like to express my sincere gratitude to my advisor Prof. Fabio Sgarbossa and to my co-advisors Ph.D. Eric Grosse and prof. C.H.Glock, for their precious contribute for the scientific research and their continuous excellent guidance and because without them none of this would have been possible.

I would like to thank Ph.D. colleagues of the *Technische Universität Darmstadt* and my second family whereby I lived for 3 months for their help in the Erasmus Exchange Program.

I would like to thank my family, my father, my mother and my sister, who always do everything possible to help me and to give me invaluable advices, and during the writing of this thesis even more.

I would also like to thank my friends, the old and the new ones, who helped me relaxing and having fun during my thesis period.

Finally, I would like to thank Sofia, always by my side and has constantly encouraged me to do my best, without stopping to believe in me.

# Abstract

The attention for the optimal working conditions who is analyzes by ergonomics, is becoming in the industrial engineering every time more important for the positive results for the minimization of the production costs, reducing failures and increasing the productivity, obtained through an acceptable work level which prevents an excessive energy expenditure, the first reason of work absences.

To reach the optimal lot size taking account of the acceptable working conditions of the operator, some suitable studies conducted in the last decades of the past century are applied in the manual material handling of items.

The present work is focused on an detailed analysis of the present models for the human energy expenditure for the MMH, identifying their limits and the range of application on a typical working scenario; then an evaluation of the results allows to find the optimal ergonomical working or travelling lot size, by minimizing the time and thus the cost of the industrial activity.

# Sommario

L’attenzione per le condizioni ottimali di lavoro di cui si occupa l’ergonomia, sta rivestendo nell’ingegneria industriale un ruolo sempre più importante per i positivi risultati dal punto di vista di minimizzazione dei costi di produzione riducendo errori ed aumentando la produttività, grazie ad un corretto livello di lavoro che impedisce un affaticamento eccessivo, prima causa di costose assenze di lavoro.

Al fine di individuare il lotto ottimale tenendo conto delle adeguate condizioni di lavoro, diversi studi sul calcolo del livello di fatica dell’operatore, condotti nell’ultimo trentennio, sono stati applicati nell’ambito dello spostamento manuale di articoli.

Il lavoro presente è focalizzato su una accurata analisi dei precedenti modelli di calcolo del livello di energia spesa nell’attività di movimentazione manuale identificando i loro limiti e i campi di applicabilità, in una implementazione in alcuni tipici scenari di attività; infine una valutazione dei risultati ottenuti permette, a seconda del caso in analisi, di poter calcolare il lotto ergonomico produttivo o di trasporto ottimale minimizzando il tempo, quindi il costo, per l’attività industriale.

# Table of Contents

# List of Figures

# List of Tables

# Nomenclature

## Acronyms

| | |
|---|---|
| AGV | automated guided vehicle |
| LGV | laser guided vehicle |
| AWL | acceptable work level |
| ET | ergonomic time of activity |
| MET | maximum endurance time |
| MMH | manual material handling |
| MWR | mean work rate |
| RA | rest allowance |
| RR | relaxation rate |
| WMSDs | work musculoskeletal disorders |
| WR | work rate |

### Symbols

| | |
|---|---|
| A | availibility |
| $C_{op}$ | cost of operator |
| $E_{pos}$ | metabolic energy expenditure due to maintenance of the i-th posture |
| n | terrain factor |
| $N_{trip}$ | number of trips |
| G | slope |
| L | length |
| q | quantity of items |
| $q_{opt}$ | optimal ergo-lot size |
| $T_p$ | time of picking |
| $T_t$ | time of travelling |
| $T_s$ | time of storing |
| V | speed |
| VO2 | volume of oxygen consumption |
| W | weight of operator |

# Introduction

Nowadays ergonomics is receiving even more attention in the industry, because of its strict correlation between the well-being of operators and the increase of productivity, although there are still many managers and design engineers who see this more as a cost than a benefit.

Technological advances in manufacturing processes often increase the use of static and intermittent muscular work (Milner, 1985) and the prolonged repetition of these activity generates work-related musculoskeletal disorders (WMSDs) (Chaffin et al., 1999; ISO, 2000; Kumar, 1994; Seth et al., 1999) as explained on the report of Washington State Department of Labor and Industries (Safety and Health Assessment and Research for Prevention, 2005), where over 50% of workers in industry have suffered from musculoskeletal disorders (Ma et al, 2009).

Thus, a practical way to reduce the risk of WMSDs is reducing fatigue in the muscle groups involved in each work; this can be obtained through the determination of rest allowance (RA), a rest time after each activity which ensures to the workers to ergonomic work conditions. However, this additional time in the manual material handling operations modifies the total amount of the time for the whole operation and this is why it is necessary to review the evaluation of the optimal lot size including ergonomics decisions (Battini et al., 2015).

The first part of this work has been conducted in the Technische Universität of Darmstadt (TUD) with the contribution of Ph.D. Dr. Eric Grosse and prof. C. H. Glock, experts on ergonomics, particularly its role in the MMH handling in the industrial systems: it has been analyzed the "state of art" of ergonomics in lot sizing decisions where low results has been found, because of its total new concept, however several fatigue models form the past studies has been found.

Thus, a deep literature research of the fatigue and energy expenditure models has been conducted, cataloging results for tasks and main variables including the limit and the respective different scenario of application. In the last period at the Technische Universität of Darmstadt (TUD), a framework was developed: this helps to evaluate the different fatigue models indicating the way to proceed identifying the most suitable ad adaptable to the specific scenario. This part of work, conducted abroad thanks to the Erasmus exchange program, was the most important because it was the basis for the following part.

In the last period of this work, using the developed framework, some of the most suitable fatigue models for the energy expenditure are selected for a sensitivity analysis; more alternatives are applied and modified adapting them to the specific situations, finding different levels of fatigue. These levels are compared with the acceptable work level, evaluating the % of rest allowance necessary to ensure an ergonomic working conditions for the operator.

Finally, a comparison of the results with Battini et al. (2015) is conducted identifying the gap of the different fatigue models and cataloguing the different scenario and contest allowing the engineer to identify the most suitable model to the specific situation.

# Chapter 1

# Ergonomics in lot sizing

## 1.1 Ergonomics

The term "ergonomics" derives from Greek words *érgon* (work) e *ńomos* (rule) and represents the science that studies the human working conditions.

Based on the definition given by the International Ergonomics Association (IEA), *"Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance"*.

Only in the last years managers and design process engineers understood its important role in the production systems; particularly in the last five years this aspect has become even more important because studies demonstrate the correlation between ergonomic working conditions and the reduction of injuries increasing the productivity of the company; thus a deep analysis of the benefits is necessary to understand this role.

### 1.1.1 Work musculoskeletal disorders

Nowadays, with the increment of automatization of the production, machines need items as input with the kanban methodology and create product as output at the end of the line. The trend of the companies is to improve the flexibility that ensure high speed to answer the customers, reaching every time its necessity: this allow a loyalty of the customer for the company. Moreover companies needs to change their products and production to follow the customers demand; thus items are even more different for weight and dimensions, thus there are problems for the flexibility of the transportation of these products to the assembly line or the supermarket or the warehouse. Human operators are involved in activities where a high flexibility, such as handling operations, manual assembly lines, order picking warehouses; speed and rapid movements are required (Battini et al., 2015) and these activities such as lifting heavy items, bending, reaching overhead, pushing and pulling heavy loads, working in awkward body postures, increase the fatigue. Moreover performing the same or similar tasks repetitively can be exposed workers to risk factors at work, WMSDs and illness causing lost workday and reduction of productivity.

Musculoskeletal disorders are associated with high costs for the employers such as absenteeism, lost productivity, and increased health care, disability, and worker's compensation costs. MSD cases are more severe than the average nonfatal injury or illness (e.g., hearing loss, occupational skin diseases such as dermatitis, eczema, or rash).

Musculoskeletal disorders account for nearly 70 million physician office visits in the United States annually, and an estimated 130 million total health care encounters including outpatient, hospital, and emergency room visits. The Institute of Medicine estimates of the economic burden of WMSDs, as measured by compensation costs, lost wages, and lost productivity, are between $45 and $54 billion annually. The Bureau of Labor Statistics reported 26,794 Carpal tunnel syndrome cases involving days away from work in 2001 reporting 372,683 back injury cases involving days away from work (Booth et al., 2004).

In 2003, the total cost for arthritis conditions was 81-128 billion $ in direct costs and 47 billion $ in indirect costs. AAWL (Arthritis-attributable work limitations) affects one in 20 working-age adults (aged 18-64) in the United States and one in three working-age adults with self-reported, doctor-diagnosed arthritis (Theis, K.A. et al., 2007). From the report of Health, Safety and Executive in UK (HSE, 2005) and the report of Washington State Department of Labor and Industries (Safety and Health Assessment and Research for Prevention SHARP, 2005), over 50% of workers in industry have suffered from musculoskeletal disorders. Particularly most cases of number of injuries and illness due to MSDs in 2007 were in the category of "laborers and material movers".

Introducing ergonomics solutions provide to reduce the stress and eliminate injuries and disorders associated with the overuse of muscles, bad posture, and repeated tasks; as well explain in Punnet and Wegman (2004), if the exposure to physical stressor, were eliminated, the proportion of reduction of the disease would be 11-66 % for manual material handling and 31-58 % for heavy physical load; this would reduce the MSDs caused in one or more body region.

These results, all founded from the scientific literature, give the important reason to consider the role of ergonomics in the industrial systems; these researches are conducted more than ten years ago where this attention is understood, however for the last years low results are founded.

## 1.2 Lot sizing

The objective of the logistic process is the determination of the optimal lot size reaching the minimum cost. Harris (1913) developed the EOQ (Economic Order Quantity) to evaluate the optimal lot size for the order or the production (EPQ: Economic Production Quantity). This size can be evaluate combining the curve of re-order/production cost that has an inverse exponential trend increasing number of items, with the storage cost curve that has a linear trend with the lot size; in fact, bigger is the produced lot,  more is the storing cost but the cost of ordering graves less on the single item.

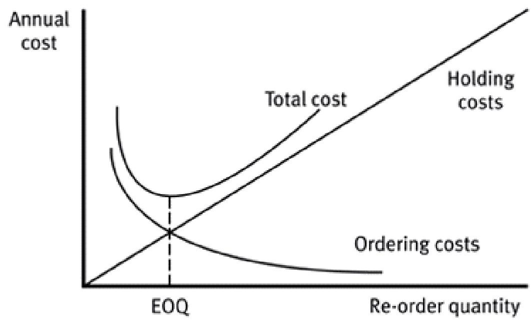


**Fig 1.1** Harris curve to evaluate the optimal re-order quantity.

As can be seen in Fig.1.1 the target is to balance the total cost, but no account of ergonomics is taken in the re-order quantity: this influences the ordering cost in terms of time necessary and changes the optimal lot size.

The contest applied in this work, is a typical logistic process: the MMH (manual material handling) of a productive lot. A typical in-house logistics process is the refilling task in an order picking warehouse form the reserve area to the forward area or the transportation of product from the final stage of a production process to a storage facility. The activity on which this work in focused is the transport of group of items form a point A to a point B with a kart or a pallet truck that can be manual or electric powered the operator pick the items from a station (point A) placing them on a trolley, travel the kart and subsequently store the items to the other station (point B). The main target of the production chain as the whole industrial engineering is reaching the minimum cost maintaining high quality standards; this can be provided through a deep evaluation of the different terms that influence the final cost and the parameters that allow good working conditions and therefore the quality of the products.

To reach the minimum cost in a typical in-house logistic process, the best lot size should be pinpointed; this evaluation depends on different terms:

- Time of picking
- Time of travelling
- Time of storing
- Cost of operator

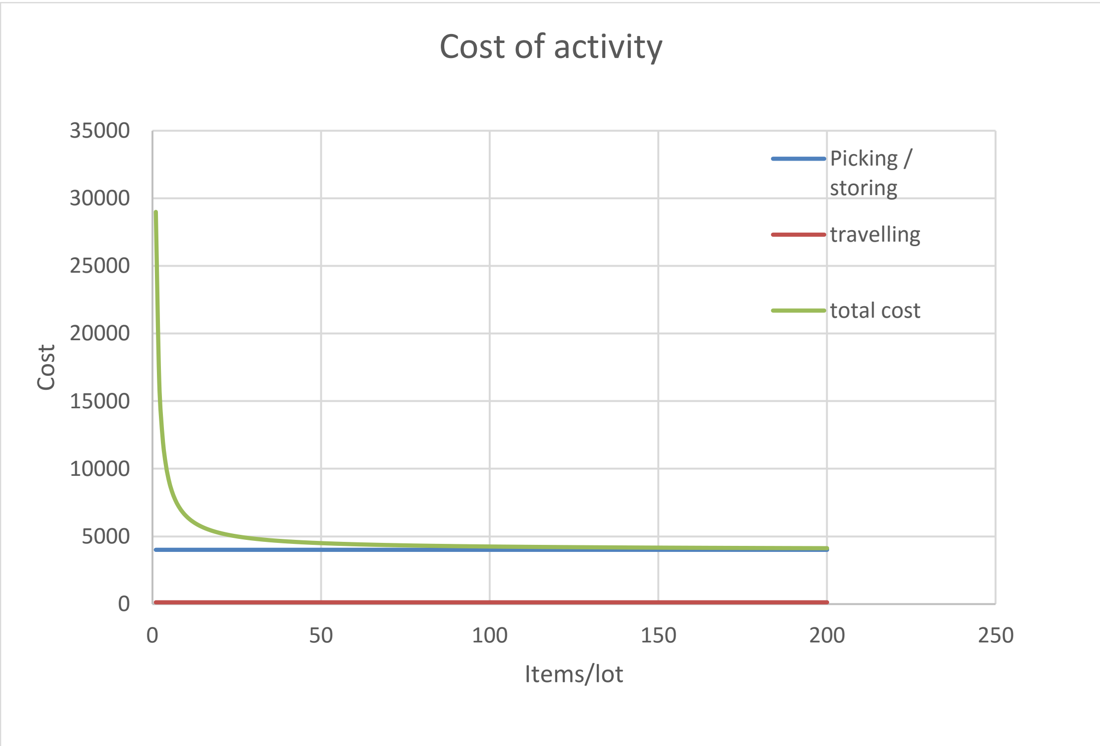


**Fig 1.2:** Cost of tasks on the total number of items travelled.

The number of items placed on the trolley indicates the lot size for the activity: increasing this value, the unitary travelling cost for single piece decreases because less travels are necessary to transfer the whole products to the point B, while the cost of picking and storing remains constant because each item is put on the trolley singularly and the total cost in the only sum of the total. As can be seen in Fig.1.2 the minimum cost is achieved travelling the total items in only one trip because the unitary travelling cost of each item is partitioned in only one trip.

Fig. 1.2 is an example of scenario with the following parameters:

- total items to be moved are 200
- the picking and storing time are 10 s
- the travelling time is 125 s.

However in Fig.2, no consideration of the role of ergonomics is taken into the evaluation of the optimal lot size in Fig.1.2: the energy expenditure due to picking, travelling and storing items influences the availability of the operator, increasing risk of injuries, forcing to make pause to avoid the compromise of the achievement of the minimum production cost. Thus, the operator needs to recover energy with a rest allowance (RA) increasing the time necessary for the operation: the picking, travelling and storing time are influenced increasing with the growth of the lot size as can be simply introduced with an example in Fig.1.3.

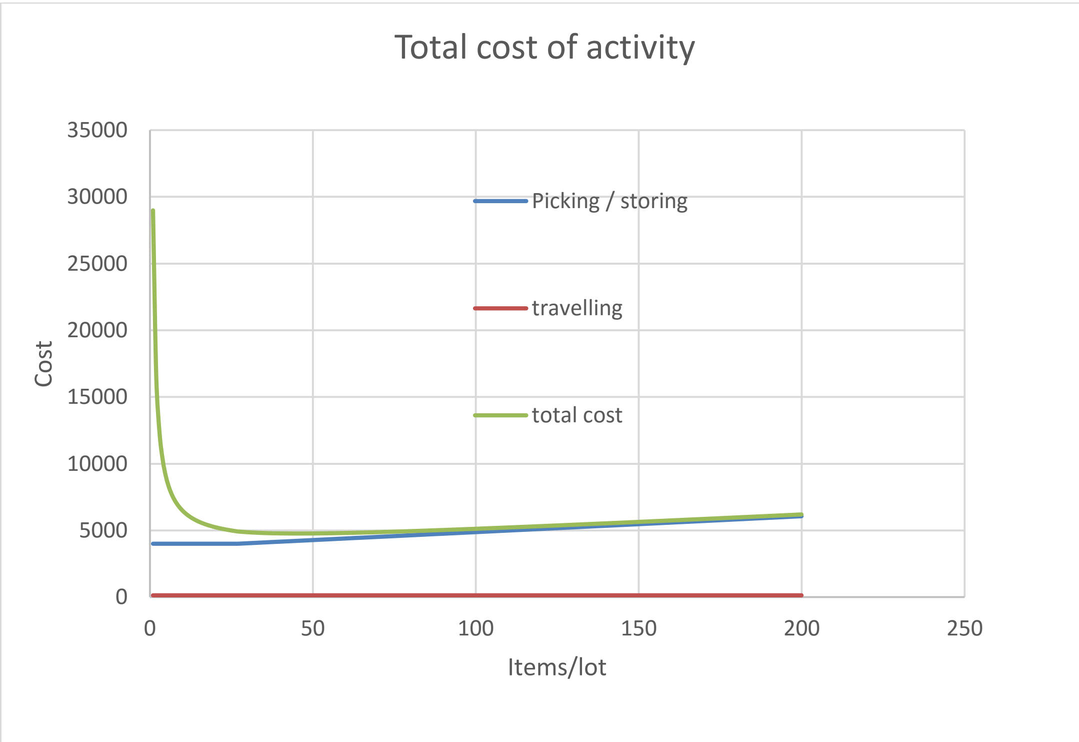


**Fig 1.3:** Cost of tasks on the total number of items travelled taking account of the rest allowance.

Without taking account of the energy expenditure of the operator, injuries may happened, thus another employee will be necessary to ensure the operation; by this

choice the cost of the industrial operation will be increase. To minimize the production cost all the elements, including the RA, should be evaluate, the target of this work.
The trend of the RA used to described the behavior in Fig.1.3 can be explained in the following Fig. 1.4 with the RA a curve; in the previous example the trend is linear, however in this work it will be appreciate the several variables that influence this trend, creating alternatives as RA b and RA c.

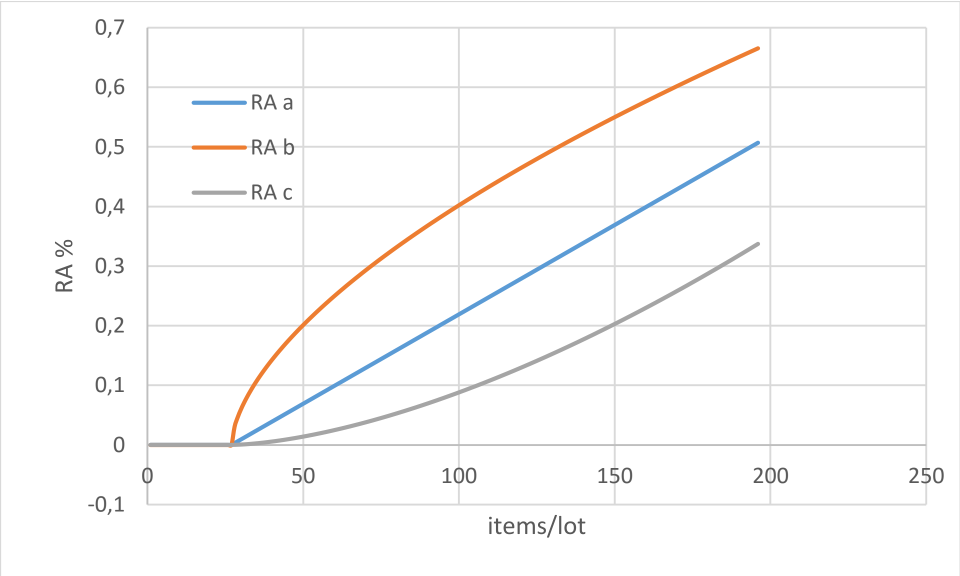


**Fig. 1.4:** Different behavior of RA increasing the lot size (items/lot).

As can be seen, for low value of lot size no rest allowance is necessary, thus the curves are all equal to zero; then, in this scenario, form 30 items/lot RA become positive with different values.

No previous studies are present in the scientific literature because of this totally new concept of lot sizing. This role will be analyzed and evaluated in this master thesis showing different result using different models and the importance of taking account of this term in the evaluation of the minimum cost to reach the optimal lot size.

# Chapter 2
# Literature research

Since the second half of the last century, many studies regarding the positive role of the ergonomics in the industrial system were published, indentifying the increment of the workers' welfare, the reduction of WMSDs and injuries: thus, the optimization of the production was obtained. Several fatigue and energy expenditure models were developed, but very few researches analyzed the relation between ergonomics and the lot sizing models.

In the next part, a systematic literature is conducted to individuate and selected the most important works. The research is based on the methodology of tertiary study (Glock et al., 2013), i.e the review of literature reviews: this ensure to analyze the total work already published and catalogue all the relevant papers:

The literature search conducted in this master thesis, consists of the following steps:

- defining relevant keywords
- searching keywords in databases
- selecting relevant paper.
- focalization on results

These steps are shown and detailed descripted in the following part, allowing to analyzed all the article present in the databases.

## 2.1 Keywords definition

At the first step, two lists of keywords were defined to identify the relevant works in literature; this ensure a deep focalization on the correct theme, without mistake made by searching words similar but not pertinent with this work.

Group A contained the keywords related to the industrial system (EOQ, EPQ, lot size, inventory management) as shown in Table 2.1, group B is composed by keywords related to the human factors (ergonomics, energy expenditure, work load).

**Table 2.1:** Keywords used in the literature research

| GROUP A | GROUP B |
|---|---|
| EPQ | HUMAN FACTORS |
| EOQ | ENERGY EXPENDITURE |
| LOT SIZING | WORK LOAD |
| INVENTORY MANAGEMENT | HUMAN FACTORS |

This research, conducted with the support of the *Technische Universität Darmstadt*, provides results strictly related to the topic of this thesis, and this ensures the most light and imporant section for the following part.

## 2.2 Papers selection

In this part of the literature research, lectors can understand how databases undertake a dominant role. As can be infer, the importance of these sources is the validity of results, without them no considerations could be assume; thus only the most important an popular databases will be considered.

Three databases were selected and used for this literature research:

1. Business source premier
2. Science direct
3. Google scholar

Moreover works were only considered if their language was English and their abstract indicated that the paper focuses on lot sizing and considers ergonomics.

## 2.3 Research strategy

Results found in literature with these keywords were so many (particularly for the group A) that it was very difficult to find papers strictly related to the topic of this work. The reason is that there were many papers containing these keywords because of the shared interest for these themes, but only a minimum part of them was strictly inherent to the topic. This because lot of authors decided in the past to conduct analysis and research about the human energy expenditure, for its influence in the industrial systems; however the theme, evaluate in this work, about the relation in the production time and cost was not considered.

Thus, it was necessary to follow a special strategy as shows in Fig.1 to obtain satisfying results: at first keywords from the group B were searched, because they were more restricted to the topic, and then among the many founded results papers containing only one of the keywords from Group A were selected. The articles that did not meet the proposed focus were excluded.

At the end of each suitable paper (and of some less suitable but interesting with the theme) references lists were analyzed to individuate other important papers.

As show in Fig.1, a research of the authors of the selected papers was conducted to find other correlated works. In the following section results are discussed.

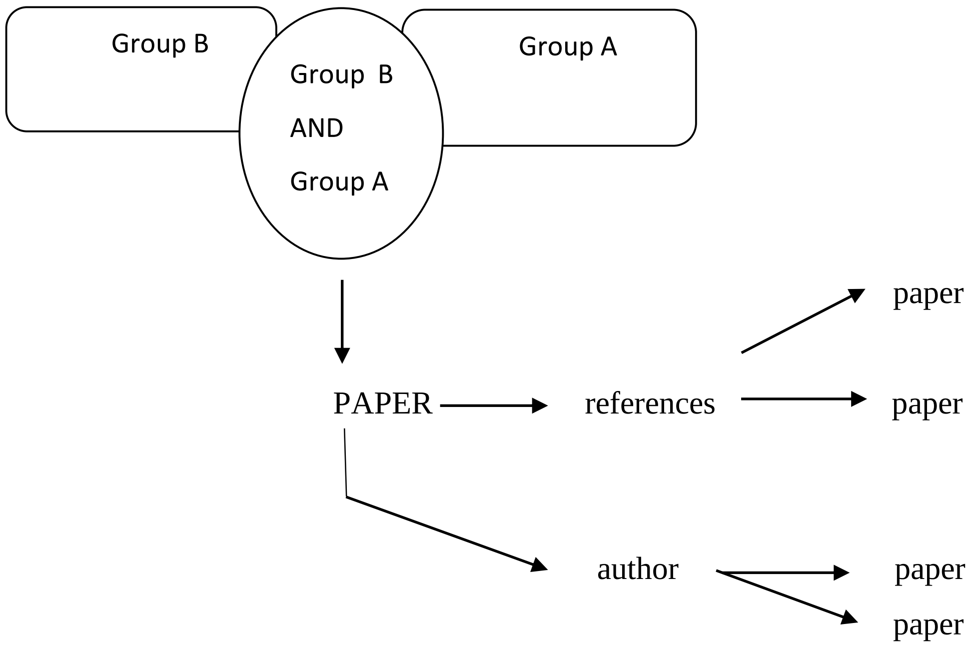


**Fig.2.1**: Research strategy adopted.

# Chapter 3
# Literature summary

In this section a literary summary is conducted: starting from the definition of "ergonomics", the worker´s recent WMSDs are analyzed. Later energy expenditure models are catalogued to reduce the risk of injuries and to allow the worker's welfare to be under the fatigue level.

## 3.1 Results of ergonomics in lot sizing decisions

In the literature the results found with the keyword "ergonomics" are thousand due to the common and established interest of this parameter in the industrial system, particularly in last years; in fact, in contrast with the common misconception that ergonomics is a cost constrain and produce loss of time (Pereira Da Silva et al., 2014), the positive economic results (de Looze et al., 2010; Da Silva et al., 2012) and the improve of productivity (de Looze et al., 2003; Battini et al., 2011) are unanimous, as demonstrated in Oxenburg et al. (2004) or in Vink et al. (2002), where after the intervention of ergonomic improvements, it was verified that there was a reduction of 15% in the workload and an increase of 10% in productivity.
This win-win approach (Battini et al., 2011) thanks to the interaction between ergonomic work conditions and productivity explains the dominant role of this theme in production systems.

However, searching a strict correlation between ergonomics and lot sizing, results found are very poor because few papers were published (Grosse et al., 2015); in fact engineers don´t consider the ergonomic solutions, particularly in the design stage called proactive ergonomics; by contrast, this advantage would reduce the risk of injuries and Musculoskeletal disorders (MSDs) when the costs for improvement are lowest and potential benefits greatest (White, 2015). Moreover, engineers still don´t consider the influence of the ergonomics in inventory models also because it will modifies the optimal lot size of the Harris' curve (Harris, 1913) due to the different time of the handling operation.

As explained in Andriolo et al. (2013) only two works have incorporated social sustainability into lot two sizing models: Arslan and Turkay (2013) considered as social metric the working hours for the employees according to the International Labour Organization (ILO). Bouchery et al. (2012) consider a structure similar to the classical EOQ formula (Harris, 1973) to quantify environmental and social impacts but they did not suggest any possible metric in order to describe the social impact.

Andriolo et al. (2013) developed a new methodological approach in order to develop a social sustainable EOQ model, considering the fatigue of workers involved in MMH tasks and recovery times.

Battini et al. (2015) introduced for the first time in the literature a new measurement techniques combining the Predetermined Motion Time Systems (PMTS) such as MTM or MOST which don´t consider the ergonomic aspects of work, with the Garg et al. (1978) model: the PMES (Predetermined Motion Energy Systems). This method allows to calculate the energy expenditure for each task (kcal/job) reducing the time spent to calculate the ergonomics measures and simplifying the ergonomics assessment of each assembly task.

**Table 3.1:** "State of art" of ergonomics in the inventory model (BSP: Business Search Premiere; SD: Science Director; GS: Google Scholar; SB: Snow-Ball search).

| No | Authors | Year | BSP | SD | GS | SB | Keywords Group A | Keywords Group B |
|---|---|---|---|---|---|---|---|---|
| 1 | Andriolo et al. | 2012 | | X | | | lot sizing , EOQ , inventory management | ergonomics, social impact, sustainibility |
| 2 | Arslan et al. | 2013 | | | | X | EOQ, supply chain management, inventory | sustainability, social criteria |
| 3 | Battini et al. | 2011 | | | | X | productivity, assembly system design | ergonomics |
| 4 | Battini et al. | 2015 | X | | | | ergo-lot-sizing, EOQ | ergonomics |
| 5 | Battini et al. | 2015 | | X | | | cost models , warehouse picking | human availability, injuries, ergonomics |
| 6 | Bouchery et al. | 2012 | | | | X | inventory models, multiobjective optimization | sustainability supply chain criteria |
| 7 | De Looze et al. | 2010 | | | | X | productivity, cost-benefit analysis | musculoskeletal disorders, health |
| 8 | Pereira de Silva et al. | 2014 | | | X | | financial benefits | ergonomics solutions |
| 9 | White | 2015 | X | | | | economic benefits, productivity and quality | proactive ergonomics |

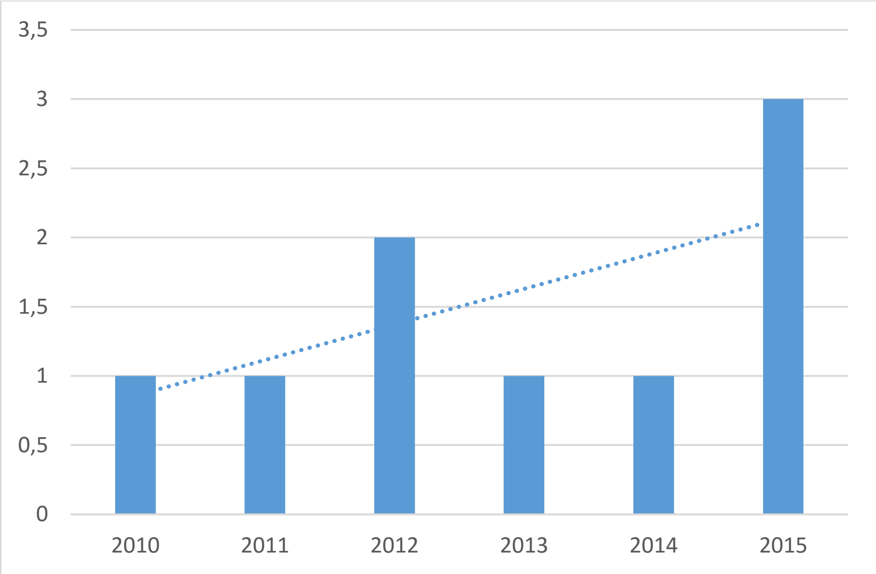


**Fig.3.1:** Numbers of papers published per year related to ergonomics in lot sizing decisions.

Table 3.1 ad Fig.3.1 show the few results found from the "state of art" strict related to the selected keywords; however these works which published are only in the last five years: this underlines the common interest and the focalization of authors on this topic.

## 3.2 Fatigue and energy expenditure models

In this section, different fatigue and energy expenditure models were searched in the literature and analyzed.

The worker's fatigue in caused by the excessive working time or by the poorly designed shift patterns. Results from prolonged exertion, sleep loss and disruption of the human internal clock are generally considered to be a decline in the worker's mental and physical performance, and this mainly happens because they are more easily fatigued if their work is machine-paced, complex or monotonous. Similar results are also in slower reactions, reduced ability to process information, decreased awareness, lack of attention (which can can lead to errors or accidents ill-health and injury) and reduced productivity. Moreover, high loads and frequent repeated and prolonged loading, especially if combined with awkward working postures cause the largest part of work-related illness health: musculoskeletal disorders (Hagberg et al., 1995).

Thus calculating the correct energy expenditure, adopting a specific fatigue model and evaluating it with the acceptable work level is the correct way to reduce this risks.

### 3.2.1 General fatigue and energy expenditure models

A literature research was conducted restricted only to those publications that explained a fatigue model deriving from a specific and detailed ergonomic model; in fact without a detailed ergonomic model taking account of the different part of the body involved in each different task, such as age, weight of the body and the load, frequencies of task, the results found from the energy expenditure model are not useful.

Several ergonomics tools were developed to asses physical risk to MSDs: OWAS (Karhu et al. 1977) and QEC analyzed body posture in combination with other physical factors such as force, repetition and duration of movements. Other methods were designed for specific part of the human body such as RULA, HAMA and PLIBE, for the identification of musculoskeletal stress factor; MFA (muscle fatigue analysis, Rodgers, 2004), characterizes the discomfort in three factors level determining the priority to change. However, there are many limitations in these methods such as the lack of precision, no immediate result from the observation and different results: these models can be suitable for static working process but not for estimating detailed MSD risks (Ma et al., 2008).

The available literature focused mainly on developing models to estimate MET (Maximum Endurance Time) (El ahrache et al., 2015) based on static work; these models estimated the ending point of a function where the maximum fatigue is reached, but never reveal the form of fatigue accumulation function (exponential, linear,..); moreover, these methods are no suitable for dynamic activities such as handling operations where loads are carrying for little time, so the problem of the maximum endurance time which an operator can keep the workpiece doesn´t exist.

Christmansson et al. (2000) developed the Ergo-SAM method (Sequence-based Activity Method), based on video recording and the Cube model (Sperling et al. 1993), considering information on weight handled or forces applied and work zone; designed to predict the physical demands of (i) work postures, (ii) force and (iii) repetition (cube model) the results are subjectively evaluate with limited values. Laring et al. (2000)

compared this method with the operator self-evaluation method (VIDAR); this method allows to optimize the productivity and biomechanical load simultaneously; however, it is not suitable for the handling operations because there is no account of the travelling task or movement of the body, thus these methods are not helpful for this work because they have no related fatigue model.

As mentioned in Battini et al. (2015), all traditional ergonomics evaluation methods, such as OCRA, NIOSH, OWAS, RULA, Borg-scale give typical risk index based on semi-quantitative evaluation of postures, movements and loads, and they require a lot of time because of the evaluation of many body-parts positions for each analyzed posture, though these methods don´t analyze each elementary activity.

Perceived rating exertion (PRE) and Swedish occupational fatigue inventory (SOFI) were developed to evaluate the muscles´ work load; to evaluate quickly human working conditions, virtual human condition have been developed such as Jack, Ergoman, 3DSSPP, Wexler, VSR, (Ma et al. 2009); however these models don´t have a related value such as heart rate or volume of oxygen intake that can be used in the rest allowance models.

### 3.2.2 New fatigue models

In this section different energy expenditure models were analyzed with the objective to evaluate the most suitable for the manual material handling operations.

Wu et al. (2002) indicated two accurate ways to calculate the energy expenditure based on the cardiorespiratory capability: the oxygen uptake (VO2) and heart rate (HR) showing how HR is greater than oxygen uptake and required a longer time to return to its baselines than VO2; thus, the calculation of VO2 is the best solution for handling operations.

Garg et al. (1978), used oxygen or metabolic consumption as analytical ergonomic measurement systems, where each movement features a specific energy expenditure, can be a valid alternative of the previous cited models; this is possible by considering the assumption that a job can be divided into simple tasks. The net metabolic energy expenditure is influenced by gender, body weight, load weight, vertical heights of lifting/lowering, lateral movements of arms in horizontal plane, speed of walking and carrying load, postures, time duration and frequency of the job and the maximum acceptable work load is affected by both the lifting technique and frequency: lifting lighter weights at higher frequencies, typically during the handling operations, is more demanding metabolically than  lifting heavier weights at lower frequencies. The limit of Garg et al. (1978) is the no account for tasks that require lifting an object above the shoulders and head, where more than half of the MMH operations are carried out with arms above shoulder height, recognizing a risk factor in the development of musculoskeletal disorders (MSD) (Bernard, 1997). Another limit of Garg´s models is the assumption of calculating the total metabolic cost as each individual activity not valid for lifting and lowering tasks (Garg et al. 1980).

Battini et al. (2015) developed a new measurement technique combining the Predetermined Motion Time Systems (PMTS) such as MTM or MOST, with the Garg et al. (1978) model: the PMES (Predetermined Motion Energy Systems) that allows to calculate the energy expenditure per each task (kcal/job) reducing the time spent to calculate the ergonomics measures and simplifying the ergonomics assessment of each assembly task.

Price (1990) considered three fatigue models: (i) the Aberg model (1968) explained the energy expenditure as the consumption of oxygen volume, summing the contributions of basic metabolism, the posture, the body and the load motion: the result depended on the speed and the weight and this fatigue models is best suited to single activities. (ii) Spitzer and Hettinger (1964) considered the total power (in terms of oxygen volume) as the sum of the basic metabolism, the body posture and the type of activity; this is suited for operations where task are classified as light, medium and heavy work. (iii) Pandolf model (1977) is suited to operation with horizontal carrying of loads, using the terrain factor, the slope and the speed.

Pimental et Pandolf (1979) developed an energy expenditure model specific for the handling operations in the U.S. Army standing or walking slowly uphill or downhill.

Taboun and Dutta (1989) developed a fatigue model that summed the walking energy expenditure with static tasks such as lifting or lowering; the fatigue is calculated in terms of volume of oxygen (VO2) and heart rate (HR). A positive aspect of these model is the two different variant for height of lifting (model I: from 75 cm to a height of 150 cm or less; model II: from the floor to 150 height or less).  In this study, authors calculate that the carrying distance is less than 12 meters as in the 99% of the cases, according to a survey (Drury et al. 1982); however, this negative point can be overlook because of the strong correlation between the predicted and the actual measured oxygen consumption that allows to predict values of VO2 for different tasks, and for the possibility of considering different MMH scenario.

In the following Table 3.2 and Table 3.3, the suited models for manual material handling are catalogued.

**Table 3.2:** Fatigue models catalogued for activities and variables

| MODELS | ACTIVITIES | | | | | VARIABLES | | | |
|---|---|---|---|---|---|---|---|---|---|
| | walking | squatting | lifting/ lowering | carrying | horizontal trasport | individual characteristics (sex, weight, age) | mechanical work (weight of object) | type of work (posture, method of handling ) | organisation and rhythm of work |
| Aberg (1968) | X | | X | X | X | X | X | X | X |
| Battini et al (2015) | X | X | X | X | X | X | X | X | X |
| Garg et al. (1978) | X | X | X | X | | X | X | | X |
| Garg et al. (1980) | | | X | | | X | X | X | X |
| Pimental et al. (1979) | X | | | X | X | X | X | X | |
| Pandolf (1977) | X | | | X | X | X | X | | X |
| Spitzer et al. (1964) | X | X | | | | X | X | X | |
| Taboun and Dutta (1989) | X | | X | X | | X | X | X | |

**Table 3.3:** Energy expenditure models catalogued for task, input and output.

| Model | Task (s) | Input(s) | Output(s) | Comments |
|---|---|---|---|---|
| Aberg (1968) | carry an object , lift both object and body, body motion and light loads, horizontal carrying, walking, lift up , lift down | body and workpiece weight, sex, age, posture, method of handling and transporting, frequency of work , enviromental factors | VO2 = oxygen uptake (l/min) = basic metabolism + posture + body + load motion | dynamic lifting, single activities with detailed load and speed; no account of container characteristics |
| Battini et al (2015) | walking, squatting, horizontal movement of arms, | body and workpiece weight, sex, age, height of lifting | VO2 = oxygen uptake (l/min) | Predetermined Motion Time Systems (PMTS) |
| Garg et al. (1978) | MMH (manual material handling activities) | metabolic energy expenditure for posture (Kcal/min), time duration posture, single tasks, time duration of job, distance, gender, body weight | average energy expenditure (kcal/min or Watt) | lift/lowers modeled to occur < 0,81 m height; no account for tasks that require lifting an object above the shoulders and |
| Garg et al. (1980) | lifting and lowering | body weight, frequency of task | VO2 = oxygen uptake (l/min) | individual lifting or lowering tasks |
| Pandolf (1977) | horizontal transportation of loads | subject weight, external load, terrain factor, velocity | W/kg of body weight | standing or walking very slowly |
| Pimental et Pandolf (1979) | horizontal transportation of loads uphill or downhill | external load and subject weight, speed, terrain factor | Watt | energy expednitures while standing or walking with loads |
| Spitzer et Hettinger (1964) | squatting, walking | | W or VO2 intake (l/min) | light medium heavy activities |
| Taboun and Dutta (1989) | MMH (manual material handling activities), lifting, carrying, walking | sex, age, box weight and width, handling pace, vertical and horizontal distance, speed, carrying distance, | oxygen consumption VO2 (l/min) and heart rate (bpm) | combined tasks of lifting and carrying , carrying distance < 12 m, different height of lifting |

## 3.3 REST ALLOWANCE

To ensure to the workers an acceptable working condition, a resting time after each task is necessary; this provides the operators´ welfare under the fatigue limit avoiding injuries, illness or WMSDs optimizing the time for production.

Thus, after a classification of the most suitable energy expenditure models for the MMH a review of the rest allowances is necessary.

### 3.3.1 Rest allowance time

In ergonomics, rest allowance (RA) is the percentage ratio between the length of an uninterrupted working period and the length of the following resting period to compensate the fatigue. Several alternatives have been offered: at Toyota automobile assembly plants, as with most companies, the practice is to allow two ten-minute breaks: one break is in the morning, one in the afternoon, with a thirty-minute lunch (Shingo, 1981). Another approach is to allow one three-to-five minute break each hour in addition to regular 15 minute morning and afternoon breaks (Grandjean, 1981).

Rest allowance time can be determined by knowing the maximum aerobic work force capacities and the metabolic requirements of tasks individuated in the fatigue models; by determining the proper rest allowance for a particular task, it can be evaluate for the total time of operation that ensure to the operator an ergonomic working conditions.

## 3.2 Rest allowance models

Several rest allowance models were developed during years (Rentschler,1988; Eksioglu, 2011; Imbeau, 2009) most of them regarding static work, thus not interesting for the dynamic operations such as handling activities.

Rohmert (1973) developed a model to calculate the correct rest allowance particularly for dynamic works: determining the amount of human work as oxygen consumption during the task, this is then converted into working kilocalories (kcal); with an exponential trend, in this model the endurance limit is the %15 MVC (maximum voluntary contractions); under this value there is no increasing of fatigue.

Price (1990) created and improved system with a linear trend using as fatigue models Aberg, Spitzer et al. and Pandolf, that are subsequently evaluate in the next part.

Santosa et al. (2012) introduced a new fatigue recovery time assessment for industrial activities, the RFad method using a constant denominator represented by a value close to the basic metabolism rate.

In Table 3.4 the cited RA models are catalogued.

**Table 3.4** Models for the relaxation allowances present in the literature.

| Models | Input | Comments |
|---|---|---|
| Spitizer (1951) | Kcal/ min | limit of 4 kcal/min |
| Rohmert (1973) | kcal/min | exponential trend , high % RA increasing the task duration or intensity |
| Price (1990) | Watt | linear trend ; work + relaxation = acceptable work level |
| Santosa et al. (2012) | Kcal/ min | muscular activity, ergonomic aspects, individual physical |

## 3.3 Framework development

Harris (1913) developed the EOQ (Economic Order Quantity) to evaluate the best lot size to order or to product (EPQ: Economic Production Quantity). This is found combining the curve of re-order/production cost that has an inverse exponential trend increasing number of items and the storage cost that has a linear trend with the lot size.

The objective of this work is the determination of the optimal lot size taking account of ergonomics; as shown in literature there are many ergonomic models but only few of them have a related fatigue model that allows to find the correct rest allowance (so the time and cost to ordering) and usually is not immediate to evaluate the most suitable for the specific scenario on analysis; thus a framework that helps in this choice is developed.

At first it is necessary to subdivide the whole activity in detailed tasks more simple to evaluate in terms of energy expenditure.

Then it is important to understand which parts of the body are mostly involved in the specific handling operation, the posture, the weight and the frequency and repetition of tasks; these parameters allow to individuate the suitable ergonomics model (OWAS, NIOSH, RULA) improving workplace conditions, reducing occupational risks and increasing productivity. However, the selected ergonomic model needs a correlation with a fatigue model (Aberg, Pandolf, Garg) or an equation of the energy expenditure, otherwise is cannot be used; comparing this result with the acceptable work level, it is possible to calculate the rest allowance necessary for the operator at the end of each task for an ergonomic work condition.

Using Table 3.2 and Table 3.3 and the framework in the following Fig 3.2 and Fig 3.3, the suitable fatigue models can be evaluate; the starting point is the operator parameters such as weight, height or age; then the attention is focused on the load (weight, size,..). Subsequently the whole activity is subdivided in different tasks: this allows to identify the specific operations that increase the energy expenditure in different intensity. Finally, the environment parameters such as distance, terrain factor and slope are controlled. More detailed is this analysis, more specific and complete is the final energy expenditure result.

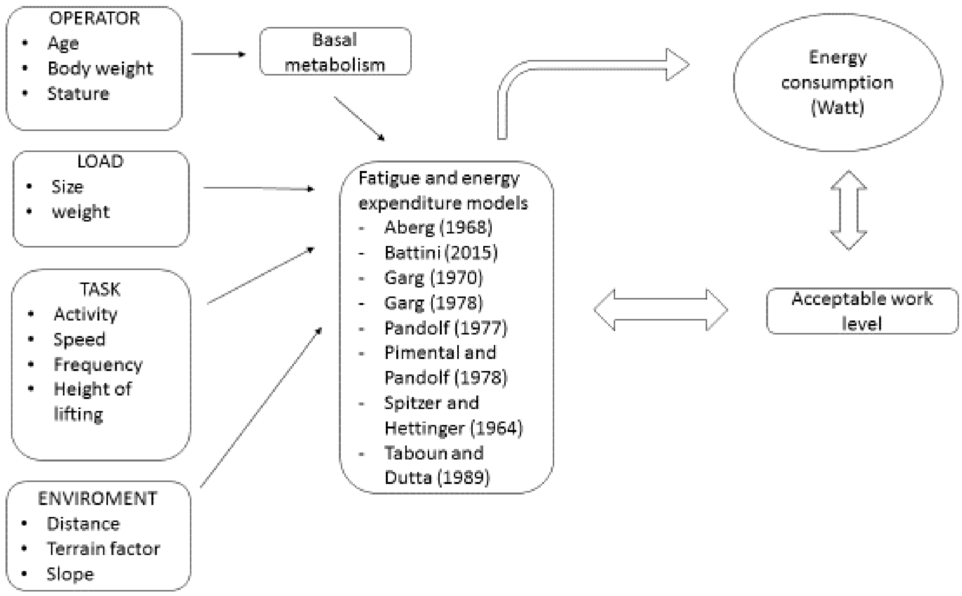


**Fig.3.2:** Framework of the structured way to proceed to identify the energy consumption and the acceptable work level.

At this point, based on the calculated energy consumption in terms of Watt, using the ergonomics theories, the suitable model for the rest allowance time can be evaluate. Then, this value is added for the calculation of the total time for the MMH activity and thus the total cost of the operation. At this point, as can be seen in the graph of Fig. 3.3, to reach the minimum cost, the economic order or picking quantity can be evaluate; this lot size takes account of the ergonomic working level ensuring an acceptable working conditions for the operator.

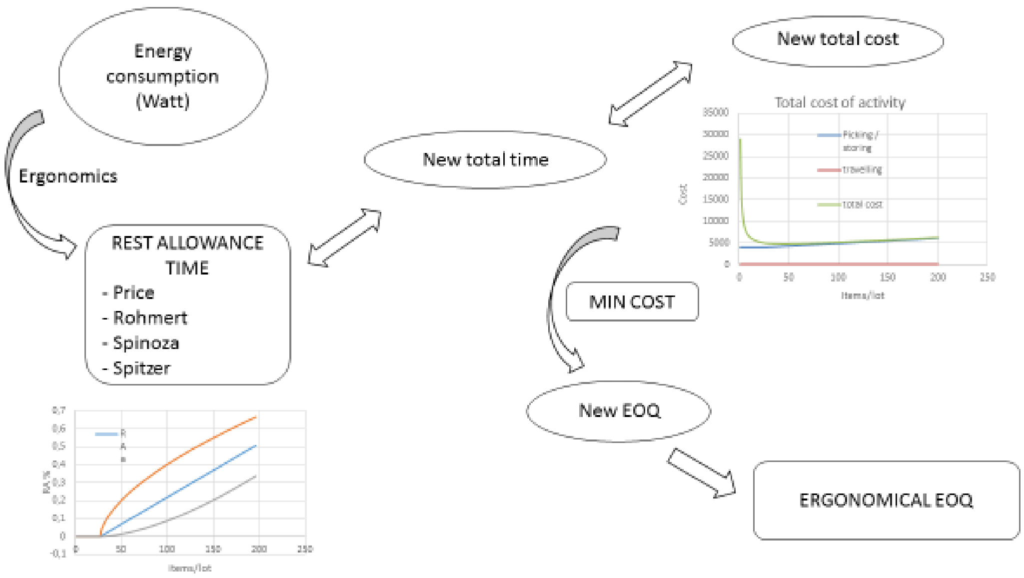


**Fig.3.3:** Framework of the structured way to proceed to identify from the energy consumption, the rest allowance time for the evaluation of the total time and the ergonomical EOQ.

The frameworks of Fig.3.2 and Fig.3.3 can be utilize in all the contests when the variable parameters are known and the suitable models for the calculation of the energy expenditure can be used. Thus these two frameworks can be considered as standard for different scenario and can be an important support for the evaluation of the minimum lot size as explained in the following part of this work.

# Chapter 4

# Problem evaluation and sensitivity analysis

In this section, based on the previous framework, the most suitable fatigue models for ergonomic lot sizing are evaluate. Then a sensitivity analysis with the model used by Battini et al. (2015) is developed, comparing founded results.

To understand which fatigue models are suitable in ergonomic lot sizing, as explained in the two frameworks, at first is necessary to focus the object to reach. In this work, the target is the optimization of the lot size including ergonomics; this method introduces rest allowance for workers, thus the time needed for each activities is bigger than the time to individuate the common re-order or production quantity from Harry´s curve (1973) without attention on worker´s welfare. However, the rest allowance time ensures an ergonomic work level, thus the operator will not have injuries or no rest time not scheduled: the result is a work evaluation more fitted to the real situation.

The second point is the analysis of the activity made by the operator: in the MMH (Manual Material Handling) workers makes several operations from which depends the choice from the most suitable models previous evaluated. As can be seen in both tables 3.2 and 3.3, there are different tasks and the identification of the correct one can help with the evaluation and it is convenient to subdivide the whole logistic process in several detailed tasks due to the different fatigue that each task required: in fact, lifting or lowering items requires more energy instead of carrying the trolley.

## 4.1 Problem evaluation

The objective of lot sizing models is the minimization of the total cost determining economic production quantities.

The analyzed basic lot-sizing problem is composed by three common terms for the time and a new item (always in terms of time) that takes account of the effort of the operator:

1. Time of picking
2. Time of travelling
3. Time of storing
4. Time for recover energy

As can be seen in Fig. 1.2, the number of trips necessary to transfer the total items from a hypothetical point A to a point B is strictly related to the travelling time; in fact, to reach the optimal lot size, an engineer, programming the operations, has to decide if it is more convenient to pick the total items and put them on the trolley and make only one trip, particularly when the travelling time is very high. However, if the lot size is too big, injuries and WMSDs can be occurred to the workers because of the energy expenditure necessary to pick the total items and to make only one trip is too high; thus, it is necessary to reduce the lot size (increasing the total time) considering the influences of human factors in the lot-sizing decision.

The total picking and storing time for all the items will be the same, even if the worker make only one trip for all the items or one trip for each item, because it depends on the activity. But, considering ergonomics, with the formula introduced by different authors, there will be an optimal lot size, so the lot picking time, depending on the number of picked items, will be different. The same thing is for the storing time, usually considered the same of the picking time to reduce the calculation.

The total travelling time doesn't depend on the number of items for each trip, but only of the number of trips necessary to transfer the total items from point A to point B; this because the travelling time is the fraction between the speed and the distance. The distance for each trip is constant, and the speed is considered independent from the weight of the kart, because this variation is not relevant. To minimize the total travelling time, the operator should put the total items in the kart and make only one trip; however, the kart couldn't travel all the items, because of the weight or the dimension of the items, and for the ergonomic reason, the energy necessary to pick and storing all the items in only one trip without any interruption, will be very dangerous for the operator.

## 4.2 Scenario analyzed: refilling the supermarket or storing items to a warehouse

In this work, based on Battini et al. (2015), it has been considered a typical logistics process: the refilling process of a supermarket on an assembly line or the storage of items in the warehouse. The line and generally the factory can work well without any interruption only if there are all the items necessary for the continuous production according with the Japanese method of "just in time"; this is provided from a solid supply chain. Operators have to refill the supermarket near the line with a cart/trolley or a powered electric or an automated vehicle (AGV/LGV): this allows to need few items near the station and only the items strictly necessary for their use on advantage for the space required behind the line. This can be considered as also the transportation of products from the final stage of production to storage facility. The operator picks from the point A items that compose the produced lot, puts them on a manual trolley, pushes the trolley to the warehouse (point B) and storages the whole lot.

Thus, it is important to calculate the time necessary for the continuous alimentation avoiding interruptions; moreover in this work a particular attention is dedicated to the acceptable work level of the operator. The RA necessary for a human well being modified the total time and thus the related cost of the process. To evaluate the best lot size that minimizes the total cost is necessary a closed formula.

## 4.3 Choice of pallet truck

In the MMH operations an important role in the travelling task is assumed by the pallet truck. This system is very common for its utilization inside the factories and allows to reduce sensibly the effort necessary for the activities with high work load, thus an analysis of the different basic pallet trucks is necessary. The biggest pallet truck are not considered in this work because of the high weight for which they are suitable; this wouldn't be inherent with the analyzed lot size, weight and dimensions in exams; thus it has been considered only small pallet truck as following explained. Moreover is not considered the cost of the pallet truck because a real hypothesis is that the purchase and maintenance cost is distributed in all the different activities, thus the impact of the pallet truck cost for the single item is considered negiglible.

In the case analyzed by Battini et al. (2015), the system used to travel the items is a manual pallet truck as shown in Fig. 4.1.


**Fig. 4.1**: Typical manual pallet truck: Toyota HPT28U.

When the operator utilizes this system for the travelling task, the energy expenditure necessary for the operation is composed by the metabolic rate as the effort for standing ,the energy required for the walking activity and for pulling task and in some models this energy is multiplied for the weight (items + trolley).

Nowadays, to improve ergonomic working conditions, increasing speed of movements, industries are equipped with electric powered pallet trucks: the operators for the travelling tasks consumes only the oxygen or Watt for the basic metabolism and walking activity, but no effort is necessary for pulling the pallet truck because of its electric power. Thus in this work the first scenario considers the use of a typical powered warehouse truck (Toyota 7HBW23) as in the following Fig.4.2

**Fig.4.2:** Typical powered pallet truck: Toyota 7HBW23.

The following evaluated models for this thesis also consider a different scenario, typical in the MMH, particular for operations with high time necessary for the picking and storing tasks; this time is compatible with a distance considers equal to 5 meters (distance analyzed subsequently), from the production line to the pallet truck (picking) or form the pallet truck to the warehouse or storing facilities to the assembly line (storing). In this scenario industries may adopted an electric powered pallet truck with a platform for the driver as in the following Fig. 4.3: this solution allows to reduce sensibly the energy for the travelling time because no effort for walking in necessary: in fact the operator stands on the platform driving the electric pallet truck and the only energy required is for the basic metabolism.

**Fig.4.3** : Platform powered truck pallet: Toyota 7PML.

The effort calculated in terms of Watt of volume of oxygen consumed decreases sensibly and this has a positive influence on the final calculation of RA necessary for the operator at the end of the activity, reducing to total time and thus the subsequently total cost of operation.

## 4.4 Current ergonomic lot sizing model

The first ergonomic lot sizing model is developed by Battini et al. (2015): the quantity that each operator handles for each trip depends on:

- Standard time
- Travel speed
- Rest allowance necessary to ensure ergonomics level
- Availability of the worker

The optimal ergo-lot size can be derived minimizing the total time spend for handling (ET (q)):

$$ET\ (q) = \frac{(T_p+T_t+T_s)*(1+RA)}{A} * N_t \quad (4.1)$$

Where:

$T_p$= time to pick the lot

$T_t$ = time to travelling

$T_s$= time to storage

$N_t$= number of trips

RA = rest allowance

A= availability

This formula can evaluate the optimal lot size taking account of the total time of picking, travelling, storing and the contribution of the RA, as it can be seen in the following part

### 4.4.1 Battini et al. (2015) I model

Battini et al. (2015) developed a method to evaluate the ergonomic lot size taking account of the RA necessary to recover energy. In this model authors consider the role of speed that follows this equation:

$$s(q) = s_{max} * (1 - s_1 * (w * q)^{s_2}) \tag{4.2}$$

Battini et al. (2015) consider a max speed is 1.2 m/s depending on the trolley or kart used; the terms $s_1$ and $s_2$ are values derived by empirical tests and are respectively equal to 0.08 and 0.4. The term w is the weight of the single item and q is the number of items for each lot travelled. Results are evaluated for items of weight of 0.2 , 0.4, and 1 kg, as considerations about the common weight of product.

In the following Fig.4.1 the behavior of the travelling speed is shown.

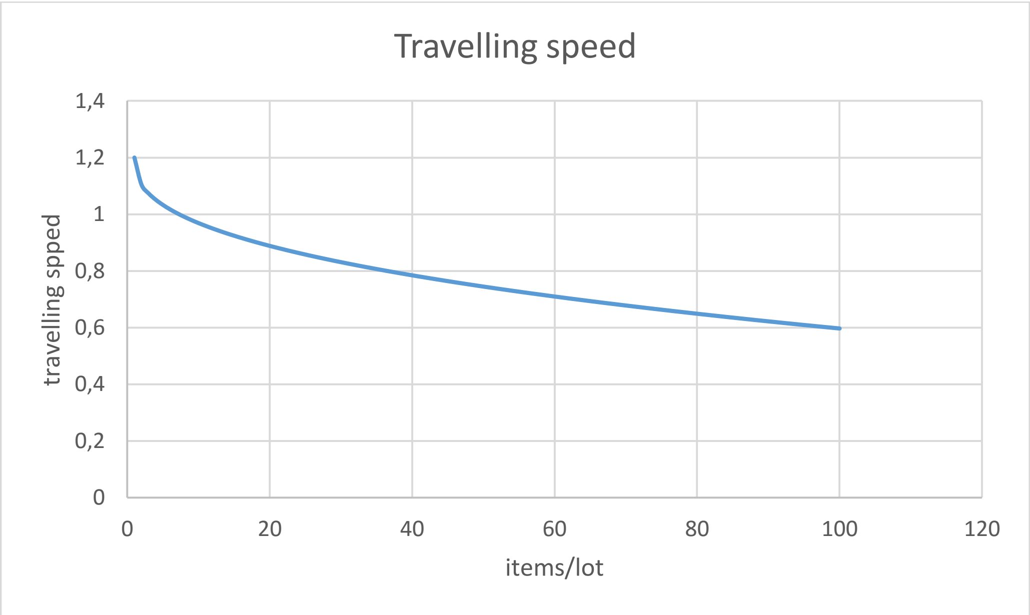


**Fig. 4.5:** Speed behavior growing of the lot size.

As it can be seen in Fig.4.1, the behavior of the speed shows a decrease growing the number of items for each single lot travelled. This is due to the increment of the total weight of the kart, which depends on the number of items travelled, and thus the increment of the energy required for the operator.

This decrement of speed increasing the number of items will be later considered excessive for the evaluation of the subsequent resting time to recover energy; in fact, with the increase of the number of items for lot considering a maximum lot size of 1000 items, following the formula (4.2), at 553 items for single trip, the travelling speed become negative; but a negative speed can't be correct. Therefore, this travelling speed evaluation can be correct only for few items for each single trip, maximum a lot size of 300 items, and not for more items considered as in this work where the whole production to be travelled is equal to 1000 items.

Another important parameter considered in the publication is the availability. The mean of this term is the time of operator on disposition for the different activities. At time zero or when the operator makes no effort, the availability is equal to 100% because there are at disposition all the energy for any tasks.

This term is affected by the accumulated manual load, which impacts to the number of injuries and their magnitude: increasing the effort and the energy required, the probability of injuries increases and this parameter consider this role.

To model this term (A) the following equation is used:

$$A = 1 - [\frac{T_p * a_{p1} * (w*q)^{a_{p2}}}{T_p + T_t + T_s} + \frac{T_t * a_{t1} * (w*q)^{a_{t2}}}{T_p + T_t + T_s} + \frac{T_s * a_{s1} * (w*q)^{a_{s2}}}{T_p + T_t + T_s}] \quad (4.3)$$

Values $a_{p1}$, $a_{p2}$, $a_{t1}$, $a_{t2}$,$a_{s1}$, $a_{s2}$, describe the behavior of and are respectively 0.006, 0.2, 0.002, 0.15, 0.006, 0.2.

When no items are travelled, the availability is 100% because the operator makes no effort and there is the minimum risk of injuries; however, increasing the items for each lot, the availability shows a decrement as can be seen in the following Fig. 4.2.

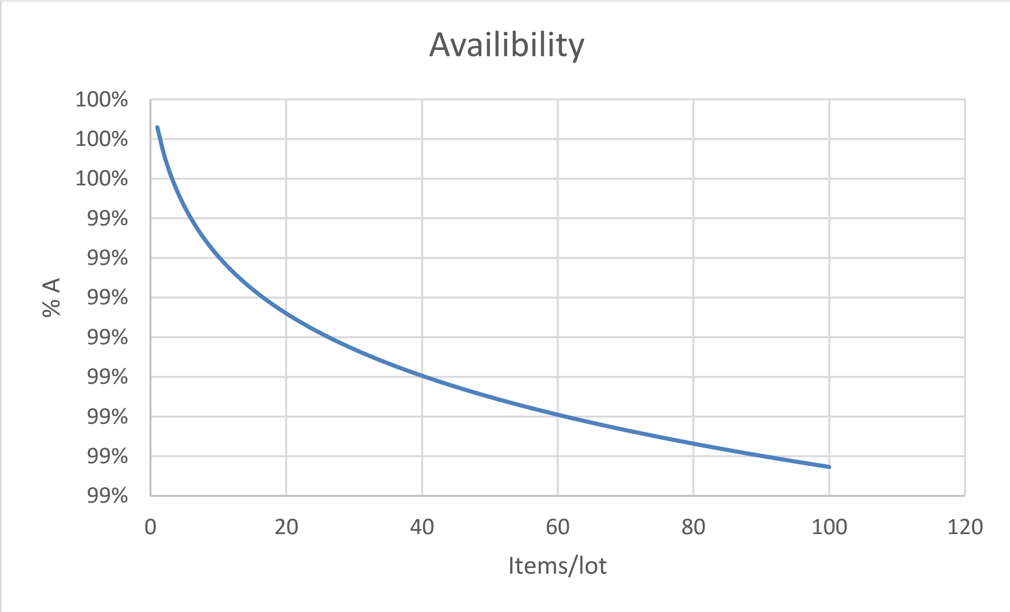


**Fig.4.6**: Decrease of availability increasing the items for lot.

This work concentrates the attention on the RA as explained in the previous formula 4.1, in particular the role of RA in the lot sizing decisions. Battini et al. (2015) used a model similar to the one introduced by Rohmert (1973) in which the rest time after a task execution increase exponentially to the time spent (picking, travelling, storing) and the energy expenditure is related to the total handled load (weight * items). The time spent is a function of q (items), while the energy expenditure is assumed increasing proportionally with the handled load (w*q). For picking and storing activities, the time is proportional to the total handled load, whilst the travelling task is affected by handled load and travel time. The equation developed adopts parameters estimated by several tests using the models of Garg et al. (1978) and Rohmert (1973) and depends on the features of the analyzed activities (kind of movements, height of picking and storing, operator weight).

In Battini et al. (2015) the load is a variable from 0.2 kg to 2 kg, the activity is composed by lifting and lowering items (static operation with high frequencies), pulling the trolley (dynamic operation) at speed that depends on the total weight (max 1.2 m/s) of the lot for the distance that is variable (25-200 m), lifting and lowering at point B and returning to point A at the max speed. In this scenario the environment factors are not considered and can be assumed a normal floor of a factory without slope.

### 4.4.2 New publication of Battini et al.

The new article of Battini et al. ("An integrated approach to include ergonomics in lot-sizing decision") allows to individuate a closed formula for the optimal lot size. This is obtained through several simplification:

- The availability term is considered not relevant, thus A is equal to 100%; in fact the tasks analyzed in this work are defined not repeatedly because after the activity the operator could do something else, thus no injuries increase growing the lot size travelled for each trip.
- The travelling time is considered constant and equal to the max speed of the trolley so it doesn't depend on the weight travelled.
- No rest allowance for travel activities: in comparison with the picking and storing, the travel doesn't influenced the RA necessary for the ergonomic working conditions.
- Unitary picking time equal to unitary storing time.
- The cost of the trolley didn't influenced the total cost because of the several trips made with the single one, thus the incidence on the single items is not relevant.
- Opposite to the first paper of Battini et al. (2015), here it has been considered the term alpha: this allows to consider with the RA necessary not only the "not producing time" during the rest, but also a "loss of production"; in fact, the system must considered when the operator doesn't work, especially for the production.

The problem under study is a typical material handling and transportation process, where a certain amount of products have to be handled inside a production facility. A typical case is the transportation of products from the final stage of a production system to a storage facility, or the refilling process performed in an order picking warehouse from the reserve area to the forward area.

The new article allows to individuate the total cost as the combination of the cost of picking, travelling, storing and the cost of RA.

$$C(q) = C_p(q) + C_t(q) + C_s(q) + C_{RA}(q) \tag{4.4}$$

The total the picking cost:

$$C_p(q) = T_p(q) * c_w * N_t(q) = q * t_p * c_w * \frac{Q}{q} = t_p * c_w * Q \quad (4.5)$$

is the product of the quantity (q) of items for single lot, for the time of picking necessary to pick the single item form the point A and to put it on the kart, for the hourly cost of operator per second, for the total trip necessary to bring all the items from point A to the kart.
The cost of total travelling time is:

$$C_t = T_t(q) * c_w * N_t(q) = \frac{2d}{s} * c_w * \frac{Q}{q} \quad (4.6)$$

Where the total time $T_t(q)$ is the fraction between the total distance necessary to reach the point B from the point A and the speed of the operator. In the precedent article of Battini et al. (2015) this value is considered dependent on the total weight of the kart so it increases with the number of items for single trip. As can be seen, the final formula (4.6) of the travelling cost depends on the number of trips necessary: if the number of items for each trip is 1, the number of total trips is equal to the total items Q.
The total storing time is:

$$C_s(q) = T_s(q) * c_w * N_t(q) = q * t_s * c_w * \frac{Q}{q} = t_s * c_w * Q \quad (4.7)$$

This formula is similar to the total cost for picking task; in fact in the paper of Battini et al. (2015) this value is considered equal to the value obtained with the formula of the cost of picking time: this can be considered a correct hypothesis and allows to increase the simplification for the final evaluation and developed of a simply closed formula.
The different terms in (4.4) on which this master thesis is based is the last formula for the determination of the cost of the RA:

$$C_{RA}(q) = RA(q) * (T_p(q) + T_t(q) * T_s(q)) * c_w * N_t(q) * \alpha \quad (4.8)$$

As it can be seen, the rest allowance (RA) is multiplied for the total time necessary for the single picking + traveling + storing operation, for the cost of operator as the other previous formula, for the number of trips necessary $N_t$ function of the items, and for a parameter $\alpha$ that takes account not only of the resting time, but also of the not productive time. In fact, the production may be affected and thus reduced by the operator if some resting time to recover energy is necessary; thus it will be nonsense if the production, produces more items that the operator can transport to the warehouse or the assembly line required more items that the worker can travelled to the supermarket.

The role of the RA is dominant and allows to consider the role of ergonomics in the lot sizing decisions, thus other considerations are necessary.

The formula derived is:

$$RA = \frac{q*t_p*r_{p1}*(w*q)^{r_{p2}}}{(T_p+T_t+T_s)} + \frac{q*t_s*r_{s1}*(w*q)^{r_{s2}}}{(T_p+T_t+T_s)} \tag{4.9}$$

This formula is derived by the theories of Garg et al. (1978) to evaluate the net energy expenditure rate as the sum of the energy expenditure rate on the total time.

So the formula (4.8) can be rewritten as:

$$C_{RA}(q) = \left(q * t_p * r_{p1} * (w * q)^{r_{p2}} + q * t_s * r_{s1} * (w * q)^{r_{s2}}\right) * (T_p(q) + T_t(q) * T_s(q)) * c_w * N_t(q) * \alpha \tag{4.10}$$

Where the parameters $r_{p1}$, $r_{p2}$,$r_{s1}$, $r_{s2}$ are estimated by several previous test using the equations introduced by Garg et al. (1978) and Rohmert (1973). As explained, these parameters are affected by the specific context under analysis: this is the main limitation of this method. To consider the correct RA several tests need to me made in order to collect data and to determine the best fit function to the data, using traditional techniques such as least squares minimization.

The new method introduced in this work allows to identify in a more simply way the value of RA using predetermined values founded by several authors as previous explained.

The general model of Battini et al. (2015) can be rewritten as follows:

$$C(q) = C_p(q) + C_t(q) + C_s(q) + C_{RA}(q) = t_p * c_w * Q + \frac{2d}{s} * c_w * \frac{Q}{q} + t_s * c_w * * Q + \left(q * t_p * r_{p1} * (w * q)^{r_{p2}} + q * t_s * r_{s1} * (w * q)^{r_{s2}}\right) * (T_p(q) + +T_t(q) * T_s(q)) * c_w * N_t(q) * \alpha \tag{4.11}$$

In this model the picking and storing activity are considered the same, as typically, thus the formula (4.11) can be rewritten as follows:

$$C(q) = 2t_{ps} * c_w * Q + \frac{2d}{s} * c_w * \frac{Q}{q} + \left(2t_{ps} * r_{ps1} * (w * q)^{r_{ps2}}\right) * Q * c_w * * \alpha \quad (4.12)$$

The innovation of this model is the evaluation of a closed formula for the optimal lot-size: this is obtained through the derivation of the cost on the time, i.e. the minimization of the total cost function:

$$\frac{dC}{dq} = -\frac{2d}{s} * c_w * \frac{Q}{q^2} + 2t_{ps} * r_{ps1} * Q * c_w * \alpha * r_{ps2} * w * (w * q)^{r_{ps2}-1} = 0 \quad (4.13)$$

The closed formula for q optimal can be written as:

$$q^* = \sqrt[r_{ps2}-1]{\frac{d/s}{t_{ps} * r_{ps1} * \alpha * w^{r_{ps2}}}} \quad (4.14)$$

With this formula every activity can be evaluate, but the main problem is the determination of the value for the correct correlation between the energy consumption founded using different parameters, and the RA necessary.

When all of the terms in the formula (4.14) are present, the minimum lot size cam be evaluated with a single simply and quickly formula.

## 4.5 Application of alternative

Using the framework previous developed and explained in Fig. 3.2 and Fig. 3.3, the analysis of the different parameters in this particular logistic process is necessary: the operator is considered of medium weight (70 kg), stature (1.75 m).

The analytical model used in the following method analyzed in this master thesis for estimating the net energy expenditure rate for any combined MMH activities is the one derived by Garg et al. (1978):

$$E_{job} = \frac{(\sum_{i=1}^{m} E_{pos} * t(i) + \sum_{i=1}^{n} E_{task}(i))}{T} \tag{4.15}$$

Where:

- $E_{pos}$= metabolic energy expenditure rate due to maintenance of the i-th posture (Kcal/min)
- *t (i)* = time duration of posture i (min)
- m = total number of body postures employed on the job
- $E_{task}$(i) = net metabolic energy expenditure for task (i) during steady state (kcal)
- *N* = number of tasks in the given job
- *T* = time duration of the job (min)

This model is based on the assumption that the net metabolic energy cost of a series of tasks could be estimated by summing the net steady metabolic costs of all individual activities involved as obtained from their separate performances.

Based on these parameters and using the Fig. 3.2 and Fig. 3.4, a suitable rest allowance model can be the one introduced by Price (1990), because it has more than one strong fatigue model at the base of the equation for the calculation of RA.
From the three considered fatigue model (Price, 1990), the most suitable is Aberg model (1968) because analyzing the developed framework, this model can evaluate different activities such as carrying, lifting, lowering and walking, strict related to the tested handling operation. However, in this work, different fatigue criteria will be evaluated, to allow the engineers to select the best model for their conditions and scenario.
The container/box characteristics, which are not considered in this model, are not important in this study.

### 4.5.1 Aberg model

The model is formulated using a relation between the amount of work and human energy expenditure, called also Johansson's rule, and can be expressed by the following formula:

$$E = E_0 + E_t + k * A \tag{4.16}$$

Where:

$E$ = total energy expenditure

$E_0$= energy expenditure due to basal metabolism

$E_t$ = energy expenditure due to the operator's movements empty-handed

$k$ = a proportionality constant

$A$ = amount of external work performed

Aberg divided the terms $E_t$, $k$, and $A$ in simple elements, which could be easily measured, using ordinary work study methods.

In the Aberg model the fatigue is calculated as volume oxygen consumption with this form:

$$VO_2 = basal\ metabolism\ (K_1) + posture\ (K_2) + body\ (K_3 + K_4) + \\ + load\ motion (K_5 + K_6 + K_7 + K_8) \quad (4.17)$$

The units selected were kilograms for weight, meters for length, minutes for time and liters per minute for oxygen uptake. The original Aberg method gives results in terms of volume of oxygen consumption; however Price (1990), developing a common for the calculation of the rest allowance necessary for the operator, converted with different Table the energy expenditure in terms of Watt. In this work it has been considered the method with the both measure units.

Price (1990) converted the original formula into SI units and separated the body and load motions associated with construction operation, thus from the volume oxygen consumption, formula are converted in Watt [W] as presented in Table 4.1:

**Table 4.1:** Factors for the Aberg model

| Factor | Activity | power (W) | |
|---|---|---|---|
| K1 | basic metabolims | 85 | W |
| K2 | Sitting | 29 | W |
| | Standing | 34 | W |
| | standing bent | 56 | W |
| K3 | Walking | 205 | W*speed |
| K4 | bend+rise | 790 | W*speed |
| K5 | horizontal arm work | 65 | W*kg*speed |
| K6 | horizontal carrying | 3 | W*kg*speed |
| K7 | lift up | 119 | W*kg*speed |
| K8 | lift down | 82 | W*kg*speed |

The basic metabolism is considered equal to 85 W (K1): this is the energy in terms of Watt required for the minimum based functions of human. If the operator is standing, there are additional 34 W (K2). Thus, the power consumed when the body is stationary with no loads applied is equal to:

$$P = K1 + K2 = 119\,W \tag{4.18}$$

Now the different activities are considered: at first, the operator lift the items of the lot from point A to put them on the trolley; this activity involved K1 = 85 W (basic metabolism), K2 = 34 W (standing), K4 = 790 W/(m/s) (bend + rise), K7 = 119 W/kg/(m/s) (lift up), K8 = 82 W/kg/(m/s) (lift down). As can be seen K4 depends on the speed of the operator and K7, K8 also from the weight.

For lifting and lowering the equation for calculating the energy expenditure is:

$$P_1 = 119 + L\,(790 + 82 * w) \tag{4.19}$$

Where 119 W is K1 + K2, L is the lifting speed, 790 W is K4, K7+K8 would be 209 W (119 W is the lift up and 82 the lift down), and w is the weight of items.
In the scenario considered, the weight of items is constant and equal to 1 kg, thus the task can be considered as "body motion and light loads": K7+K8 = 82 W. The operator pick only one items for each task, thus the energy expenditure is constant increasing of the number of items for lot picked in the trolley and subsequently stored in the supermarket.
The value of the first formula for the evaluation of energy is:

$$P_1 = 816.6\,W \tag{4.20}$$

Now it is considered the energy expenditure for the travelling operations.
Carrying an object is different involved K1+K2 as lifting, K3 (walking = 205 W/ (m/s)), K6 (horizontal carrying), thus:

$$P_2 = 119 + L\,(205 + 3 * w) \tag{4.21}$$

Where w is the weight of the trolley and the load (with different scenario) and L is the travelling speed that decreases with the increasing of the weight travelled. It has been considered a constant travelling speed. The value of this component increase with the number of items carried because the operator pull the trolley with the total items of the lot considered.

After the storage, the operator has to return to point B; thus other energy is necessary for walking at max speed (0.8 m/s):

$$P_3 = 119 + L\,(205 + 3 * w) \tag{4.22}$$

Where w is represent only by the weight of the trolley. The total energy expenditure is the sum of the picking and storing and travelling:

$$P_{tot} = 2 * P_1 + P_2 + P_3 \tag{4.23}$$

Now, it is important to consider the method necessary to evaluate the correct energy expenditure. Each single component $(P_1, P_2, P_3)$ has to be multiplied for the time of the task: $P_1$ * time of picking, $(P_2 + P_3) *$ time of travelling.

With this method, the correct energy expenditure will be multiplied for the related duration, obtaining the following formula for the work rate:

$$WORK\ RATE = (specific\ energy\ expednditure) * (duration) \tag{4.24}$$

Subsequently the work rate is divided for the total time of the task (picking + travelling + storing time of the single lot): this is the mean work rate (MWR):

$$MWR = \frac{total\ work\ rate}{total\ time} \tag{4.25}$$

The energy consumption will be later used in the formula of Price (1990) to calculate the rest allowance necessary for an ergonomic work level.

Results and behavior of the MWR are shown in the following Fig. 4.7

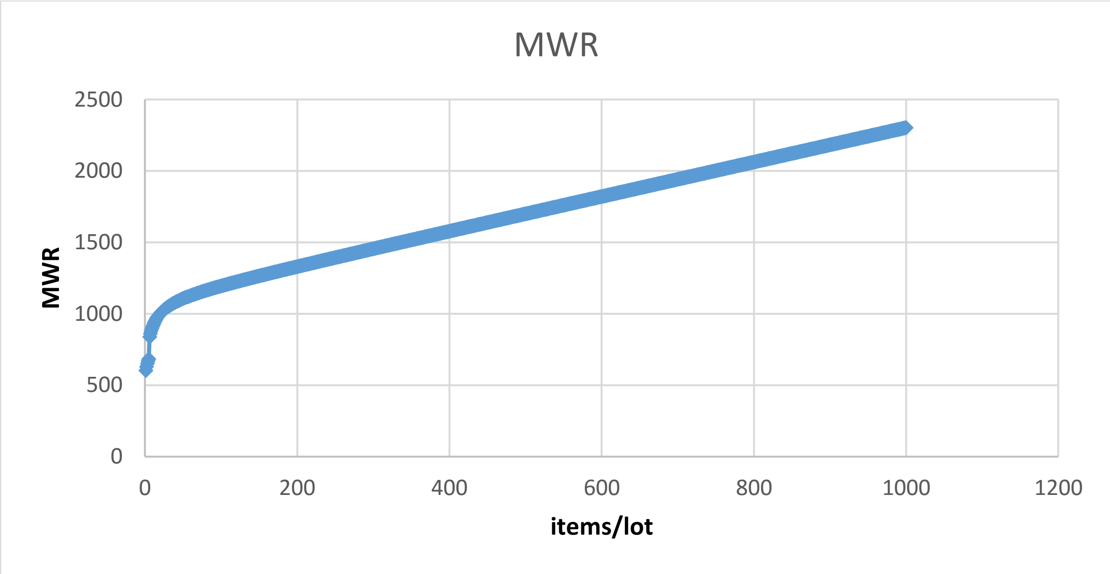


**Fig. 4.7**: MWR increasing the lot size

### 4.5.2 Aberg alternative (VO2)

Instead of the calculation of the energy expenditure in terms of Watt, an alternative is the calculation of the resting time with the volume of oxygen consumption (VO2). In fact this measure unit was the measure unit that Aberg et al. (1968) utilized to calculate from several tests the values for each single activity, deriving the following formula:

$$VO_2 = basic\ metabolism\ (K_1) + posture\ (K_2) + body\ (K_3 + K_4)\ + \\ load\ motion(K_5 + K_6 + K_7 + K_8) \qquad (4.26)$$

From the equation (4.26) the total consumption of energy can be derived.

Through a comparison of the volume of oxygen necessary for the work + relaxation and the acceptable work level that provides ergonomic working conditions, it can be understood if the operators need recovery time.

In this method an alternative scenario is applied: instead of the use of the electric powered pallet truck, in this scenario a platform powered truck pallet as shown in Fig. 4.3 is utilized. This allows to reduce totally the energy necessary for walking in the travelling task, considering the energy required only for the little movements from the pallet truck to the storage facilities or the supermarket; thus it is necessary to subdivided the tasks in more operation as shown in the following table which considers values inherent with the analysis of this work:

| Task | Watt | time (s) |
|---|---|---|
| travelling in picking task | 284.2 | 7 |
| picking | 816.6 | 3 |
| travelling | 34 | 125 |
| travelling in storing task | 284.2 | 7 |
| storing | 816.6 | 3 |

The following table shows the respective values of oxygen consumption.

**Table 4.2:** Values of oxygen consumption.

| | Factor | activity | Value | Unit |
|---|---|---|---|---|
| **Basal metabolism** | $k_1$ | basal metabolims | 0.0035 | l*O2/kg/min |
| **Body motion** | $k_2$ | sitting | 0.001 | l*O2/kg/min |
| | | standing | 0.0014 | l*O2/kg/min |
| | | standing bent | 0.0018 | l*O2/kg/min |
| **Body** | $k_3$ | walking | 0.00014 | l*02/kg/m |
| | $k_4$ | bend+rise | 0.00054 | l*02/kg/m |
| **Load motion** | $k_5$ | horizontal arm work | 0.0003 | l*O2/kg/min |
| | $k_6$ | horizontal carrying | 0.00014 | l*02/kg/m |
| | $k_7$ | lift up | 0.0057 | l*02/kg/m |
| | $k_8$ | lift down | 0.0039 | l*02/kg/m |

The work rate of a general activity for each trip is evaluated from the formula:

$$MWR = BW * k_1 + BW(GCB * k_3 + GCB * k_4) + (WWP + WT) * (L_{ha} * k_5 + \mu * L_{hc} * k_6 + L_{vu} * k_6 + L_{vd} * k_8) \quad (4.27)$$

Where:

*BW* = body weight

*GCB* = horizontal displacement per time unit of the body's centre of gravity

$WWP$ = weight of work piece

$WT$ = weight of tool

$L_{ha}$ = horizontal displacement per time unit of tool and work piece, arm work

$L_{hc}$ = horizontal displacement per time unit of tool and work piece, carrying or dragging

$L_{vu}$ = upward vertical displacement per time unit of tool and work piece, lifting

$L_{vd}$ = downward vertical displacement per time unit of tool and work piece, lifting

μ = coefficient of friction in horizontal movement

$k_1 - k_8$ = constants represent in Table 4.2

The units selected were kilograms for weight, meters for length, minutes for time and litres per minute for oxygen uptake.

Results and behavior of the MWR are shown in the following Fig.

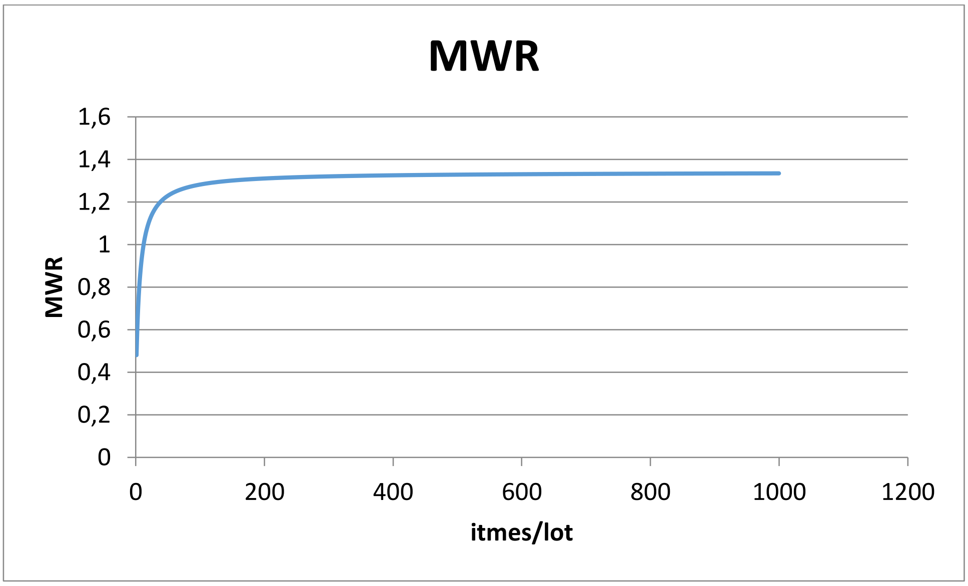


**Fig. 4.8**: MWR of Aberg (VO2) increasing the lot size

As it can be seen the results found are different form the Aberg method used by Price (1990) because of the different hypothesis and calculation for the MWR from Watt to volume of oxygen consumption.

### 4.5.2 Spitzer and Hettinger model

Another suitable model for the evaluation of the mean work rate is the Spritzer and Hettinger model (Spitzer and Hettinger, 1964) that comprises three sections and takes the form of the following equation. The total power is evaluate in terms of Watt:

$$Total\ power = (A + B + 76.7) \tag{4.28}$$

Factors A is derived from body posture as shown in table

**Table4.3**: Power relating to body posture (A).

| Body posture | power [W] |
|---|---|
| Sitting | 21 |
| Kneeling | 36 |
| Squatting | 36 |
| Standing | 42 |
| bent over | 56 |
| Walking | 118 |
| climbing unladen | 52 |

Factors B represent the type and grade of activity as shown in Table.

**Table 4.4:** Factors B including the type of activity and the power necessary.

| | | power W<br>grade of activity | |
|---|---|---|---|
| activity | light | medium | heavy |
| Hand work | 21-42 | 42-63 | 63-84 |
| one arm work | 49-84 | 84-118 | 118-153 |
| both arms work | 105-140 | 140-174 | 174-209 |
| body work | 174-279 | 279-418 | 418-592 |

The energy necessary for the picking task is the sum of standing + squatting + light body work because the considered weight of the box is 1 kg: the value of the picking activity is:

$$WR\ pick = standing + squatting + light\ body\ work =$$
$$= 36 + 42 + 226.5 = 304.5\ W \tag{4.30}$$

For the travelling activity it is considered only the walking energy expenditure because the activity of travelling involved low energy in comparison with the picking or storing task.

$$WR\ travelling\ task = energy\ for\ walking = 118\ W \qquad (4.31)$$

The MWR necessary for the storing task is the same vale of the MWR for picking evaluate in formula 4.30.

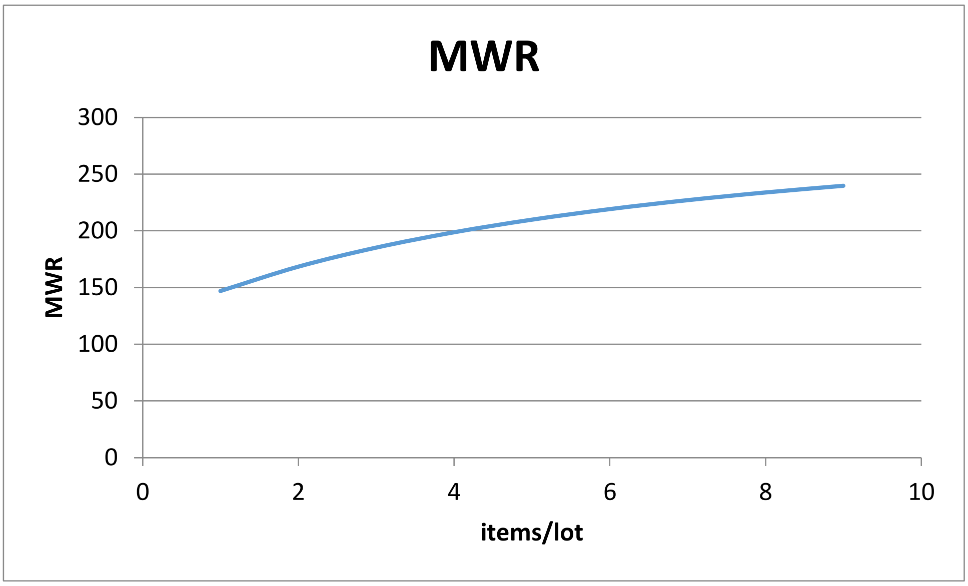


**Fig. 4.9**: MWR of Spitzer and Hettinger increasing the lot size

### 4.5.4 Pandolf model

Givoni and Goldman developed an empirical relationship for energy expenditure prediction as a function of speed, external load, body weight and grade of terrain (Givoni and Goldman, 1971). The relation was limited to speeds ranging from 0.7 to 2.5 m/s; therefore Pandolf et al. developed the following relationship for wider application (Pandolf and Goldman, 1976; Pimental and Pandolf, 1979):

$$WR = 1.5\ W + 2 * (W + L) * \left(\frac{L}{W}\right)^2 + n(W + L) * (1.5 * V^2 + 0.35 * V * G) \qquad (4.32)$$

Where:

$M$ = metabolic rate [W]

$W$ = subject weight [kg]

$L$ = External load [kg]

$n$ = terrain factor (1 for treadmill)

$V$ = velocity (m/s)

G = slope

This model is suited only to operations involving the horizontal transportation of load, but in this work different scenario involved every time only horizontal transportation because is the typical movement in a factory for an operator that has to move a trolley or a kart from a point A to point B. Otherwise, several test should be necessary to evaluate the correct oxygen consumption and the energy expenditure, but this represent only a unusual scenario, thus this work is focalized on the common activities involved in typical industry.

The above formula (4.32) was simplified by Price (1990) for small gradients by considering a standard worker of 70 kg and assuming that positive and negative gradients cancel each other out, thus eliminating two of the variables. The equation (4.32) become:

$$WR = 1.5 * 70 + 2 * (70 + L) * \left(\frac{L}{70}\right)^2 + n(70 + L) * (1.5 * V^2 + 0) \quad (4.33)$$

In this work the considered variables in the formula (4.33) are:

$L$ = 1 kg * items

$n$ = 0.9

$V$ = 0.8 m/s

$G$ = 1

This model considers the energy expenditure based on oxygen consumption, for the picking and storing and for travelling tasks. For travelling task the equation consider the lot, i.e. items travelled at each trip. As can be in Fig. 4.3 it has an exponential increase.

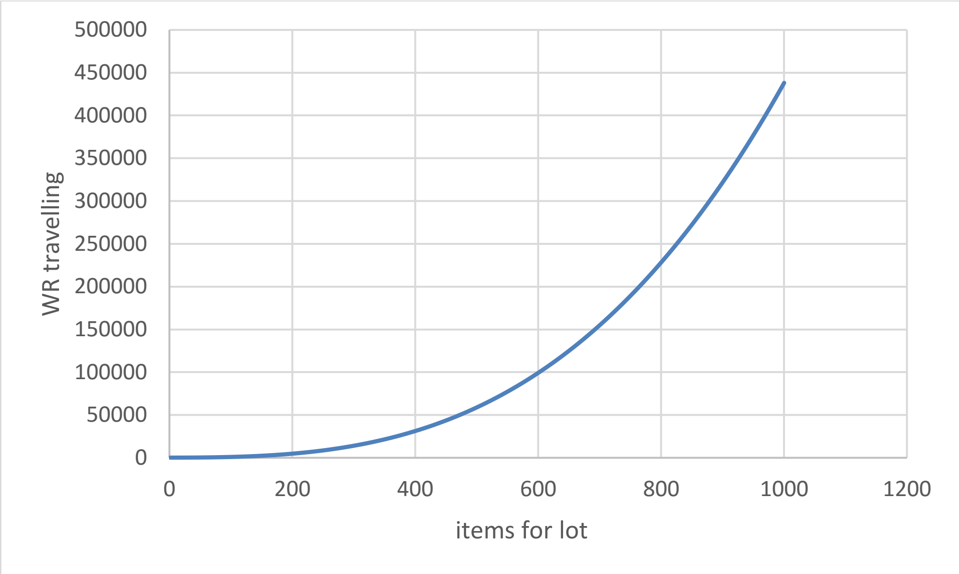


**Fig.4.10:** Work rate for travelling activity

For picking and storing activity the equation is the same of the travelling activity but in this formula the items travelled is always 1 kg because in each motion the operator pick one items each time. Thus the value of energy expenditure for picking and storing time is constant and equal to:

$$WR = 1.5 * 70 + 2 * (70 + 1) * \left(\frac{1}{70}\right)^2 + 1(70 + 1) * (1.5 * 0.8^2 + 0) = = 184.26\, W \quad (4.34)$$

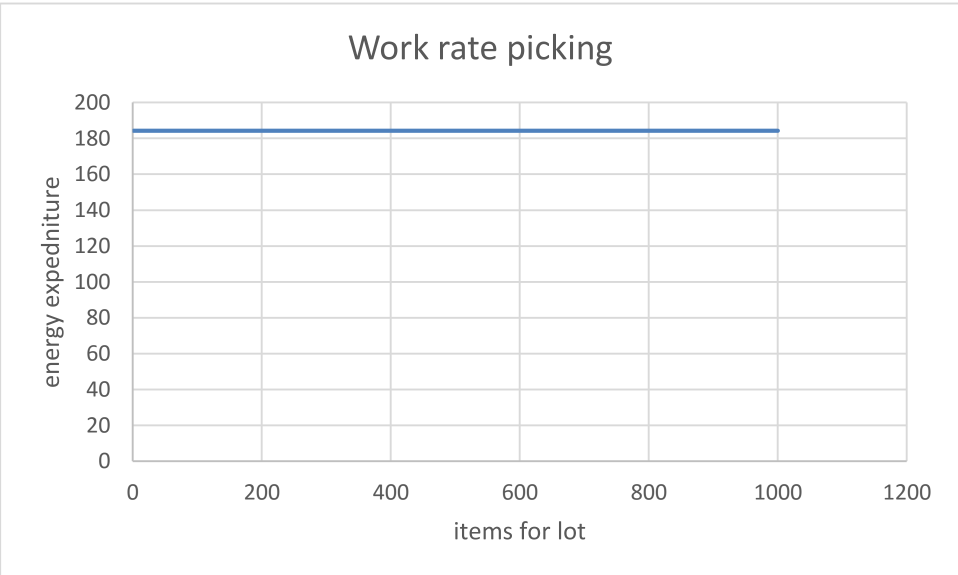


**Fig. 4.11:** Work rate for picking/storing activities

Fig 4.7 shows the constant value of the energy consumption in terms of W for picking and storing tasks.

The total energy expenditure is the sum of the picking and storing activities for the relative time necessary for the operation:

$$Energy\ expenditure = WR_{pick-stor} * (time\ of\ picking\ +\ storing) + \\ +WR_{trav} * (\ travelling\ time) \quad (4.35)$$

The mean work rate (MWR) is obtained through the formula:

$$MWR = \frac{energy\ expenditure}{total\ time} \quad (4.36)$$

And results present the following behavior:

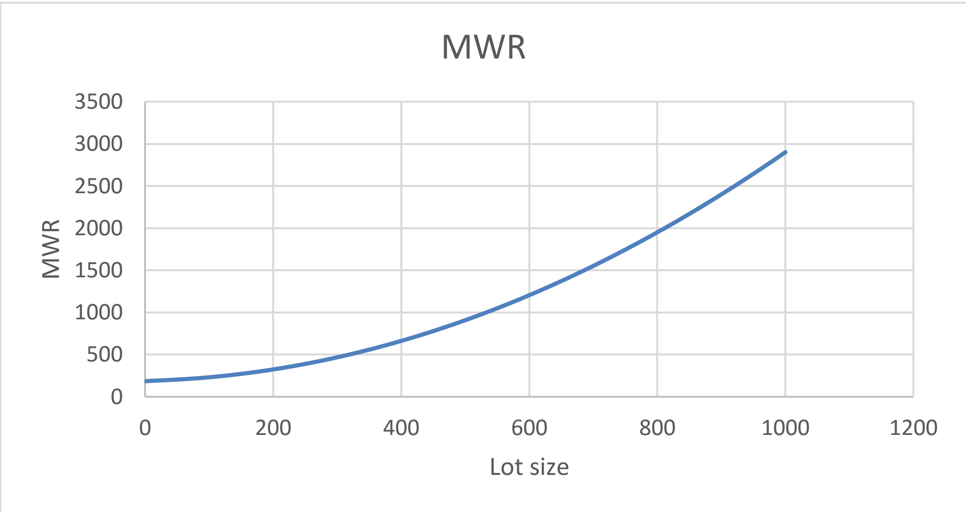


**Fig. 4.12:** Mean work rate (MWR) on the number of items for lot.

As can be seen in Fig.4.12, the mean work rate (MWR) shows a low exponential increase with the growth of the items for each single lot because the energy necessary for the travelling task depends on the total weight of the items travelled for each trip. For 1 item for trip the MWR is equal to 184.26 W. Then, while the energy expenditure for picking and storing remains constant, the energy consumption for travelling increase due to the increase of the weight of the trolley. Results founded will be used in the following part considering the RA necessary to recover energy.

### 4.5.5 Taboun & Dutta model

Another alternative model to evaluate the energy expenditure is the one introduced by Taboun & Dutta (1989). This method calculates the energy expenditure in terms of oxygen consumption, later converted in Watt and used in Price (1990) to calculate the rest allowance. Taboun and Dutta takes values from results obtained through the monitoring of an operator on a treadmill walking at 4 m/s with combined task of lifting and carrying objects of different weight in different frequencies. The operations considered are similar to the task analyzed in this work: in fact each subject picked up the required tote box from a shelf, stepped on a treadmill and carried it for the required distance, stepped out of the treadmill, replaced the box on the shelf and waited for the next command. For the data were selected five load levels (8, 13, 18, 23, 28 kg); the range of these loads is made because following reports by Drury et al. (1982) that indicated that 98% of the loads handled in industry are less than 28 kg. In the study of Taboun and Dutta (1989) five different work paces (1, 2, 3, 4, 5 handlings/min) were incorporated to take into account the effect of slow as well as rapid pace of work. These work pace are suitable with the tasks considered in this master thesis because Battini et al. (2015) considered a picking and storing time of 10 seconds and a travelling time of 125 seconds; if the lot size for each trip is equal to 1 items, the total time necessary is 145 seconds, thus 0.4 handling/min. If the operator brings 10 items for each trip, the total time necessary is:

$$Total\ time = T\ picking + T\ travelling + T\ storing =$$
$$= 10 * 10 + 125 + 10 * 10 = \quad 325\ s \tag{4.37}$$

So the handling is:

$$\frac{Handling}{min} = \frac{60}{325} = 0.18\ handling/min \tag{4.38}$$

A survey (Drury et al. 1982) shows that in the MMH about 99% of the carrying distance is less than 12 m. In the work of Taboun and Dutta five levels of carrying distances were considered (0, 3, 6, 9, 12 m) and four height ranges of lifting (0, 0-0.75, 0.75-1.5 and 0-1.5 m); values representative of the ambit of industry and because they require the use of different muscle groups (Mital and Akoblie, 1982).

Moreover the effect of box width had a significant increase on both oxygen uptake and hear rate for lifting tasks as reported by Asfour (1980) and Mital and Ayoub (1981). Five different box widths (15, 25, 35, 45, 55 cm) were considered. In this work the items transported are always the same and the weight is equal to 1 kg; then a reasonable width for the object is 20 cm (0.2 m).

The dependent variables monitored during the study were the work rate, ventilation rate and oxygen consumption, computed using Wier's method. The experiments were confined to males students engaged in part time: this sample is different from a normal sample formed by operator involved regularly in the industry. The effect of this contrast is the higher level of energy necessary for the task because part of the effort is consumed for positions and movements that only with several practice will be reduced.

The subject's height was between 1.60 and 1.8 m and the weight for the operator was considered between 65 and 90 kg, thus the 70 kg considered in this work is reasonable. Results were derived from several tests and were calculated in term of volume of oxygen intake (VO2) express in l/min and heart rate (HR) express in bpm (beats per minute). Taboun and Dutta (1989) developed a regression equation which follows the data collected by tests:

- for the load [kg]:

$$V_{O_2}\left(\frac{l}{\min}\right) = 0.6611 + 0.02711 * load \tag{4.39}$$

$$HR\ (bpm) = 86.0611 + 1.3439 * load \tag{4.40}$$

- for frequency of lifting (cylces /min):

$$V_{O_2}\left(\frac{l}{\min}\right) = 0.5053 + 0.2039 * frequency \tag{4.41}$$

$$HR(bpm) = 78.5081 + 10.0897 * frequency \tag{4.42}$$

- for carrying distance (m):

$$V_{O_2}\left(\frac{l}{\min}\right) = 0.8536 + 0.0445 * distance \tag{4.43}$$

$$HR\ (bpm) = 95.929 + 2.2224 * distance \tag{4.44}$$

**Table 4.5:** Variables present in the previous equations.

| dependent variable | regression equation | correlation coefficient |
|---|---|---|
| load (kg) | VO2 (l/min) = 0.6611+0.0277*load | r = 0.9926 |
| | HR (bpm) = 86.0611+1.3439*load | r = 0.9975 |
| frequency of lifting (cycles/min) | VO2 (l/min) = 0.5053+0.2039*frequency | r = 0.9945 |
| | HR (bpm) = 78.5081+10.0897*frequency | r = 0.9917 |
| carrying distance (m) | VO2 (l/min) = 0.8536+0.0445*distance | r = 0.9945 |
| | HR (bpm) = 95.929+2.2224*distance | r = 0.9906 |

Based on the following data:

**Table 4.6:** Variables present in the previous equations.

| Parameter | Value | Unit |
|---|---|---|
| body weight | 70 | Kg |
| Operator cost | 15 | €/h |
| weight item | 1 | kg |
| frequency | 1,2,3,4,5,6 | cycles/min (t pick = 10 s) |
| distance picking/storing | 5 | m |
| height range lift | 1.2 | m |
| width | 0.2 | m |

The following results shown in the Table can be evaluated:

**Table 4.7:** Variables present in the previous equations.

| dependent variables | VO2 (l/min) | HR (bpm) | frequency |
|---|---|---|---|
| load (kg) | 0.68821 | 87.405 | |
| frequency of lifting (cycles/ min) | 0.7092 | 85.66371524 | 1 (cycle/min) |
| | 0.9131 | 87.72100507 | 2 (cycles/min) |
| | 1.117 | 89.7782949 | 3 (cycles/min) |
| | 1.3209 | 91.83558473 | 4 (cycles/min) |
| | 1.5248 | 93.89287456 | 5 (cycles/min) |
| | 1.7287 | 95.95016439 | 6 (cycles/min) |
| Carrying distance (m) | 1.0761 | 107.041 | |
| ergonomic working conditions | 0.91 | 90.516 | |

A significant observation related to the oxygen consumption for combined tasks indicated that handling loads greater than 13 kg at the rate of 4 handlings/min (i.e. 15 seconds for the total operation) exceeded the recommended limit of 1 l/min of oxygen consumption for an eight hour work shift.

Similarly, handling loads weighing more than 13 kg over a height range of lift from the floor level to 150 cm exceeded that limit too.

As explained in Taboun and Dutta, all subjects indicated that tasks involving lifting from 75 cm up to 150 cm height level are more stressful as compared to tasks which involve lifting from the floor up to a height of 75 cm. These results could be related to the fact that lifting loads from 75 cm up to 150 cm height are pure arm lifting tasks; the arm strength is the limiting factor regardless of the nature of the tasks. Lifting loads from floor up to 75 cm involve the use of shoulder and back. As indicated in Taboun and Dutta the most stressful task is the combined carrying and lifting from floor to above the shoulder height (150cm). Therefore, to reduce the risk of injury, the carrying distance for such combined tasks should be reduce as much as possible.

The data gathered from the several tests conducted were used to develop models for combined manual material handlings. Using the proc-stepwise (stepwise regression procedure) of SAS software two models that satisfying the testing criteria were developed by Taboun and Dutta; then with the GLM procedure and the PLOT procedure, the final form of each model were tested.

#### 4.5.5.1 Taboun and Dutta (Model I)

The first model can be used to predict oxygen consumption for both individual carrying tasks and/or combined carrying and lifting tasks. This model is restricted to tasks that start from a height of 75 cm (0.75 m), height coherent with a normal table, to a height of 150 cm or less; this limit is due to the shoulder height. In fact the height limit of 150 cm is the shoulder height; if the operator pick or make any kind of movement upper to this limit, the effort and thus the oxygen consumption will be completely different and the energy consumption will increase significantly with the danger of the overcoming of the ergonomic working conditions.

The formula of the first model is the following:

$V_{O_2} = 0.1809 + [(BW + L) * (2.6112 * (BW + L) + 92.594 * D * H) + F * (318.16 * L + 7.9185 * BW * D + 49.1565 * L * D)] * 10^{-5} + 2.2956 * \frac{WID}{L}$ (4.45)

Where:

$V_{O_2}$= volume of oxygen consumption (l/min)
*BW* = body weight (kg)
*L* = load handled (kg)
*F* = frequency (handlings/min)
*D* = carrying distance for picking and storing task (m)
*H*= height range of lift (m)
*WID* = box width (m) along the sagital plane

### 4.5.5.2 Taboun and Dutta (Model II)

This model is applicable for combined lifting and carrying tasks where lifting starts from the floor to 150cm or less. The limit of the two models can be summarized in the following Table.

**Table 4.8:** The application limit of the two energy expenditure models of Taboun and Dutta.

| height | Starts | Ends |
|---|---|---|
| **Model I** | from 75 cm (table height) | to 150 cm or less |
| **Model II** | from 0 cm ( floor ) | to 150 cm or lesss |

The energy expenditure equation of second model can be written as following:

$V_{O_2} = 0.0738 + [(BW + L) * (3.9918 * (BW + L) + 61.226 * D * H) + L * F * (424.131 + 81.926 * D)] * 10^{-5} + 3.851 * \frac{WID}{L}$ (4.46)

Where:

$V_{O_2}$= volume of oxygen consumption (l/min)

*BW* = body weight (kg)

*L* = load handled (kg)

*F* = frequency (handlings/min)

*D* = carrying distance for picking and storing task (m)

*H* = height range of lift (m)

*WID* = box width (m) along the sagital plane

The frequency is calculated in terms of handlings/min; this represent the repetition of the activity at each trip. If the operator has to pick only one item, the frequency is 1 handling/min with 1000 repetition necessary for the total transportation; indeed, if the lot size to transfer is equal to 10 items/lot, and the picking time is constant and equal to 10 seconds, the operator makes 6 handling/min and the load time necessary is:

$$Total\ time = 10 * 10 = 100\ s \tag{4.47}$$

$$Frequency = 6 \frac{handlings}{min} \tag{4.48}$$

This represent the maximum frequency of the operator in this task and the same results are obtained for the storing task because the time involved is the same as hypothesis of Battini et al. (2015). This frequency is suitable with the values of handlings/min considered by Taboun and Dutta for their tests and from a lot of 6 items the handlings/min remain constant as shown in the following Table.

**Table 4.9:** Frequency (handlings/min) on items for lot.

| items/lot | total time(s) | Handlings/min |
|---|---|---|
| 1 | 10 | 1 |
| 2 | 20 | 2 |
| 3 | 30 | 3 |
| 4 | 40 | 4 |
| 5 | 50 | 5 |
| 6 | 60 | 6 |
| 7 | 70 | 6 |
| 8 | 80 | 6 |
| .. | .. | 6 |

As explained in the specification terms of the model, the term D takes account of the distance for picking and storing and the involved travelling distance but this distance is not the distance from point A to point B, but the only meters necessary for the operator to pick items from the production line and to place them on the trolley: this distance is much less than the common travelling distance considered in the previous models.

The height conditions of the first model are more suitable for this work, if the operator pick items form a transportation roller or a common table and put the items on the trolley always under the higher limit of the shoulder height (150 cm). But in the storing activity or refilling of supermarket, the operator pick the items from the trolley (floor height) and stores them on the table height, thus in this case the second mode will fit better.

In this model no account of the energy expenditure necessary for the travelling time in considered according to the method used by Battini et al.; this way is different from the other previous considered models but is it reasonable in the case of the use of an automatic trolley or when the energy necessary for the travelling can be considered much minor that the effort fort picking and storing.

The calculation of the total energy expenditure necessary for the total activity can be evaluated as following:

$$Total\ energy\ expenditure = energy\ (model\ I) * T_{pick} + energy * \\ * T_{travelling} + energy\ (model\ II) * T_{storing} \tag{4.49}$$

This equation can evaluate correctly the energy necessary summing different contributes:

- the picking task can be evaluated by the model I because of the height involved in the activity;
- the energy expenditure in the travelling task can be evaluated taking account of the effort make by operator in a standing position. This case is verified when the trolley is for example an electric vehicle where the operator stands in front; thus the energy necessary is the minimum and the only required to the standing positon. This represent the main modification to the model of Taboun and Dutta that developed a relationship limited only to the picking and storing activity.

- The storing task indeed, can be considered by model II because the height at which the operator pick the items to store them on the supermarket or the warehouse is the floor.

The weight of the items picked and stored is the same and equal to 1 kg.

As can be seen in the following Table 4.10 the energy necessary for picking and storing from 6 items for each lot is the same and remains constant till 1000 items for lot.

**Table 4.10:** The evaluation of the energy expenditure increasing the number of items for lot.

| Items / lot | N trip | picking model I | travelling | storing model II |
|---|---|---|---|---|
| 1 | 1000 | 1.199676 | 0.343 | 1.314387 |
| 2 | 500 | 1.23325 | 0.343 | 1.322725 |
| 3 | 333.3333 | 1.266825 | 0.343 | 1.331062 |
| 4 | 250 | 1.3004 | 0.343 | 1.3394 |
| 5 | 200 | 1.333974 | 0.343 | 1.347737 |
| 6 | 166.6667 | 1.367549 | 0.343 | 1.356075 |
| 7 | 142.8571 | 1.367549 | 0.343 | 1.356075 |
| 8 | 125 | 1.367549 | 0.343 | 1.356075 |
| 9 | 111.1111 | 1.367549 | 0.343 | 1.356075 |
| 10 | 100 | 1.367549 | 0.343 | 1.356075 |
| .. | .. | 1.367549 | 0.343 | 1.356075 |
| 1000 | 1 | 1.367549 | 0.343 | 1.356075 |

The evaluation of the MWR (mean work rate) necessary for each trip can be calculate as the previous models using the following equation:

$$MWR = \frac{total\ energy\ expediture}{total\ time} \tag{4.50}$$

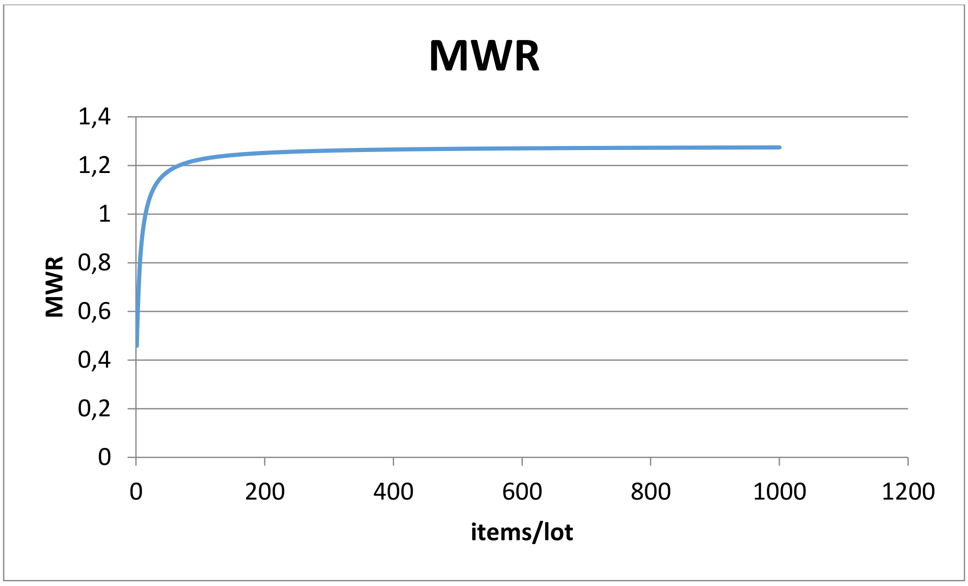


**Fig. 4.13**: MWR obtained with Taboun and Dutta method.

## 4.6 Rest allowance

Based on the Table (3.2) and (3.3) individuated in the first part of the thesis, the most suitable energy expenditure can be considered. When the production engineers or the ergonomists have calculated the energy expenditure in terms of VO2 or Watt, the RA has to be evaluated. However, otherwise the correlation between energy expenditure and the suitable RA model is necessary, often is not so immediate; without a solid relation between the two models, no account of the energy expenditure can be evaluated for the subsequent calculation of the total time and cost necessary. This is the reason why before only the last years, no account of the human well-being in manual material handling operations was considered by authors. In fact, authors developed solid models for the evaluation of the energy expenditure, but no correlation of time necessary was individuated, thus the calculations was not considered in the production processes.

Battini et al. (2015) is the first work that developed a direct correlation for the calculation of RA. In the subsequent part, other models are considered.

### 4.6.1 Price (1990)

Results show the linear increase of the RA necessary to recover energy for ergonomic working conditions, differing from Rohmert (1973) that has an exponential progression with the increasing of the items contained for each single lot.
After the individuation of the energy necessary for the task, a correlation between energy expenditure and rest allowance is necessary.
Price (1990) developed a simply method to evaluate the RA necessary to recover energy, using the following equation:

$$\text{Work} + \text{relaxation} = \text{acceptable work level} \tag{4.51}$$

The first term is:

$$\text{Work} = (\text{MWR})^{*}\ \text{Wt} \tag{4.52}$$

Where MWR is the value founded with the just explained method; Wt is the working time (picking + travelling + storing) necessary for the single lot.

The term relaxation is composed by the relaxation rate (RR) and the resting time (Rt): RR is a term considered by Price as the Watt necessary to the metabolic energy expenditure, when the operator doesn't work:

- Relaxation rate standing : 130 W
- Relaxation rate sitting : 105 W

The second term of the balancing energy formula is the acceptable work level (AWL): is the energy required to satisfied acceptable working conditions that granted work without risk of injuries derived by too much load for the operator. As explain in Price (1990), previous research has shown that over an 8 hour working day an acceptable work level is approximately equivalent to a third of the maximum oxygen intake rate (VO2) (Legg and Myles, 1981; Deivanayagam and Ayoub, 1979; Lehmann, 1958; Murrel, 1960 ; Muller and Franz, 1952). Research by Astrand (1980) indicated that for a variety of building operatives, the maximum oxygen intake ranged between 2.29 and 3.17 l/min (with an average of 2.73 l/min); thus an acceptable work level on 8 hour working day is :

$$AWL\ (l/\text{min}) = \frac{1}{3} * 2.73 = 0.91\ l/min \qquad (4.53)$$

This value will be used directly for the original method indicated by Aberg (1968), where the energy expenditure is calculated in l/min. But in the method used by Price (1990), a conversion in Watt is necessary.

This value is also the recommended limit (1 l/min) introduced by Taboun and Dutta (1989) for the oxygen consumption for an eight hour shift.

One liter of oxygen consumed per minute is equivalent to 350 W; therefore the acceptable work level over an 8 h day is:

$$AWL\ (W) = 0.91 * 350 \approx 300\ W \qquad (4.54)$$

The formula of the balance between work + relaxation and the acceptable work level can be re-writed as:

$$MWR * Wt + RR * Rt = AWL * (Wt + Rt) \qquad (4.55)$$

But AWL= 300 W, thus substituting in the (4.55)

$$MWR * Wt + RR * Rt = 300 * (Wt + Rt) \qquad (4.56)$$

The relaxation allowance (RA) considered by Price (1990) is the fraction between the resting time (Rt) necessary to recover energy to allow acceptable working conditions and the working time (Wt):

$$RA = \frac{Rt}{Wt} (* 100\%) \qquad (4.57)$$

Thus:

$$Rt = Wt * RA \qquad (4.58)$$

Substituting Rt in (4.56) the equation become:

$$MWR * Wt + RR * (Wt * RA) = 300 * \big(\ Wt + (Wt * RA)\big) \qquad (4.59)$$

$$RA * (Wt * RR - 300 * Wt) = 300 * Wt - MWR * Wt \qquad (4.60)$$

Simplifying the Wt term:

$$RA * (RR - 300) = 300 - MWR \tag{4.61}$$

Thus the final formula for the rest allowance necessary to recover energy is:

$$RA = \frac{MWR - 300}{300 - RR} \tag{4.62}$$

In this work RR is considered equivalent to 130 W, the metabolic energy expenditure for a standing worker.

## 4.7 Results

In this section results of the RA founded form the previous model are explained and discussed.

### 4.7.1 Battini et al. (2015)

Battini et al. developed the evaluation of the RA using values founded from several tests, adapted to the specific scenario analyzed.

As can be seen in Fig.4.14 the behavior of the RA shows a low exponential trend increasing the number of items for lot according whit Rohmert model

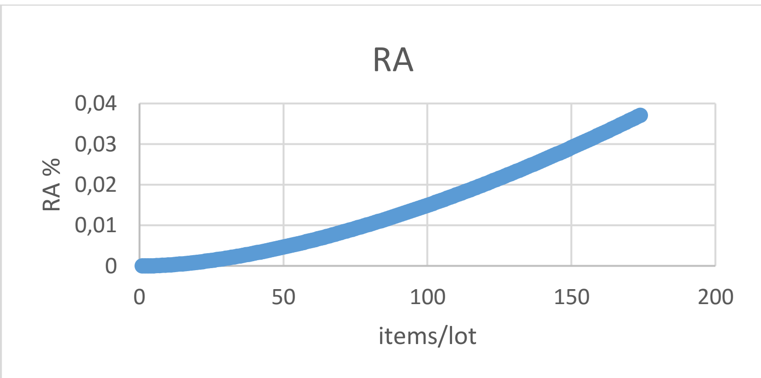


**Fig. 4.14:** The trend of the RA increasing the number of items for lot

Values of RA are present in the following Table.4.11

**Table 4.11:** Values of RA

| **Items/lot** | **RA** |
|---|---|
| 1 | 1.38E-06 |
| 25 | 0.0013797 |
| 50 | 0.0046473 |
| 75 | 0.0092329 |
| 100 | 0.0149166 |

As can be seen the results are limited for low items/ lot (max 100 items) different with the scenario analyzed in this work that collect data for 1000 items and thus the possibility of 1000 items / lot ( 1 trip for the whole items).

The total cost using this trip can be simply evaluated considering the hour cost of the operator:

- Hour cost of operator : 25 € / h

Using the following formula:

$$Total\ cost = Total\ time * (number\ of\ trips) * Hour\ cost\ operator \quad (4.63)$$

Results are explained in the following Fig.

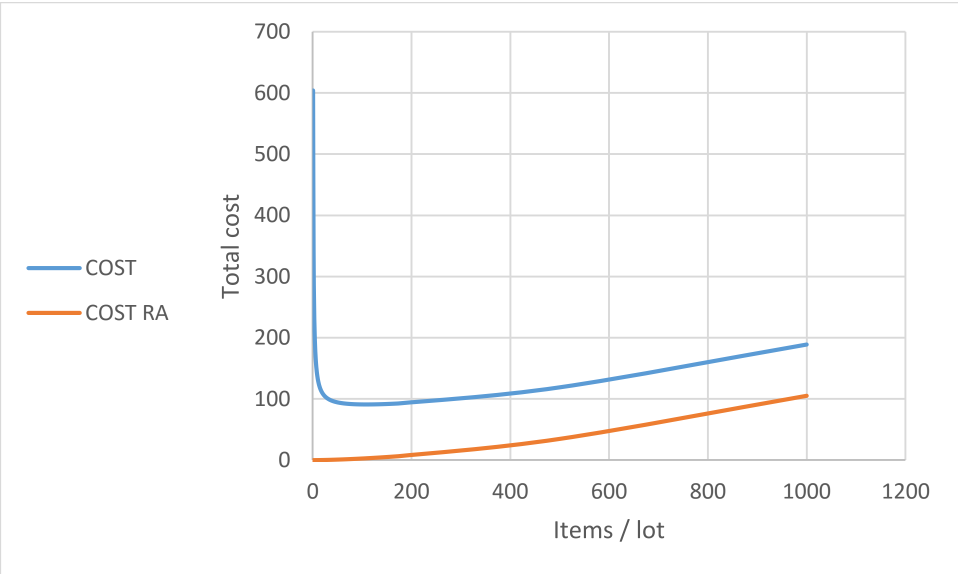


**Fig. 4.15:** The trend of the total cost of the whole transportation and the RA profile.

As can be seen in Fig.4.15, the maximum cost is reached when the lot size in the minimum: 1 items for lot. The consequence of this lot size is the necessity of the

maximum trip (1000 trips); thus the total time involved to transfer from point A to point B all the products in the maximum.
The minimum cost can be reached through the excel formula of searching the minimum value of cost:
With Battini et al. the minimum cost reached is:

$$Minimum\ COST\ (q) = 91.14\ € \tag{4.64}$$

This value match with the following value of items for single lot:

$$Optimal\ lot\ size : 108\ items/lot \tag{4.65}$$

The closed formula for q optimal can be written as:

$$q^* = \sqrt[r_{ps2-1}]{\frac{d/s}{t_{ps}*r_{ps1}*\alpha*w^{r_{ps2}}}} = 108 \text{ items/ lot} \tag{4.66}$$

giving the same results of the values found with the excel optimization: this demonstrates that the both formula and method to find the optimal ergo lot size are correct.

## 4.7.2 Price 1990

In the following section the calculation of the RA using the MWR previous evaluate is developed considering the different methods and subsequently evaluating the result founded.

### 4.7.2.1 Aberg (W)

After the evaluation of the MWR (mean work rate) in terms of Watt, Price (1990) developed a method for the calculation of the RA necessary for acceptable working conditions using the following relationship:

$$RA = \frac{MWR-AWL}{AWL-RR} \tag{4.67}$$

Where: AWL is the acceptable work level, typical 300 Watt, and RR is the relaxation rate, the energy required for the only basic metabolism and posture (standing sitting, ..)

Results are shows in the following Table and Figures.

**Table 4.12:** RA increasing the lot size for each trip.

| Items/lot | N trip | RA (%) | Items/lot | N trip | RA (%) |
|---|---|---|---|---|---|
| 1 | 1000 | 1.672 | 200 | 5 | 5.694 |
| 25 | 40 | 4.027 | 500 | 2 | 7.737 |
| 50 | 20 | 4.458 | 750 | 2 | 9.407 |
| 100 | 10 | 4.946 | 1000 | 1 | 11.07 |

As it can be seen, increasing the numbers of items for lot, the RA required for an acceptable working level increases, with a linear trend shown in the following Fig. 4.8, different Rohmert that increases exponentially.

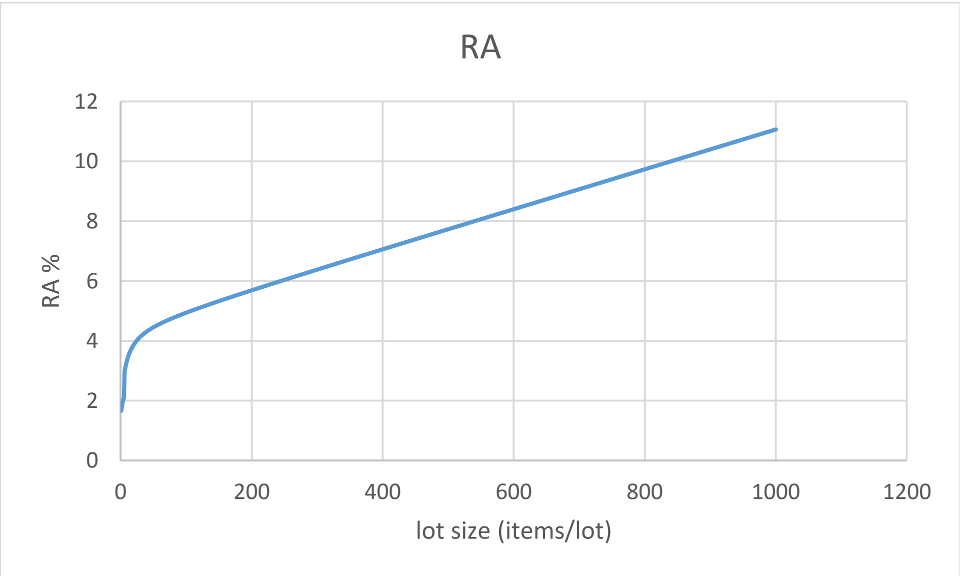


**Fig. 4.16:** The trend of RA increasing the number of items for each trip.

Using the previous formula, the evaluation of the RA in terms of time required to maintain an acceptable work level can be calculated by summing this value in the picking travelling and storing time. The behavior of the total time increasing the number of items/lot can is shown in the following Fig. 4.19

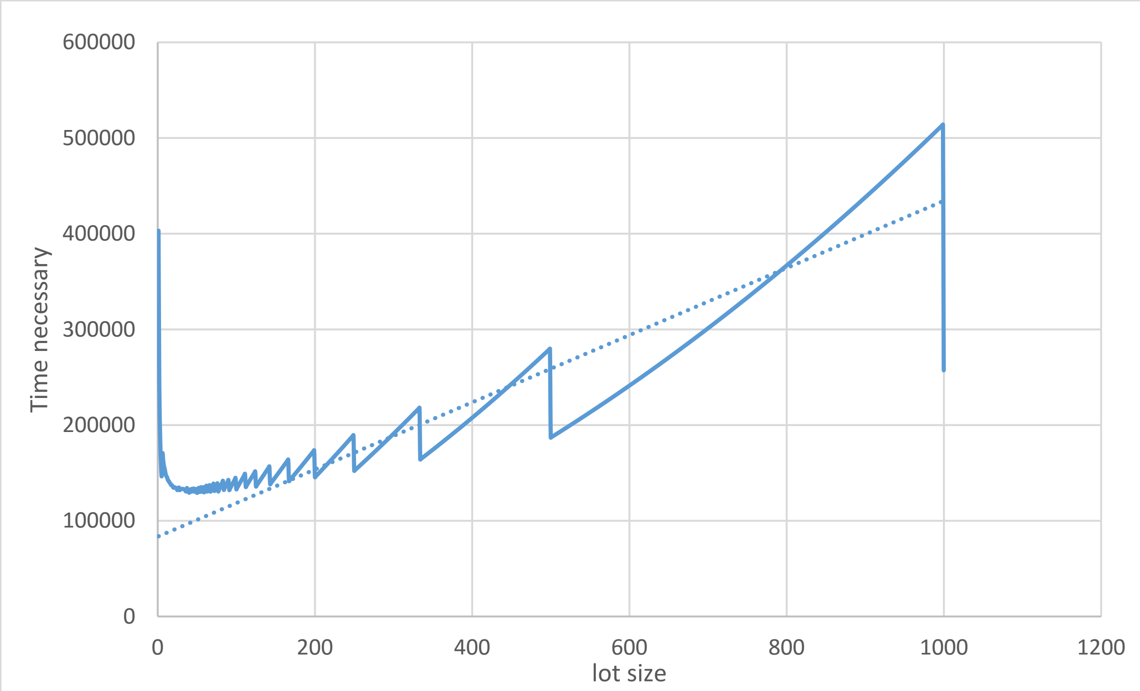


**Fig. 4.17:** The behavior of time on the lot size.

From the total time necessary for the operation the total cost can be evaluated with the cost of operator equal in this work to 25 €/h:

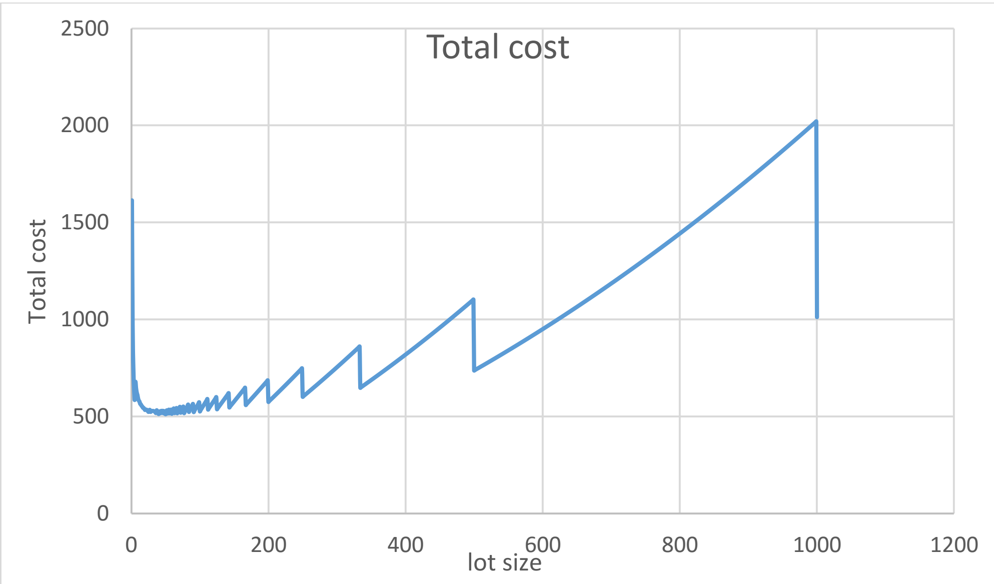


**Fig. 4.18:** The total cost on the items / lot.

This segmentation shown in Fig.4.10 is derived by the necessity of taking the close next superior value for the trip as shown in the following Table 4.13

**Table 4.13:** The approximation to the close superior value

| items/lot | N trip | N int sup |
|---|---|---|
| 1 | 1000 | 1000 |
| 2 | 500 | 500 |
| 3 | 333.333333 | 334 |
| 4 | 250 | 250 |
| 5 | 200 | 200 |
| 6 | 166.666667 | 167 |
| 7 | 142.857143 | 143 |
| 8 | 125 | 125 |
| 9 | 111.111111 | 112 |
| 10 | 100 | 100 |
| 11 | 90.9090909 | 91 |
| 12 | 83.3333333 | 84 |
| 13 | 76.9230769 | 77 |
| 14 | 71.4285714 | 72 |
| 15 | 66.6666667 | 67 |
| 16 | 62.5 | 63 |
| 17 | 58.8235294 | 59 |
| 18 | 55.5555556 | 56 |
| 19 | 52.6315789 | 53 |
| 20 | 50 | 50 |

The minimum cost is reached for 50 items/lot and is equal to 511.72 €:

$$Minimum\ cost = 511.72\ € \tag{4.68}$$

$$Optimal\ lot\ size = 50\,\frac{items}{lot} \tag{4.69}$$

#### 4.7.2.2 Aberg alternative (VO2)

Price (1990) derived the evaluation of the energy expenditure in terms of Watt, from the original method of Aberg in terms of Volume of oxygen consumption.

In this work is has been considered also the evaluation of energy expenditure in terms of VO2 for the calculation of the correct RA necessary to recover energy, implementing more models possible from the list of the suitable.

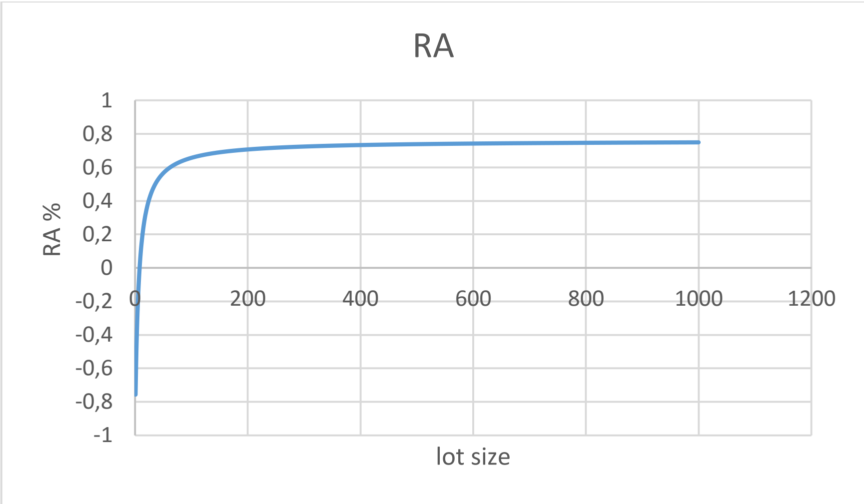


**Fig. 4.19:** Rest allowance with Aberg (VO2): the behavior increasing the lot size.

In the Fig.4.19 the negative value of RA is caused by the surplus of energy of the operator at the end of the task because the effort necessary for the activity is in the acceptable working conditions; increasing the lot size, more fatigue is spent and the RA increases surpassing the limit of zero when the operator need no rest allowance fot recovery time.

The optimal lot size obtained through the implementation of this method is 76 items/lot as shown in the following Fig. 4.20

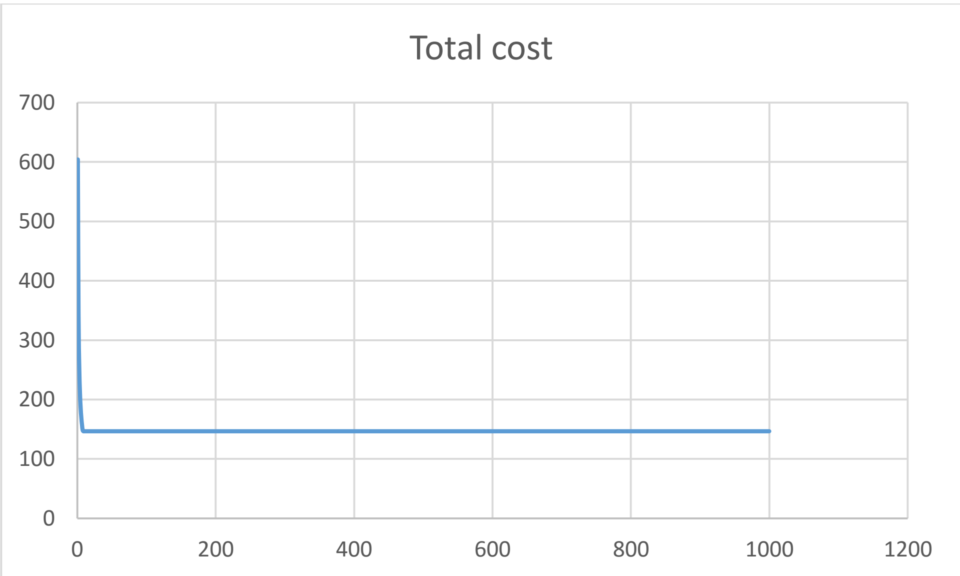


**Fig. 4.20:** Total cost with Aberg (VO2) method: the graphic evaluation of the ergonomic lo size.

In this scenario the minimum lot size, is reached for 76 items:

$$Minimum\ cost = 146.72\ € \quad (4.70)$$

$$Optimal\ lot\ size = 76\,\frac{items}{lot} \quad (4.71)$$

### 4.7.2.3 Spitzer

The second evaluated model considers different parameters. From the previous evaluation of the energy expenditure and using the selected formula, the RA shows the behavior in Fig. 4.10

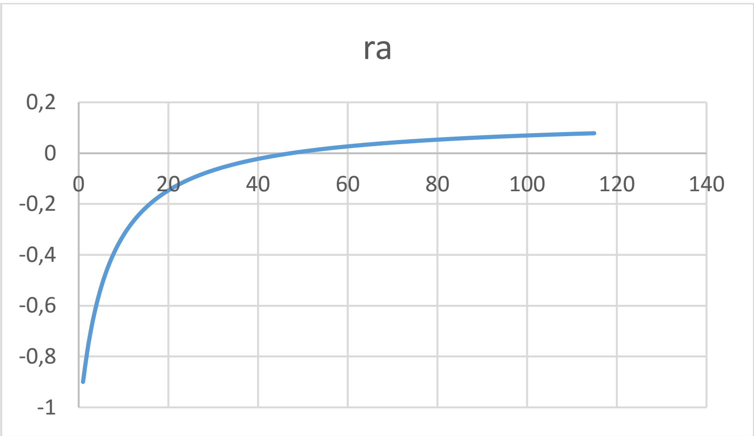


**Fig. 4.21:** The behavior of the RA increasing the number of items / lot.

In the following table results can be appreciated allowing to identify the optimal lot size equal to 50 items/lot.

**Table 4.14 :** The approximation to the close superior value

| items/lot | RA (%) | Total cost | Total time |
|---|---|---|---|
| 1 | 0 | 145000 | 604.16 |
| 10 | 0 | 32500 | 135.416667 |
| 20 | 0 | 26250 | 109.375 |
| 30 | 0 | 24650 | 102.708333 |
| 40 | 0 | 23125 | 96.3541667 |
| 50 | 0.00594771 | 22633.8235 | 94.307598 |

| | | | |
|---|---|---|---|
| 60 | 0.02618202 | 23114.75 | 96.3114583 |
| 80 | 0.0525746 | 23603.9853 | 98.3499387 |
| 100 | 0.06903114 | 22716.9118 | 94.653799 |
| 200 | 0.10344029 | 22758.4559 | 94.8268995 |
| 500 | 0.1251053 | 22783.3824 | 94.9307598 |
| 1000 | 0.13250639 | 22791.6912 | 94.9653799 |

The previous table give the results of RA%, total time necessary for the whole operations and the total cost: as it can be seen the optimal lot size is 50 items/lot, value that ensure the minimum cost of the transportation task.

$$Minimum\ cost = 94.31\ € \quad (4.72)$$

$$Optimal\ lot\ size = 50\,\frac{items}{lot} \quad (4.73)$$

In the following Fig. result are shown in the graph allowing to appreciate the trend and the behavior of the total cost with Spitzer method.

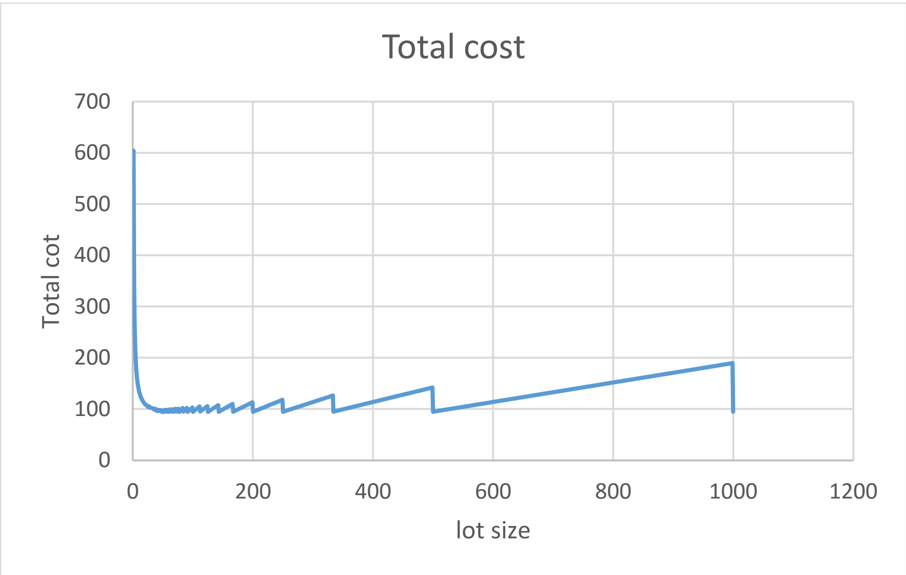


**Fig. 4.22:** The optimal cost on the items /lot implementing Spitzer model.

#### 4.7.2.4 Pandolf

The third method considered by Price (1990) is the Pandolf model. Using the same relationship for the calculation of the RA, the following results are founded and shown in the following table:

**Table 4.15**: The RA (%), total time and cost increasing of the lot size.

| Lot size (items/lot) | RA (%) | Total time | Total cost |
|---|---|---|---|
| 1 | 0 | 14500 | 604.16 |
| 20 | 0 | 26250 | 109.375 |
| 40 | 0 | 23125 | 96.35417 |
| 60 | 0.830002 | 41220.8 | 171.7534 |
| 80 | 2.142569 | 70472.11 | 293.6338 |
| 100 | 4.050574 | 107324.7 | 447.1862 |
| 200 | 26.55578 | 568338 | 2368.075 |
| 500 | 344.7317 | 7001066 | 29171.11 |
| 1000 | 2574.905 | 51840084 | 216000.3 |

From results, for few items/lot the RA gives a negative values that are converted to zero in the Table 4.15: this is due to the quantity of effort that for few items doesn't require any kind of relaxation rate because the ergonomic working conditions are still maintained. Increasing the number of items for each lot the RA necessary increase with an exponential trend as shown in the following Fig. and the first value for which the RA gives a positive % is for 41 items/lot.

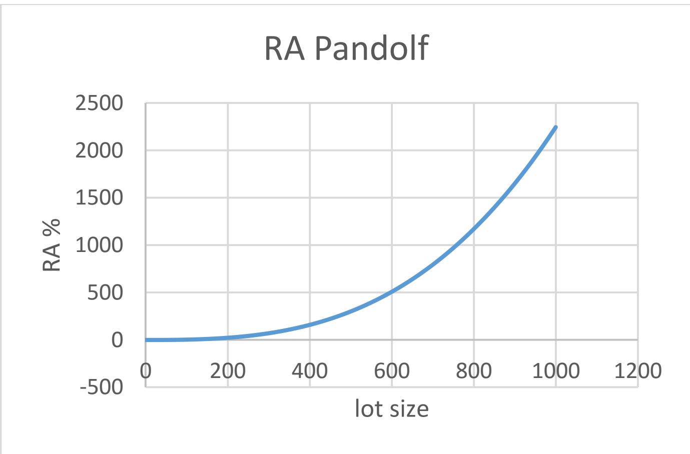


**Fig. 4.23:** Rest allowance increasing the lot size using Pandolf method.

Thus, the total time and the total cost can be evaluated using the same formula that take account of the hour cost of operator and the total time necessary for the whole transportation.

It is important to remember that the number of trips are approximated for the next close upper value.

Result of the total time and cost are shown in the following Fig. 4.24 and Fig.4.25.

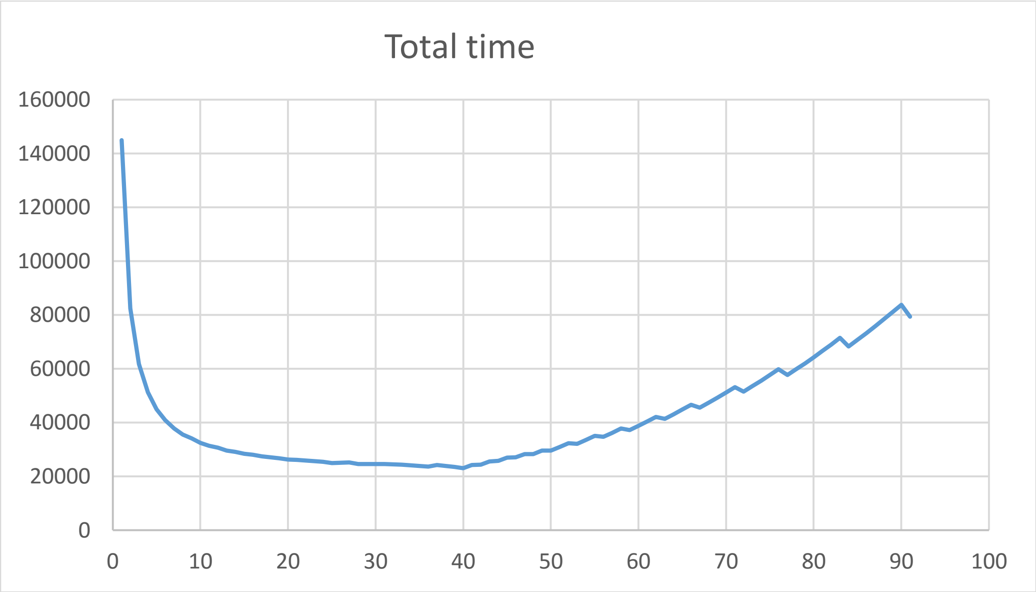


**Fig. 4.24:** The optimal time on the items / lot can with Pandolf method.

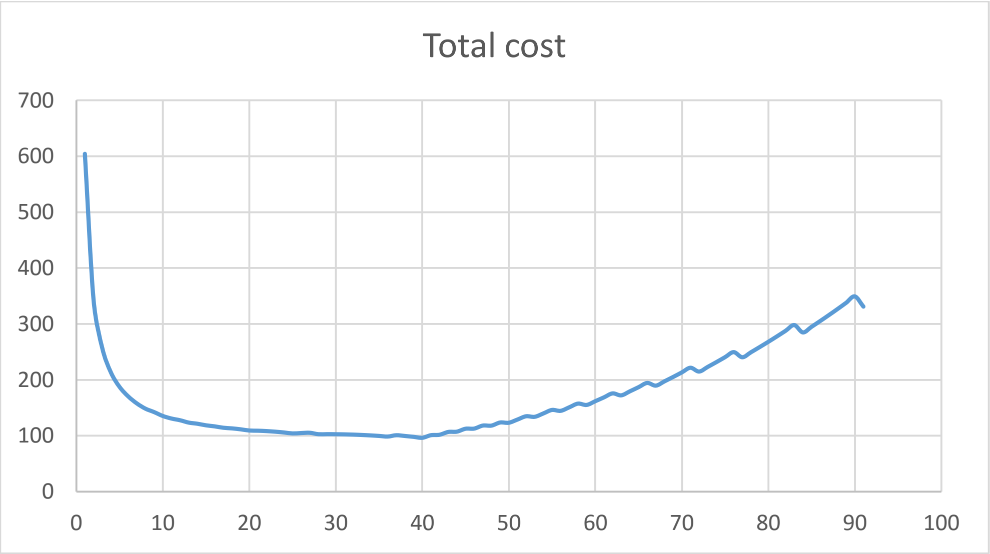


**Fig 4.25:** The trend of the total cost increasing the lot size with Pandolf method.

Using the minimization of the total cost the minimum cost of the whole operation can be evaluated:

$$minimum\ cost = 96.35\ € \tag{4.74}$$

This value allows to individuate the optimal lot size:

$$Optimal\ lot\ size = 40\ items/lot \tag{4.75}$$

### 4.7.2.5Taboun and Dutta

The last model used to individuate the correct lot size which allows optimal ergonomic working condition is the method of Taboun and Dutta.
As can be seen in the following Fig.4.26, from 1 to 7 items/lot, the % of RA remains constant and equal to 0 because the effort made by the operator is less than the acceptable limit for the ergonomic working conditions. Then a rapid increase and then a low increase growing the number of items/lot because the time necessary for the picking and storing tasks remains equal and in this model the effort depends on the frequency of activity.

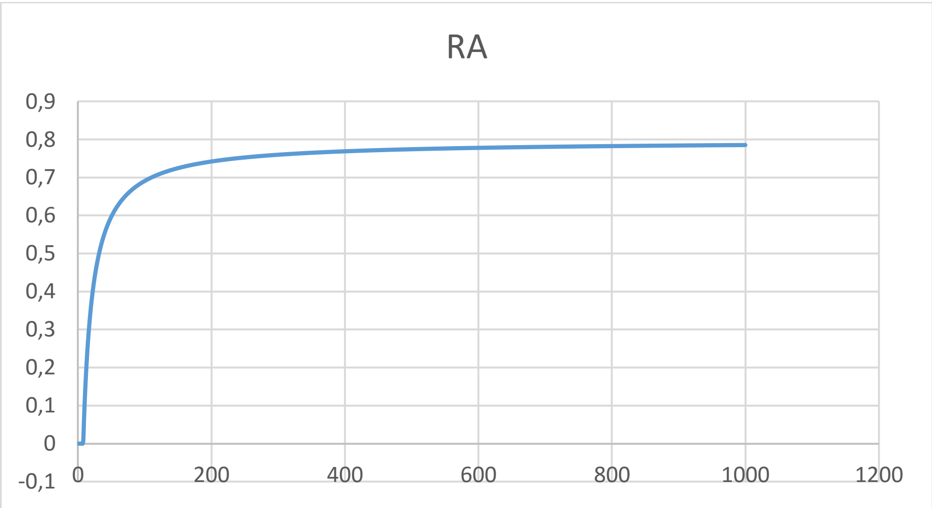


**Fig 4.26:** The trend of RA (%) increasing the lot size with Taboun and Dutta method.

As form the other models, the total time and the total cost are evaluated to search the optimal ergo-lot-size.

**Table 4.16**: Values of RA, total time and total cost with the lot size.

| Lot size (items/lot) | RA (%) | Total time | Total cost |
|---|---|---|---|
| 1 | 0 | 145000 | 604.1667 |
| 20 | 0.258600682 | 33038.27 | 137.6594 |
| 40 | 0.428681855 | 33038.27 | 137.6594 |
| 60 | 0.496072509 | 33699.03 | 140.4126 |
| 80 | 0.532209526 | 34359.8 | 143.1658 |
| 100 | 0.554742019 | 33038.27 | 137.6594 |
| 200 | 0.601855413 | 33038.27 | 137.6594 |
| 500 | 0.631519403 | 33038.27 | 137.6594 |
| 1000 | 0.641653063 | 33038.27 | 137.6594 |

Using the minimization of the total cost the minimum cost of the whole operation can be evaluated as shown in previous table:

$$minimum\ cost = 137.66\ € \tag{4.76}$$

This value allows to individuate the optimal lot size:

$$Optimal\ lot\ size = 100\ items/lot \tag{4.77}$$

Results of the total time and total cost of the activity are shown in the following Fig.4.27.

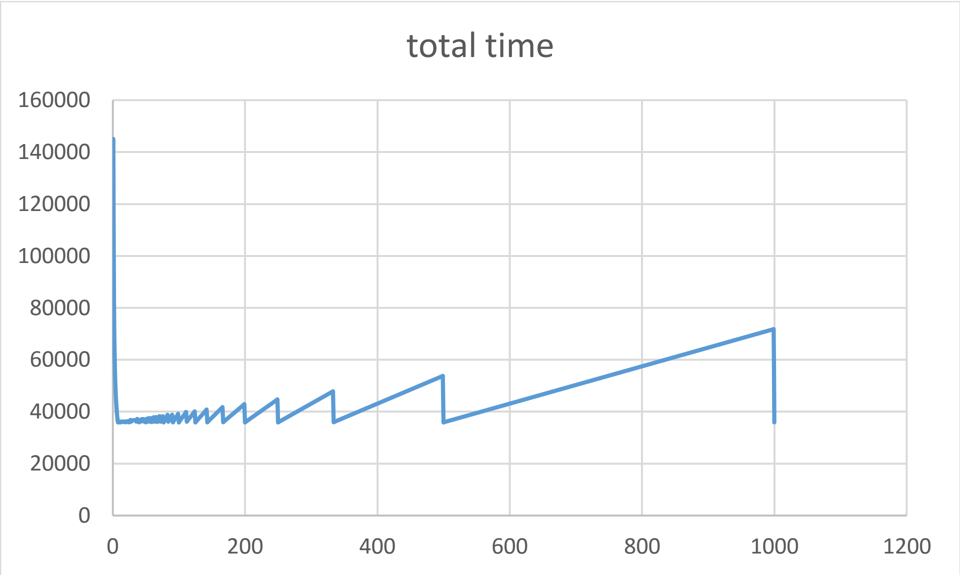


**Fig 4.27:** The trend of the total time increasing the lot size

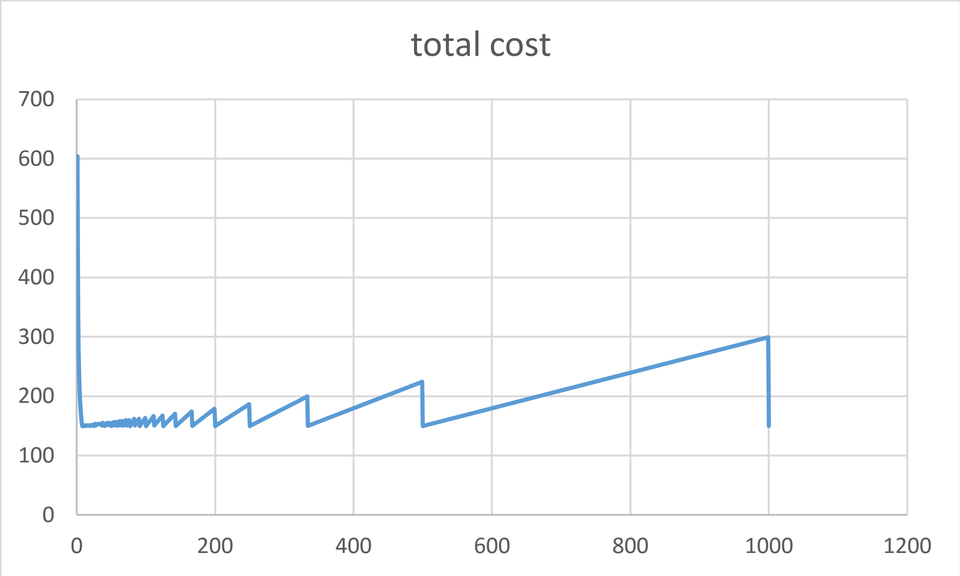


**Fig 4.28:** The trend of the total cost increasing the lot size using Taboun and Dutta method.

## 4.8 Comparison

Results founded in the previous sections are summarized and compared with values of Battini et al. (2015). The discussion is conducted only for the rest allowance, leaving unchanged the results of speed and availability.

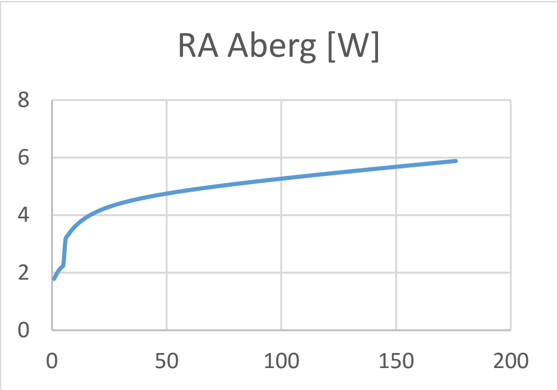


**Fig. 4.29a**: RA of Aberg in terms of Watt

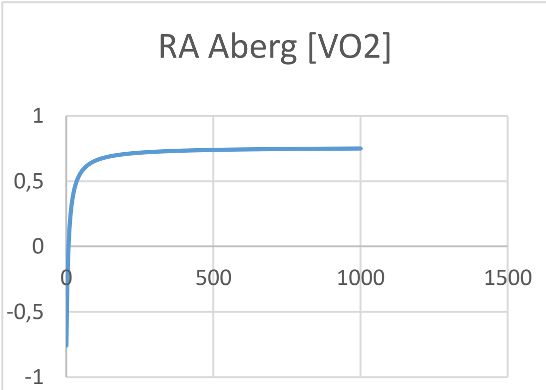


**Fig. 4.29b**: RA of Aberg in terms of oxygen

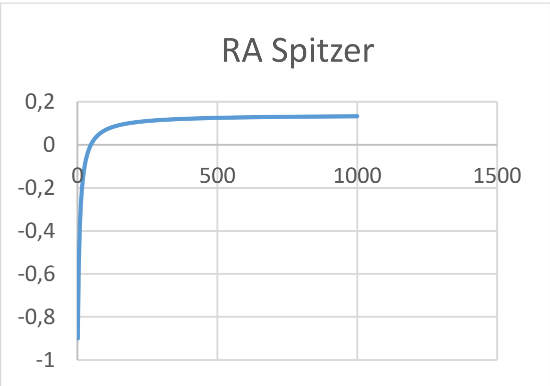


**Fig. 4.30a**: RA of Spitzer in terms of Watt

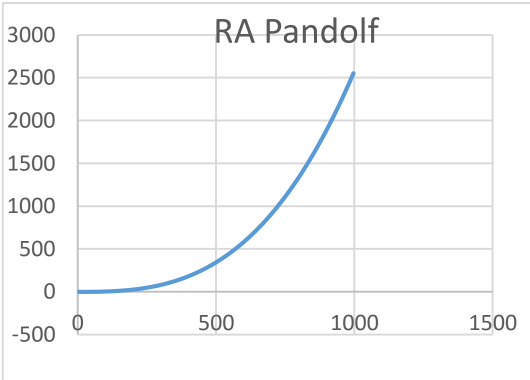


**Fig. 4.30b**: RA of Pandolf in terms of Watt

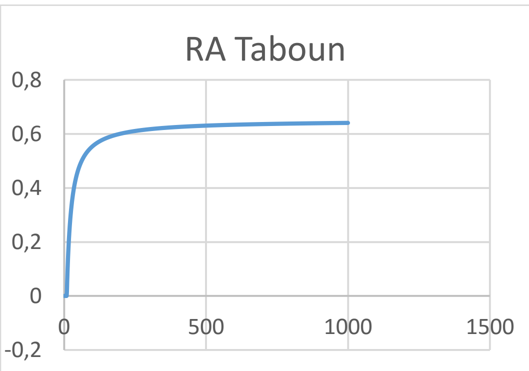


**Fig. 4.31a**: RA of Taboun in terms of oxygen consumption

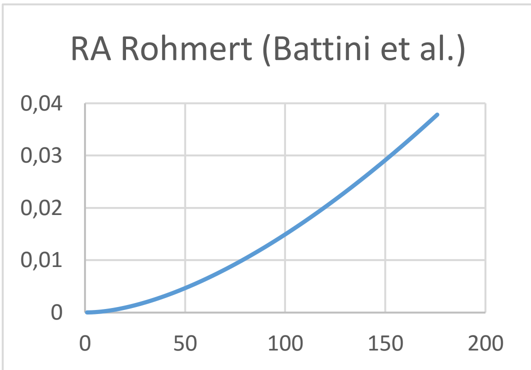


**Fig. 4.31b**: RA of Battini et al.

As it can be seen all the models implemented show a higher or lower increase with the growth of the lot size: this confirms the validity of results, because increasing the effort spent for the picking activity without resting time to recover energy, the % of RA to ensure ergonomic working conditions increases as shown in the results of the all considered models.

In the following table, the presented models are summarized and catalogued for the total cost and the optimal lot size. All the models give results similar to the values found by Battini et al. (2015); this confirmed the validity of this master thesis and the possibilities for the production engineers to consider the other models for the calculation of the total cost taking account of the energy expenditure.

**Table 4.17:** Summarization of results

| Model | Total cost (€) | optimal ergo lot size |
|---|---|---|
| Battini | 91.14 | 108 |
| Aberg [W] | 538.77 | 50 |
| Aberg [VO2] | 146.71 | 76 |
| Spitzer | 93.3 | 50 |
| Pandolf | 96.35 | 40 |
| Taboun and Dutta | 137.66 | 100 |

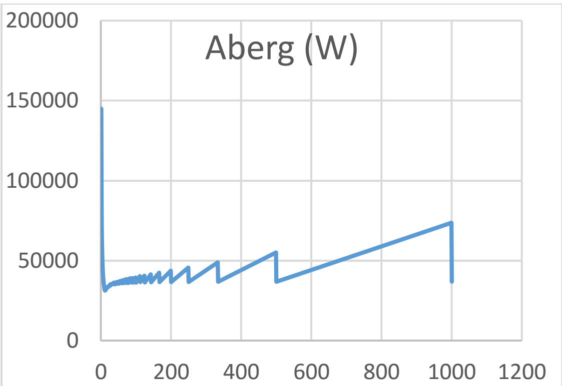


**Fig. 4.32a**: Total cost with Aberg model (W)

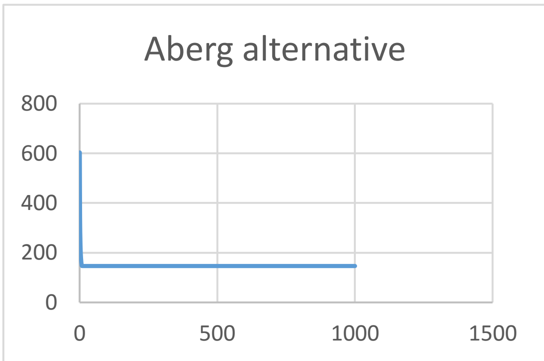


**Fig. 4.32b**: Total cost with Aberg model (VO2)

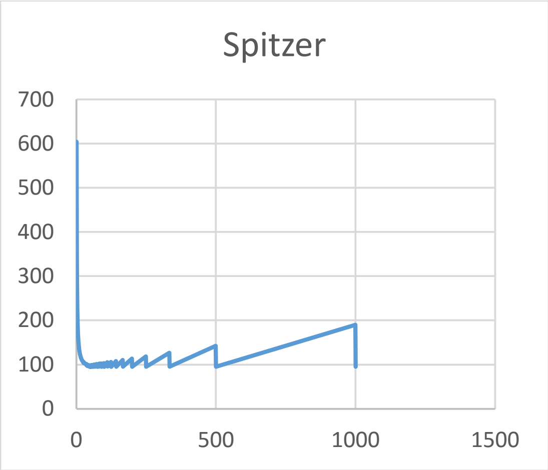


**Fig. 4.33a**: Total cost with Spitzer model (W)

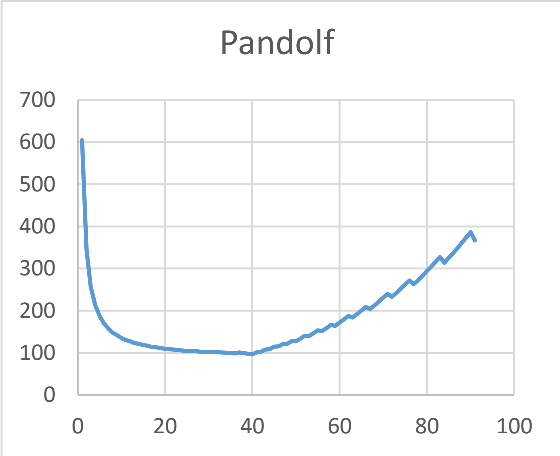


**Fig. 4.33b**: Total cost with Pandolf model (VO2)

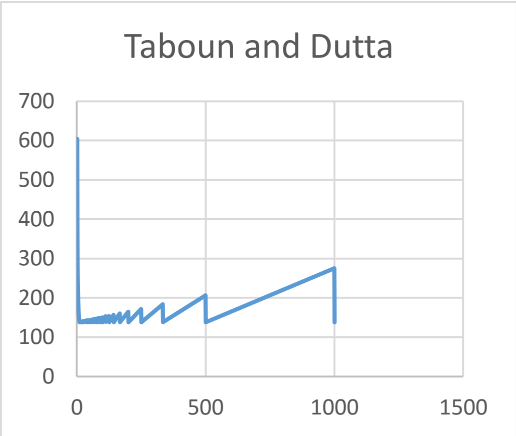


**Fig. 4.34a**: Total cost with Taboun model (VO2)

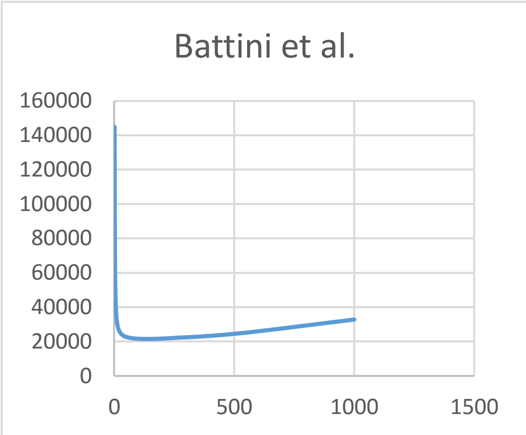


**Fig. 4.34b**: Total cost with Battini model

# Chapter 5
# Conclusion

As can be seen in Fig , all the models selected and implemented in this master thesis show the increment of the energy necessary for the activity on the increasing of the lot size: this is caused by the increase of the energy expenditure in the picking and storing time without pauses, evaluated in terms of oxygen consumption/min and Watt/min. Making a comparison with the acceptable work level, when the energy expenditure overpass this value, RA become positive and influences the total time necessary for the operation; this results allows to evaluate the correct lot size taking account of the ergonomics aspects ensure an acceptable work level.

These results are correct with the basic work of Battini et al. which this thesis refers to, appreciating the validity of the values founded with different models with differents parameters.

The different behavior of the Fig is caused by different parameters used in the formula. As can be seen from this work, the most suitable method is the model derived by Taboun and Dutta thanks to the dependents variables as load, carrying distance and frequency of lifting is the most adaptable to different situations possible in the MMH. In fact this method, different form the others, is the only one that includes the role of the frequency of handling, the first and the most critical task variable in MMH activities.

To reduce the risk of injury, the carrying distance for such combined tasks should be reduced as much as possible.

Simply modifications of the value in the formula can be conducted by the industrial engineer to adapt the explained formula to the specific scenario analyzed.

## 5.1 Future work

This master thesis allows to extend the results for different scenarios specific for the analyzed MMH. Using the formula developed in the previous analisy other studies can be conducted for different cases modifying the distance of travelling, consider in this work equal to 50 meters, or the picking and storing distance (5 m); also the time for picking and travelling can be modified evaluating its influence in the contest and the evaluation of the RA necessary to recover energy, the frequency of handling and the different tasks involved. The use of the pallet truck can be modified as in this thesis where in the first scenario is has been used a manual pallet truck and in the second an electric powered pallet truck reducing the effort for the travelling activity.

Moreover, because of this new method for the evaluation of the total time necessary for the operation, a lot of alternative can be found, increasing also the number of scientific publication about the role of ergonomics in lot sizing decisions.

# Bibliography


Aberg, U., Elgstrand, K., Magnus, P., & Lindholm, A. (1968). Analysis of components and prediction of energy expenditure in manual task. *The International Journal of Production Research*, *6*(3), 189-196.

Andriolo, A., Battini, M., Persona, A., & Sgarbossa, F. (2012). A new integrated procedure towards a sustainable inventory management

Andriolo. (2013). Ergonomic lot sizing: a new integrated prodcedure towards a sustainable inventory management.

Arslan, M., & Turkay, M. (2013). EOQ revisited with sustainability considerations. *Foundations of Computing and Decision Sciences*, *38*(4), 223-249.

Battini, D., Faccio, M., Persona, A., Sgarbossa, F. (2011). New methodological framework to improve productivity and ergonomics in assembly system design. *International Journal of Industrial Ergonomics*, *41*(1), 30-42.

Battini, D., Glock, C. H., Grosse, E. H., Persona, A., & Sgarbossa, F. (2015a). Ergo-Lot-Sizing: Considering Ergonomics in Lot-Sizing Decisions (No. 73333). Darmstadt Technical University, Department of Business Administration, Economics and Law, Institute for Business Studies (BWL).

Battini, D., Delorme, X., Dolgui, A., Persona, A., & Sgarbossa, F. (2015b): Ergonomics in assembly line balancing based on energy expenditure: a multi-objective model, International Journal of Production Research, DOI: 10.1080/00207543.2015.1074299

Battini, D., Calzavara, M., Persona, A., Sgarbossa, F. (2015). Linking human availability and ergonomics parameters in order-picking systems. *IFAC-PapersOnLine*, *48*(3), 345-350.

Bernard, B.P., (1997).Musculoskeletal disorders and workplace factors: a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity and low back. Public, pp. 97–141 (Cincinnati, DHHS (NIOSH)).

Booth-Jones A., P. Sestito J., Alterman T., Harrison R. (2004) Carpal tunnel syndrome (CTS). In: Chapter 2: Fatal and nonfatal injuries, and selected illnesses and conditions. In: Worker health chartbook 2004. NIOSH publication no. 2004-146. Washington, D.C. Available from: http://www.cdc.gov/niosh/docs/2004-146/ch2/ch2-6-1.asp.htm

Bouchery, Y., Ghaffari, A., Jemai, Z., & Dallery, Y. (2012). Including sustainability criteria into New models. *European Journal of Operational Research*, *222*(2), 229-240.

Chaffin, D. B., Andersson, G., & Martin, B. J. (1999). *Occupational biomechanics* (pp. 91-130). New York: Wiley.

Christmansson, M., Falck, A. C., Amprazis, J., Forsman, M., Rasmusson, L., & Kadefors, R. (2000). Modified method time measurements for ergonomic planning of production systems in the manufacturing industry. *International Journal of Production Research*, *38*(17), 4051-4059.

De Looze, M. P., Van Rhijn, J. W., Van Deursen, J., Tuinzaad, G. H., & Reijneveld, C. N. (2003). A participatory and integrative approach to improve productivity and ergonomics in assembly. *Production Planning & Control*, *14*(2), 174-181.

De Looze, M. P., Vink, P., Koningsveld, E. A., Kuijt-Evers, L., & Van Rhijn, G. J. (2010). Cost-effectiveness of ergonomic interventions in production. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *20*(4), 316-323.

Deinvanayagam, S. and Ayoub, M.M. (1979). Prediction of endurance time for alternating workloads tasks, *Ergonomics 22*, 279-290.

Drury, C.G., Law, C. and Pawenski , C.S., (1982) . *A survey of industrial box handling. Human Factors, 24 (5): 553-565.*

Eksioglu, M. (2011). Endurance time of grip-force as a function of grip-span, posture and anthropometric variables. *International Journal of Industrial Ergonomics*, *41*(5), 401-409.

El ahrache, K., Imbeau, D., Farbos, B., 2006. Percentile values for determining maximum endurance times for static muscular work. International Journal of Industrial Ergonomics 36, 99–108.

Garg, A., Mital, A., Asfour, S.S. (1980) A comparison of isometric strength and dynamic m lifting capability, Ergonomics, 23:1, 13-27, DOI: 10.1080/00140138008924714

Givoni, B., & Goldman, R. F. (1971). Predicting metabolic energy cost. *Journal of Applied Physiology*, *30*(3), 429-433.

Glock, C. H., Grosse, E. H., & Ries, J. M. (2014). The lot sizing problem: A tertiary study. *International Journal of Production Economics*, *155*, 39-51.

Grandjean E. (1981). Fitting the task to the Man: An ergonomic approach. *Taylor and Francis*

Grosse, E. H., Glock, C. H., Jaber, M. Y., & Neumann, W. P. (2014). Incorporating human factors in order picking planning models: framework and research opportunities. *International Journal of Production Research*, (ahead-of-print), 1-23.

Hagberg, M., Silverstein, B., Wells, R., Smith, M. J., Hendrick, H. W., Carayon, P., & Pérusse, M. (1995). Work related musculoskeletal disorders (WMSDs): A reference book for prevention. London: Taylor & Francis.

Harris, F. W. (1913). How many parts to make at once.

HSE, 2005. Self-reported Work-related Illness in 2004/05. Tech. rep., *Health, Safety and Executive.* http://www.hse.gov.uk/statistics/swi/tables/0405/ulnind1.htm.

Imbeau, D., & Farbos, B. (2006). Percentile values for determining maximum endurance times for static muscular work. *International Journal of Industrial Ergonomics*, *36*(2), 99-108.

Imbeau, D. (2009). Comparison of rest allowance models for: static muscular work. *International Journal of Industrial Ergonomics*, *39*(1), 73-80.

ISO, 2000 International Organization for Standardization (ISO), 2000. Ergonomics – Evaluation of Static Working Postures – ISO11226, Geneva.

Legg, S.J. and Myles, W.S. (1981). Maximum acceptable lifting workloads for an 8 hour work-day using psychophysical and subjective rating methods. *Ergonomics, 24(12),* 907-916.

Lehman, G. (1958).). Pysiological measurement as a basis of work organization in industry, *Ergonomics*, *1*, 328-344.

Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: a practical method analysis. *Applied ergonomics*, *8*(4), 199-201.

Khalid. (2008). Comparison of rest allowance models for static muscular work.

Kumar, S. (1994). A conceptual model of oxerexertion, safety, and risk of injury in occupational model settings. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *36*(2), 197-209.

Ma, L., Chablat, D., Bennis, F., & Zhang, W. (2009). A new simple dynamic muscle fatigue model and its validation. *International Journal of Industrial Ergonomics*, *39*(1), 211-220.

MacLeod, D. (2006). The ergonomics kit for general. CRC Press.

Marimon. (2013). EOQ Model: The Case in Which the Placing of Orders Is rewarded.

Milner 1985

Mital, A. Ayoub M.M. (1981). Effect of task variables and their interactions in lifting and lowering loads. Amer. Ind. Hyg. Assoc. J, 42 (2): 134-142.

Mital, A. and Okoblie, S.T. (1982). Influence of container shape, partitions, frequency, distance and height level on the maximum acceptable amount of liquid carried by males. Amer. Ind. Hyg. Assoc, J., 43 (11) 813-819.

Murrell, E.A. and Franz, M. (1952). The physiological basis of rest pauses in heavy work. *Arbeitsphysiologie,14*, 499.

Murrell, K.F.H. (1960). The nature and measurement of industrial fatigue. *Work study and Indust Engn*, *December,* 424-426.

Oxenburgh, M., Marlow, P., & Oxenburgh, A. (2004). Increasing productivity and profit through health & safety: The financial returns from a safe working environment. Boca Raton, FL: CRC Press.

Pandolf, K. B., Givoni, B., & Goldman, R. F. (1976). Predicting energy expenditure with loads while standing or walking very slowly (No. USARIEM-M-3/77). *Army research inst of environmental medicine Natick ma*

Pandolf, K. B., Pimental, N. A., (1979). Energy expenditure while standing or walking slowly uphill or downhill with loads. *Ergonomics*, *22*(8), 963-973.

Page, E., (1964). Determining fatigue allowances. *Industrial Management*, *14*, 1-3.

Pereira Da Silva, M., Amaral, F. G., Mandagara, H., & Leso, B. H. (2014). Difficulties in quantifying financial losses that could be reduced by ergonomic solutions. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *24*(4), 415-427.

Price, A. D. (1990). Calculating relaxation allowances for construction operatives—Part 1: Metabolic cost. *Applied ergonomics*, *21*(4), 311-317.

Punnett, L., & Wegman, D. H. (2004). Work-related musculoskeletal disorders: the epidemiologic evidence and the debate. *Journal of Electromyography and Kinesiology*, *14*(1), 13-23.

Rentschler, D. (1988). *Assembly line balancing utilizing fatigue constraints and task grouping* (Doctoral dissertation, Texas Tech University).

Rodgers, S.H., 2004. Muscle fatigue assessment: functional job analysis technique. *Handbook of Human Factors and Ergonomics Methods*. CRC Press, pp.12.1–12.10.

Rohmert, W. (1973). Problems of determination of rest allowances Part 2: Determining rest allowances in different human tasks. *Applied Ergonomics*, *4*(3), 158-162.

Safety and Health Assessment and Research for Prevention (SHARP), 2005. Worker related musculoskeletal disorders of the neck, back, and upper extremity in Washington State, 1995-2003. *Washington State Department of Labor and Industries. Tech. rep.*

Santosa, M. S., Vidal, M. C. R., & Moreira, S. B. (2012). The RFad Method–a new fatigue recovery time assessment for industrial activities. *Work*, *41*, 1656-1663.212± 220

Sato, H., Ohashi, J., Iwanaga, K., Yoshitake, R., & Shimada, K. (1984). Endurance time and fatigue in static contractions. *Journal of human ergology*, *13*(2), 147-154.

Schneider, E., Irastorza, X. (2010). OSH in figures: work-related musculoskeletal disorders in the EU—facts and figures. *European Agency for Safety and Health at Work*.

Seth, V., Weston, R. L., & Freivalds, A. (1999). Development of a cumulative trauma disorder risk assessment model for the upper extremities. *International Journal of Industrial Ergonomics*, *23*(4), 281-291

Shingo S., (1981). Study of Toyota Production System from Industrial engineering viewpoint, Japan Management Association.

Sperling, L., Dahlan, S., Kilbom, Å. and Kadefors, R., (1993). A cube model for the classification of work with hand tools and the formulation of functional requirements. *Applied Ergonomics*, **24**, 212± 220

Spitzer, H., & Hettinger, T. (1964). Tafeln fur den Kalorienumsatz bei korperlicher Arbeit. *Verband fur Arbeitsstudien REFA EV Darmstadt*.

Taboun, S. M., & Dutta, S. P. (1989). Energy cost models for combined lifting and carrying tasks. *International Journal of Industrial Ergonomics*, *4*(1), 1-17

Theis, K. A., Helmick, C. G., & Hootman, J. M. (2007). Arthritis burden and impact are greater among US women than men: intervention opportunities.*Journal of Women's Health*, *16*(4), 441-453.

Vink, P., Miedema, M., Koningsveld, E., & van der Molen, H. (2002). Physical effects of new devices for bricklayers. *International journal of occupational safety and ergonomics*, *8*(1), 71-82.

White, C.M. (2015). Proactive Ergonomics: Stopping Injuries Before They Occur. *Professional Safety*, *60*(06), 69-73.

Wu, H.-C., Wang, M.-J. J. 2002, Relationship between maximum acceptable work time and physical workload, *Ergonomics*, **45**, 280-289.