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FOUNDATIONS FOR ECONOMIC EVALUATION OF EXOSKELETONS IN MANUFACTURING

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Abstract: *In order to remain competitive, the manufacturing companies should improve continuously their processes as the core of their value-adding activities. Manual assembly workplaces in production, having workers as the most important resource for creating value-added are particularly affected by manipulation of heavy loads, vibrations and hazardous operations. These workplaces are coping with challenges as decreasing employment rate, high fluctuation, and increasing illness rate. The processes at manual assembly workplaces can be optimized by employing wearable robotics – Exoskeletons - in order to support the workers physically and cognitive. This paper presents a literature review of economic evaluation methods of technical support systems, as a base for the development of an innovative method to evaluate the economic impact of exoskeletons in manufacturing.*
Key words: *Exoskeleton, Manufacturing, Economic evaluation*

1. INTRODUCTION

Globally, costs are rising sharply combined with increasing cost pressure, especially in the case of manufacturing companies. This development is particularly strong to observe in high-wage countries [1].

Manipulators are usually based on a standard mechanical design and are generally different to clamping tools. Their main objective and function is to assist workers in lifting. In most cases, this does not reduce the forces exerted by the worker in horizontal load movement. Even the daily movement of loads between 5 and 35 kg with a corresponding number of lifting operations leads to health risks for the worker. The field of Exoskeleton application is broad and ranges from military applications to rehabilitation. The type of application has a direct influence on the functions that these support systems contain. While the aim in the military field is to increase the body's own strength, the main task in the rehabilitative field is to enable movements that no longer function. In the industrial sector, the focus is on the prevention of potential physical limitations and damage [2].

In general, according to ISO 11226, for safety and ergonomic reasons, frequent manual material handling can be carried out if the component moved or the material is less than 3 kg [3].

Workers are key enablers of flexibility and productivity in Europe’s industry, especially in manufacturing processes where full automation is not feasible due to small lot sizes, large product variety, and layout constraints. Such workplaces are often characterized by manual manipulation of heavy loads, hazardous conditions as well as high level of vibrations. Tasks taking place in these workplaces require increased cognitive efforts in order to maintain sustained levels of vigilance, leading to higher levels of mental fatigue, which in turn have a negative impact on both workers and workplaces, and contribute to jobs being lost or relocated outside Europe, therefore affecting European manufacturing as a whole. 26% of all lost work days in Germany are caused by musuloskeletal disorders (MSD) [1].

At European manufacturing level, these issues have led to extra cost (e.g. total annual cost of MSD in excess of 240 billion euro, or circa 2% of GDP of the European economy) and contribute to the 3.5 million manufacturing jobs lost between 2008 and 2014 [4].

Looze et al. (2016) describes an exoskeleton as "…a wearable, external mechanical structure that enhances the power of a person. Exoskeletons can be classified as 'active' or 'passive'.

An active exoskeleton comprises one or more actuators that augments the human's power and helps in actuating the human joints. …A strictly passive system does not use any type of actuator, but rather uses materials, springs or dampers with the ability to store energy harvested by human motion and to use this as required to support a posture or a motion" [5].

If workplaces cannot be ergonomically optimised due to physical conditions, the exoskeleton can help to establish a balance by stabilising certain body regions and reducing the amount of force required.

An objective evaluation is indispensable for the integration of exoskeletons at workplaces. The influence of exoskeletons on the production system (new capabilities, flexibility with a large variety of products through intuitive operability, etc.), but especially the ergonomic influences [6, 7, 8] due to the exoskeletons are besides the optimized integration and design of workplace of great importance.

The use of exoskeletons can have positive side effects within the workplace environment, such as increased productivity and efficiency. For example, increased productivity can already be seen in various subtasks, as working with the exoskeleton is more intuitive and faster than working with a more expensive mobile lifting assistance system [9].

The introduction of new technologies like exoskeletons that have product character are subject to the corresponding risks due to their novelty.

Not only the uncertainty regarding the benefit to be achieved and possible costs of an investment, but also the time dimension plays an important role here.

The time of investment in a new technology is therefore of decisive importance. The early gathering of experience and the resulting competitive advantages speak for the reduction of risks of failure against an early investment in new technologies.

This paper shows the state of the art with regard to the economic evaluation of exoskeletons usage in industry.

The second chapter gives reasons for an evaluation. In addition, various monetary and non-monetary evaluation measures are explained.

The third chapter lists criteria and shows a first rough method for the economic evaluation of employing exoskeletons in manufacturing industries.

2. METHODS FOR ECONOMIC EVALUATION: OVERVIEW

Evaluation usually refers to the assessment and appraisal of projects, processes and functional units (e.g. of devices, objects) as well as organizational units. Context, structure, process, effort and result can be adressed, as well. In general, evaluation can be understood as a fundamental examination of whether and to what extent something appears suitable to fulfil a desired purpose.

In linguistic usage, evaluation, investigation and analysis are also equally important in the sense of an inventory without special purpose orientation [10].

Overall, economic evaluation involves placing a certain value on things, in this case different investment opportunities. The economic evaluation motivates the decision-maker to overthink the investment and to do a possible re-allocation of the resources.

Analysis and evaluation methods are usually used to examine and evaluate solution variants. The aim of the analysis and evaluation is to find a suitable solution with regard to the key performance indicators used (Figure 1).

In the following chapter the necessity of evaluation tools is stated out. In paragraphs 2.2 and 2.3, common methods from the state of the art are presented. These approaches are classified according to their monetary and non-monetary analysis and valuation targets.

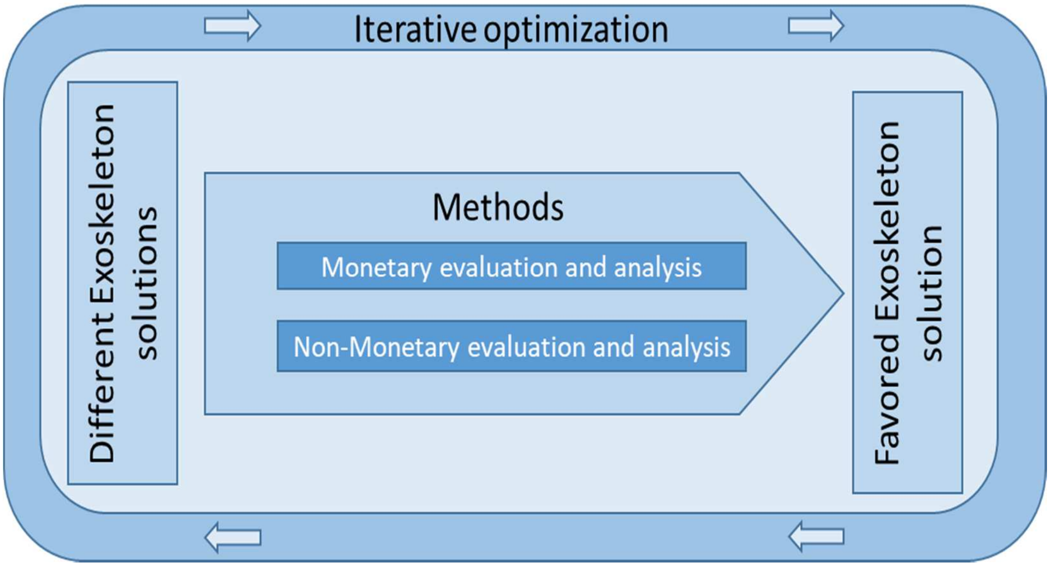

Fig 1. Classification of methods and procedures for analysis and evaluation. Representation on the basis of [11].

2.1 Uncertainty in decision making

This paragraph briefly presents the basics and the necessity for an evaluation process.
A distinction should be made between different types of information in the decision-making process.

The difference between the decision under certainty and the decision under uncertainty lies in how future conditions can be predicted.

For decisions under security, the decision-maker has sufficient information to be able to predict future conditions (e.g. environment, technology, costs, etc.) with certainty. In reality, however, this is the rarer case. In most cases, exact conditions cannot be predicted and in this case, it is a decision under uncertainty [12].

Uncertainty in business decision theory means risk, incertitude and unknowingness (Figure 2). The risk is the product of the probability of occurrence and the severity of the event for future events that are known or estimable.

The effects of these events can be both negative and positive. In the event of incertitude, the possible characteristics of the future are known, but there are no concrete probabilities. Even if the conditions cannot be opened up, it is a matter of unknowingness [13].

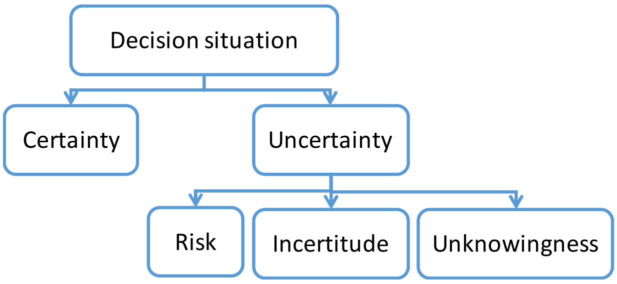

Fig 2 Types of information in the decision situation [12].

2.2 Monetary analysis and evaluation

Investment calculation methods are used to assess the advantages of an investment project from the point of view of making a profit and thus to determine the profitability of the investment. Investment calculations are carried out to support a choice between alternatives.

With this method, the profitability of an investment and an assessment of the investment risk can be assessed and thus the achievement of objectives can be verified [14].

Investment calculation methods are in this work divided into two categories: static and dynamic. The static methods relevant in the context of this work are above all the amortization calculation, the profitability calculation and the determination of the Return of Invest (ROI) in several variations. Static procedures are characterized above all by hiding the time reference, i.e. it is not differentiated when an investment is made and to which period statements refer [15].

In the dynamic investment calculation methods, the temporal effects are taken into account in the form of interest rates and compounded interest. Well-known methods are the net-present-value method, the internal-interest-rate method and the amortization calculation [16, 17].

Following figure shows several static and dynamic investment calculation methods. A method of each type is briefly described.

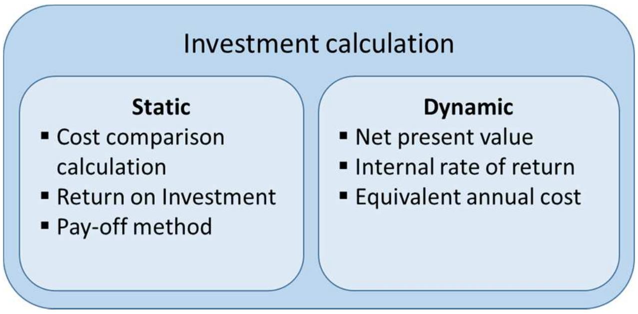

Fig 3. Classification of the investment calculation methods [11].

Return on Investment (RoI)

The Return on Investment (RoI) calculation compares the average annual profit (before deduction of imputed interest) with the average capital employed. Compared to the cost and profit comparison, the profitability calculation has the advantage that very different investment projects can be assessed. RoI is a business management indicator for measuring the return on an entrepreneurial activity, measured by profit in relation to capital employed [18]. Overall, the RoI shows how much value a company gets from their spending decision.

Net present value (NPV)

The most common method for profitability analyses of production plants is the dynamic Net present value (NPV) analysis. For this purpose, the entire period from the investment decision through commissioning to the end of the operating time of a production plant is considered. The net present value method is based on the cash flows for the investment, i.e. all income minus all expenses, in for each period of the period under review. The four pillars of cash flows are investment costs, sales and fixed and variable operating costs. In the case of fixed operating costs, it should be noted that depreciation is not included in fixed costs in the dynamic net present value analysis because it is already included as expenditure in the investment phase. To arrive at the key figure of the net present value, the cash flows are uniformly discounted back to a point in time using a risk-adjusted, imputed interest rate and totalled. The capital value therefore does not represent the profits, but the added value of a project, which is generated when for example, the investment sum is invested on the capital market or in alternative projects [19], [20]. The other individual procedures are not discussed in more detail here. Further information can be found in the literature [21, 11, 22].

Cost-benefit analysis (CBA)

Another monetary analysis method is the Cost-benefit analysis. Criteria are established for each investment that are important for the investment process. These criteria are then weighted differently. Subsequently, each investment alternative is examined according to these criteria. The property that performs best in comparison with the other investment alternatives is ranked first, while the property in last place is the least suited to the workplace requirements. The ranking is then evaluated by weighting and the individual results are totalled. The property that best meets the criteria set has the lowest valuation ratio. The benefit analysis is also very interesting because this selection procedure can also be applied to other operational problems. The decision-maker is forced to think about the individual selection criteria and their weighting [23].

The static procedures always refer to only one period and do not take changing dependencies into account. Moreover, they are only based on costs and performance. In practice, these methods are often used despite the limitations, as they are relatively easy to use. The disadvantages lie primarily in the short-term approach and the lack of time considerations. The dynamic methods are much more suitable than the static methods for demonstrating the advantages of an investment.

This is because all periods of the investment are considered and financial mathematical methods are used. The use of financial methods makes it possible to take into account the significance of the data over time. This is done with the support of the interest rate, which makes it possible to compare income and expenditure.

2.3 Non-monetary analysis and evaluation

For both static and dynamic investment calculations, only quantifiable parameters are processed and calculated. The following methods are mainly used to evaluate investments that cannot only be evaluated with quantifiable performance.

CUA – Cost-utility analysis (CUA)

The Cost-utility analysis can be used for a qualitative evaluation of alternatives [21]. Usually, non-monetary criteria are used for this analysis, but monetary criteria would generally also be possible. The procedure is based on a theoretical decision model [23].

The overall benefit of alternatives is determined step by step in order to be able to make a decision based on the result [21]. It is therefore mainly suitable for investments that cannot be evaluated with quantifiable indicators.

The calculation procedure is as follows. Different criteria are formed for each investment, which are weighted differently. Criteria are for example progressiveness, financial security, productivity, workplace safety, operability and many other possibilities. Subsequently, each investment alternative is examined according to these criteria.

The one with the best performance compared to the other investment alternatives is ranked "1". The object in the last rank is the least suitable in comparison. The ranking is then evaluated by the weighting and the individual results summed up. The investment that meets the criteria best has the lowest value.

Technology assessment

The aim of technology assessment is to identify and assess the significance of technologies or the results of technology decisions [24].

The evaluation can be carried out quantitatively or qualitatively with defined evaluation standards. Classic criteria are functionality, economy, prosperity, safety, health, environmental quality as well as personal development and social quality [25]. A variety of methods are available for the evaluation and impact assessment of technologies for example Brainstorming, Risk-Analysis, Delphi expert survey, Cost-benefit analysis and Cost-Utility analysis.

Since none of the existing evaluation methods is specifically designed for the application on exoskeletons, the methods of profitability calculation, in particular the extended profitability calculation, are to be considered in general terms first.

The principle of profitability describes that the ratio between the degree of target fulfilment (utility) and the use of resources (expenditure) must be maximised. The next chapter shows a first method for the economic evaluation of exoskeletons.

3. METHODS FOR THE ECONOMIC EVALUATION OF EXOSKELETON EMPLOYMENT IN INDUSTRY

At present, there are no methods to evaluate exoskeletons used in industrial workplaces. First, there is a tendency in all organizations to measure and evaluate in order to provide executives with a basis for decision-making.

New technologies in particular wearable robotics - exoskeletons, which have never been used before in manufacturing industries, must be made measurable in terms of the cost-benefit ratio.

3.1 Economic evaluation criteria for exoskeletons

In order to carry out an evaluation, the criteria must be selected. The more goal-oriented criteria are selected, the more meaningful the result become.

Following table shows some criteria, which were identified during several performed research and industry projects. The criteria are clustered according critical characteristics and consist of qualitative and quantitative factors.

Table 1

Criteria for exoskeleton usage evaluation

General purchasement and usage costs
- Purchase cost
- Maintenance cost
- Training/Wearing/Storage cost
- Energy and other usage costs
- Patents / licence fees
- Development costs (for in-house development)
- ...
Workplace related factors (mostly process related)
- Cycle time: the time for completion of a specific task
- Down time: Results of an exoskeleton breakdown or an exoskeleton changeover. The production line has to stop
- Throughput: How many products/parts are produced in this task by the worker
- Productivity (Quantity of produced products)
- Overall Equipment Effectiveness (OEE): Multi-dimensional metric is a multiplier of Availability x Performance x Quality and it is usable to identify the overall effectiveness of a piece of production equipment, in this case the exoskeleton as tool.
- Reduction overtime
- Increased flexibility (Exoskeleton tool can be used for different workplaces and adjustments are possible)
- Setting/Put-on/put-off
- Charging time (for active exoskeletons)
- …
Product and Process quality
- Quality of work (increasement due the exoskeleton usage, better quality in wielding or less transportation damage)
- Flexibility (human precision and work assignment flexibility)
Worker related factors
- Ergonomic parameters – Overall ergonomic parameters retrieved by the digital simulations
- Health-care parameters (Illness rate possibly reduced due exoskeleton usage) – How to measure the effect when workers have less MSD because of their working conditions, how to measure it how to weigh it.
- Worker motivation
- Comfort
- Mental harassment
- …
Exoskeleton specific factors
- Setup time: Put-on put-off time, initialisation time for the certain workplace
- Battery load time / Exchange time
- ….
Other criteria for the evaluation
- Safety instructions for exoskeletons
- Training for exoskeleton usage
- Ethical issues due of the use of exoskeleton
- ….

There are also approaches in engineering to measure the performance of technical processes such as Methods Time Measurement (MTM) [26], [27] or REFA [28]. This is also an input factor for the method developed later.

Further criteria can be captured by the digital workplace design and optimisazion through simulation. Criteria that can be identified with the help of simulation, in particular the parameters that can be identified by ergonomics analyses represent valuable factors [29, 30, 31, 32].

These ergonomic factors are very important for evaluation, as there is a lot of potential here. The reduction of sick days and the increase in employee motivation have both qualitative and quantitative effects on the result. The core benefit represents the increase of innovation potential, mainly in social and technical aspects. This should be also taken into consideration as well as many other not yet discovered factors.

3.2 Possible economic evaluation method for exoskeletons

To perform an economic evaluation of the exoskeleton technology employment in industry, several steps must be carried out. The method consists of three phases. The second and third phases are iterative.

The first phase of the method the, “It-Is” analysis, is the analysis of the actual situation. Here, the previous and required data of the workplace is captured holistically.

This includes all important qualitative and quantitative factors as described in the previous chapter as well as key-performance-indicators. The iterative and creative part of the method begins with the second phase.

This phase will gradually identify which exoskeletons can be used and employed in the selected workplace.

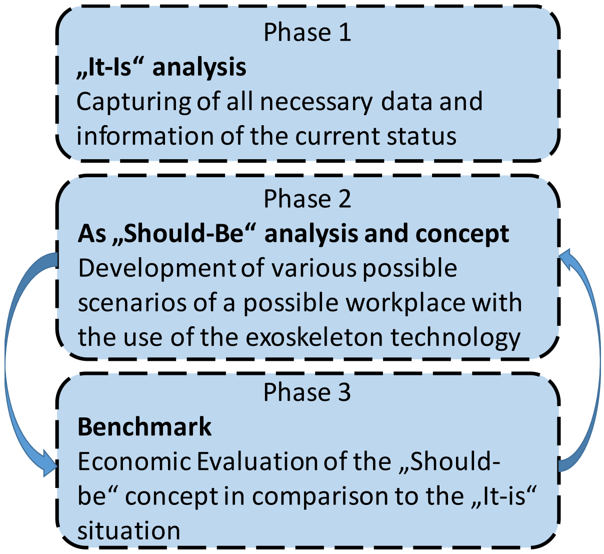

Fig 4. Phases of the method for the economic evaluation of exoskeletons in industrial workplaces.

The concept takes into account the existing basic requirements of the workplace and its objectives. The resulting "should-be" concept represents the ideal target state according to the knowledge of the workers. In the third phase, the evaluation of the "should-be" concept is developed. The current "it-is" situation is then compared with the "should-be" concept. Based on this, an iteration with another new concept is triggered or the result is accepted as the best possible variant for the set objectives.

In the following, an example with the cost-utility analysis for the second phase is shown. This non-monetary method is selected as an example. Which method is ultimately used has yet to be analysed. The various selection criteria are weighted and multiplied by the rank. The exoskeleton technology with the lowest value is the best exoskeleton to be used for this certain workplace. Of course, the cost-utility analysis for the exoskeleton has to be compared with the cost-utility analysis of the initial situation. If the exoskeleton technology is still superior from the utility value, it will be selected and used. The selection criteria in this example are superordinate criteria, which can of course be refined into subcriteria. Due to the limited space available, only a few criteria are listed in this paper for demonstration purposes.

Table 2

Cost-utility analysis for the exoskeleton employment decision

Cost-utility analysis (CUA)							
Aim of the decision: Purchasement of an Exoskeleton for the workplace 'Working-over-the-Head'							
Requirements	1. Maximum price 10.000€ 2. Process time not affected negative 3. Worker statisfaction increased by 20%						
Exoskeleton type		Exoskeleton Model "A"		Exoskeleton Model "B"		Exoskeleton Model "C"	
Selection criteria	Weighting	Rank	WxR	Rank	WxR	Rank	WxR
General purchasement	0,20	3	60	2	40	1	20
Workplace related factors	0,10	1	10	3	30	2	20
Product and process quality	0,10	2	20	3	60	1	10
Work related factors	0,30	1	30	2	60	3	90
Exoskeleton specific factors	0,10	3	30	1	30	2	20
Other Criteria	0,20	2	40	1	40	3	60
Σ	1,00		**190**		260		220

The method is helpful to get a first overview and a comparison of different technologies and their evaluation. In this case exoskeleton model "A" was selected. The method will later include a monetary and non-monetary combination. So, behind this lightly described method, many methods must be examined with regard to their possible uses. The aforementioned methods were described in chapter 2.2. Some of the different methods can be partially combined or other links can be made. The aim is to feed the most important factors as input with the most meaningful methods in order to ultimately obtain the best selection of exoskeleton technology for the certain workplace. The monetary perspective in particular is an important point of view.

4. CONCLUSION AND FUTURE WORK

This paper shows several monetary and non-monetary methods for economic evaluation. An initial selection of criteria for evaluating the technology is also presented.

The method consists of three phases, the actual “As-it-is” analysis, the “As-should-be” analysis with the consideration of a possible exoskeleton candidate to be employed and the comparison of these two states.

The future work aims at partially combine the right methods with each other, to select the targeted factors as input data.

This then serves as the basis for an upcoming software tool that supports the selection of the right exoskeleton technology for various workplaces.

Of course, there is also the possibility that the exoskeleton technology is not suitable because another technology is more advantageous.

Another important point is the consideration of the time factor. An investment in exoskeleton technology must be evaluated over a longer period of time. The interest rate must then be used as a parameter for the monetary evaluation.

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Fundaţii pentru evaluarea economică a exoskeletonilor în productie

Rezumat: Pentru a rămâne competitivi, companiile de producţie ar trebui să-și îmbunătăţească continuu procesele ca nucleu al activităţilor lor cu valoare adăugată. Asamblarea manuală a locurilor de muncă în producţie, având lucrătorii ca cea mai importantă resursă pentru crearea de valoare adăugată, este afectată în special de manipularea încărcăturilor grele, a vibraţiilor și a operaţiunilor periculoase. Aceste locuri de muncă se confruntă cu provocări, precum scăderea ratei de ocupare a forţei de muncă, fluctuaţiile mari și creșterea ratei bolii. Procesele la locurile de muncă de asamblare manuală pot fi optimizate prin utilizarea roboticii purtătoare - Exoskeletons - pentru a sprijini lucrătorii fizic și cognitiv. Această lucrare prezintă o revizuire literară a metodelor de evaluare economică a sistemelor de suport tehnic, ca bază pentru dezvoltarea unei metode inovatoare de evaluare a impactului economic al exoskeletonelor în industria prelucrătoare.

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