SIMULATION-BASED MULTI-OBJECTIVE OPTIMIZATION OF ERGONOMIC AND PRODUCTIVITY FACTORS

RESEARCH PROPOSAL

Aitor Iriondo Pascual
aitor.iriondo.pascual@his.se
2019-11-05
University of Skövde

SUPERVISORS

Anna Syberfeldt, anna.syberfeldt@his.se
Dan Högberg, dan.hogberg@his.se
Erik Brolin, erik.brolin@his.se
ABSTRACT

Simulation software is used in industry to simulate production as it allows predicting behaviours, calculate times and plan production already at virtual stages of the production development process. There is also software to simulate humans working in production, commonly called digital human modelling (DHM) tools. When humans are simulated, ergonomics evaluations can be carried out in order to assess whether workstation designs offer appropriate ergonomic conditions for the worker. However, these human simulations are usually carried out by human factors engineers or ergonomists, with the purpose of validating workstations, without integrating these simulations with those performed in production by production engineers. Due to this, simulations performed to predict production are usually done separately from human simulations performed to evaluate ergonomics. This can lead to suboptimal solutions when the factory is optimized to improve productivity and ergonomics. This research proposal contains a frame of reference, literature review, research questions, proposed approach, motivation, expected results, philosophical paradigm, research methodology, method, challenges and planning, founded in the hypothesis that more optimal solutions for workstation design, layout and line balancing can be obtained in simulations by optimizing productivity and ergonomic factors at the same time instead of improving them separately. Hence, the aim is to carry out research in the development of a multi-objective optimization method of productivity and ergonomic factors, and to implement the method into a simulation tool in order to test and communicate the method. From an academic perspective, the overall objective is to contribute to knowledge and publish findings in the academic community, eventually leading to a PhD thesis. From an application perspective, the overall objective is to contribute to the development of efficient methods for how to find successful designs of productive and ergonomic workstations.

Keywords:

Ergonomics, Simulation, Optimization, Productivity, Digital Human Modelling
## CONTENTS

1. **INTRODUCTION** .................................................................................................................. 1

2. **FRAME OF REFERENCE AND LITERATURE REVIEW** ......................................................... 4
   2.1 **FRAME OF REFERENCE COMPOSITION** ........................................................................... 4
   2.2 **LITERATURE REVIEW** .................................................................................................... 6
   2.3 **THE RESEARCH DOMAIN** ............................................................................................... 7
       2.3.1 **ERGONOMIC EVALUATIONS** .................................................................................... 8
       2.3.2 **OPTIMIZATION IN PRODUCTION** ............................................................................. 11
       2.3.3 **COMPLEXITY OF OPTIMIZATION IN PRODUCTION** ............................................. 12
       2.3.4 **MULTI-OBJECTIVE OPTIMIZATION** ........................................................................ 13
       2.3.5 **MULTI-LEVEL OPTIMIZATION** ............................................................................... 14

3. **RESEARCH QUESTIONS AND PROPOSED APPROACH** ..................................................... 16
   3.1 **RESEARCH QUESTIONS** .................................................................................................. 16
   3.2 **OBJECTIVES** ................................................................................................................... 16
   3.3 **PROPOSED APPROACH** .................................................................................................. 17
   3.4 **EXPECTED RESULTS** ..................................................................................................... 17
   3.5 **MOTIVATION** .................................................................................................................. 19
       3.5.1 **KNOWLEDGE GAP** ................................................................................................ 19
       3.5.2 **NEED OF A TOOL FOR OPTIMIZATION OF ERGONOMICS AND PRODUCTIVITY** ....... 20

4. **PHILOSOPHICAL PARADIGM AND RESEARCH METHODOLOGY** ..................................... 22
   4.1 **PHILOSOPHICAL PARADIGM** .......................................................................................... 22
   4.2 **RESEARCH METHODOLOGY** ........................................................................................... 22

5. **METHOD** ............................................................................................................................. 24
   5.1 **INTERVIEWS** .................................................................................................................. 24
   5.2 **USE CASES** ..................................................................................................................... 24
   5.3 **DEVELOPMENT OF THE METHOD OF MULTI-OBJECTIVE OPTIMIZATION OF ERGONOMICS AND PRODUCTIVITY** ............................................................................. 25
   5.4 **DEVELOPMENT OF THE TOOL** ....................................................................................... 25
   5.5 **TIMELINE OF THE THESIS** ............................................................................................ 26

6. **PROCESS DIAGRAM OF THE DEVELOPMENT OF THE METHOD** ....................................... 27

7. **CHALLENGES** ....................................................................................................................... 29
7.1 COMPLEXITY OF THE INTERACTION BETWEEN ERGONOMICS AND PRODUCTIVITY .... 29
7.2 LACK OF ERGONOMIC EVALUATION METHODS TO MEASURE ERGONOMIC
IMPROVEMENTS IN OPTIMIZATIONS ................................................................. 29
7.3 COMPLEXITY OF MULTI-LEVEL MULTI-OBJECTIVE OPTIMIZATIONS ............... 30

8 PLANNING ........................................................................................................... 31

9 ETHICAL DIFFICULTIES ...................................................................................... 32

10 INTERNAL AND EXTERNAL VALIDATION ....................................................... 33

REFERENCES ........................................................................................................... 34
1 INTRODUCTION

There is a constant strive in industry to reduce costs while keeping or increasing productivity and quality. In manual work, such as in manual assembly, work-related musculoskeletal disorders (WMSDs) are often associated with high costs for production companies (Sultan-Taïeb et al., 2017). Studies concerning costs due to WMSDs are increasing, trying to quantify the impact of WMSDs on the industry (European Agency for Safety and Health at Work, 2017). Hence, when designing factories, in order to reduce WMSDs and their cost to the industry, it is important to consider ergonomics. In production, workers typically performs tasks that can be strenuous, with the consequent risk of WMSDs. However, sometimes it is impossible or hard to replace or adapt certain tasks, either due to lack of means or the complexity of the task itself. This means that, despite aspiring to take ergonomics into consideration, most of the time there still will be some non-ergonomic tasks (e.g. repetitive or high physical effort) that are hard or expensive to resolve.

Not assigning such tasks to a worker would improve ergonomics, but production would be affected negatively since the tasks would have to be done in some other way, likely to lead to reductions of productivity, or require time and investments for a new solution. Hence, it can be observed that in some cases ergonomics will not go hand in hand with productivity, and decisions will have to be made so that productivity is affected as little as possible while reducing the risk of WMSDs for workers. But first, what is considered with the terms productivity and ergonomics in this research proposal must be defined.

Productivity is defined as “The effectiveness of productive effort, especially in industry, as measured in terms of the rate of output per unit of input” (Oxford Dictionaries, 2017). This means that throughput is the main indicator of the productivity in industry. Reducing the production time and increasing the throughput therefore mean an improvement in productivity.

Ergonomics (and its synonymous human factors) is defined as “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.” by the International Ergonomics Association (IEA, 2019). Ergonomics is typically separated into these three domains: Physical Ergonomics, Cognitive Ergonomics and Organizational Ergonomics (IEA, 2019). This research proposal focuses on physical ergonomics, and more specifically on the consideration of biomechanical loads on the human body during work. The research will, to a degree, also consider anthropometric diversity of workers. Other issues or domains, e.g. temperature, noise, cognitive ergonomics or organisational ergonomics will not be considered in this research.
As a way to support objectivity when assessing physical ergonomic conditions, there is a range of ergonomics evaluation methods available. The methods are typically developed by researchers, to be used to assess certain types of work or aspects (Takala et al., 2010). The outcome is regularly a numerical value, representing the risk of WMSDs of the work tasks being assessed. Examples of established ergonomics evaluation methods are: RULA (Rapid Upper Limb Assessment) (McAtamney and Nigel Corlett, 1993), OWAS (Ovako Working Posture Assessment System) (Karhu et al., 1977), and NIOSH (National Institute for Occupational Safety and Health) Lifting Equation (Waters et al., 1993). The EAWS (Ergonomic Assessment Worksheet) is a holistic ergonomics evaluation method, which combines risk factors from four risk areas (body postures, action forces, manual materials handling, upper limbs), and combine these into an overall risk value (Schaub et al., 2012). EAWS enables the evaluation of ergonomics for longer work tasks, up to a full working day. The importance to consider time aspects when evaluating ergonomics is addressed in (Wells et al., 2007). There are methods that combines the process to evaluate ergonomics with the estimation of required times for doing work tasks. Examples of predetermined time systems (PTS) are MTM-1 (Maynard et al., 1948) and MTM-2, MTM-3 and MTM-UAS (Matias, 2001). AviX (“AVIX,” 2019) is a software that facilitates balancing work tasks on production lines on basis of times per work tasks determined by PTS. Human Work Design (MTM-HWD®) is a recently development method, which concurrently assess motions and associated time estimations of work tasks, as well the ergonomics (risks of WMSDs) of these work tasks (Kuhlang et al., 2018). Such approach facilitates creating “blocks” of work tasks, which contain both a value for time and for ergonomics.

This research proposal is based on the hypothesis that it would be advantageous to be able to concurrently optimize productivity of factories and ergonomics of workers, i.e. multi-objective optimization, and that the optimization should be possible to perform at virtual stages of the production development process. In order to optimize both factors at the same time, in virtual worlds, simulations of both human activities and production are required. There are numerous digital human modelling (DHM) tools available on the market, such as Siemens Jack (Boros and Hercegfi, 2020), and IPS IMMA (Högberg et al., 2016). Such tools facilitate studies related to anthropometric variability among workers (Brolin et al., 2019), simulation of work sequences (Mårdberg et al., 2014), and assessments of work conditions according to established ergonomics assessment methods, such as RULA, OWAS and NIOSH Lifting Equation mentioned above. There are also numerous production simulation software to simulate production flows of factories, robots and workstations, such as FACTS Analyzer (Ng et al., 2007) and Siemens Tecnomatix Plant Simulation (Siderska, 2016). These production simulation software usually offer the possibility of improving the productivity of the stations, optimizing the layout and the configuration of the production lines (Kłos et
However, there exists no method nor tool that offers a solution to concurrently optimize productivity and ergonomics. Due to this, a need and opportunity is to create a method that considers both ergonomics and productivity, and to implement the method in a digital tool, so that both ergonomics and productivity can be optimized at the same time.
2 FRAME OF REFERENCE AND LITERATURE REVIEW

In this section the key terms of this research proposal were studied, as well as the interactions between these terms. Once the terms were defined and it was found that they can form the basis of this research proposal, an initial study of the available literature was carried out. This study signified the importance of the field of study of the research proposal, as well as existing knowledge and possible knowledge gaps.

2.1 FRAME OF REFERENCE COMPOSITION

Four main terms are considered to be involved in this research proposal: ergonomics, productivity, simulation and optimization. The combination of these four terms build the entire research proposal, but the different combinations of these terms build the background of the research proposal. The four main terms and the combinations can be seen in Figure 1.

![Figure 1. Main terms and combinations of terms of the research proposal](image)
If the combined terms are organized by number of relations, it can be seen that each combination leads to a different area of study. All the combinations can be found in Table 1.

<table>
<thead>
<tr>
<th>Relations</th>
<th>Number</th>
<th>Element</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>Ergonomics</td>
<td>Ergonomics</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>Productivity</td>
<td>Productivity</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>Simulation</td>
<td>Simulation</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>Optimization</td>
<td>Optimization</td>
</tr>
<tr>
<td>2</td>
<td>2.1</td>
<td>Ergonomics + Productivity</td>
<td>Ergonomics and productivity relation</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>Ergonomics + Simulation</td>
<td>Human simulation based ergonomic evaluations</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>Ergonomics + Optimization</td>
<td>Optimization of human ergonomics</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>Productivity + Optimization</td>
<td>Optimization of production systems</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>Productivity + Simulation</td>
<td>Simulation of production systems</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>Simulation + Optimization</td>
<td>Simulation based optimization</td>
</tr>
<tr>
<td>3</td>
<td>3.1</td>
<td>Ergonomics + Productivity + Optimization</td>
<td>Multi-objective optimization of ergonomics and productivity</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>Ergonomics + Productivity + Simulation</td>
<td>Human simulation in production systems</td>
</tr>
<tr>
<td></td>
<td>3.3</td>
<td>Ergonomics + Simulation + Optimization</td>
<td>Simulation based optimization of human ergonomics</td>
</tr>
<tr>
<td></td>
<td>3.4</td>
<td>Productivity + Simulation + Optimization</td>
<td>Simulation based optimization of productivity</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>Ergonomics + Productivity + Simulation</td>
<td>Simulation based multi-objective optimization of ergonomics and productivity factors</td>
</tr>
</tbody>
</table>

The main area in this research proposal will cover the relation of the four terms (i.e. Relation 4 in Table 1): *Simulation based Multi-Objective Optimization of Ergonomics and Productivity*. The other areas of studies will be used as a background of the research proposal and to get a deeper understanding of certain aspects. The target is to converge all the terms into the Simulation based Multi-Objective Optimization of Ergonomics and Productivity area.

The research proposal also covers *multi-level optimization*. That is, to optimize productivity and ergonomics, the method developed in the research should consider not only the design of workstations (considered as representing single-level) but concurrently also consider the balancing of work tasks in production lines (considered as representing multi-level). Existing methods for simulation-based optimizations will be studied in order to include all the terms and levels mentioned.
2.2 LITERATURE REVIEW

As mentioned in Section 2.1, the four main terms for the frame of reference of this research are: simulation, ergonomics, optimization and productivity. These four terms compose the major part of the literature review. For that, a study of online databases and available references was made to have a prior understanding of the existing knowledge in this field. The two main search engines used for the search are Scopus and Web of Science since they are the main multi-disciplinary search engines in the context of these terms. However, searching for these terms individually gives a high quantity of results and most of the results are not focused in this search. A filter was used so that the terms were to appear in the article title, abstract or keywords. That means that terms that do not appear in these sections, and only appear in the article body, will not be counted. The results are noted in Table 2.

<table>
<thead>
<tr>
<th>Search term</th>
<th>Web of Science</th>
<th>Scopus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ergonomics</td>
<td>12.973</td>
<td>53.596</td>
</tr>
<tr>
<td>Productivity</td>
<td>247.978</td>
<td>367.454</td>
</tr>
<tr>
<td>Simulation</td>
<td>2.432.871</td>
<td>3.561.866</td>
</tr>
<tr>
<td>Optimization</td>
<td>979.876</td>
<td>1.506.581</td>
</tr>
</tbody>
</table>

The most published terms are simulation and optimization, while ergonomics is the least published term (Table 2). Also, it can be seen that Scopus has more results indexed than Web of Science (Table 2). Due to the large quantity of identified publications, it is unfeasible to study the four terms in depth and independently. To refine the search, the following search string was used, i.e. all the four terms have to appear in the search results:

- Simulation AND Ergonomics AND Optimization AND Productivity.

This resulted in 18 results for Scopus and 15 results for Web of Science. This search is too limited and only shows the results that contain all the four terms. In order to make a wider search the terms were expanded, taking into account all the ways that researchers mention the terms in publications, for
example, ergonomics is sometimes mentioned as human factors. The terms were expanded with the following terms:

- Ergonomics: human factors, ergonomics.
- Optimization: evolutionary algorithms, genetic algorithms, balancing, optimization.
- Productivity: manufacturing, assembly, production, industry, factory, design, develop, productivity.

After expanding the terms, it was noticed that searching for specific words can limit the search, for example, sometimes instead of “ergonomics” it is mentioned “ergonomic”. To avoid limiting the results due to the ending or the exact spelling (e.g. UK versus US English spelling) of the words, the results were expanded by making the search flexible, for example, “ergonom*” was used instead of searching for “ergonomics”. Also, in searches of a term with multiple words it was allowed that the term can have flexibility, for example, allowing “genetic algorithms” to be “genetic evolutionary algorithms”. Taking these changes into account, the final search string was defined as:

- (DHM OR ("digital human" NEAR/1 model*) OR simulat*) AND (ergonom* OR (human* NEAR/1 factor*)) AND (optimi* OR ((evolution* OR genetic*) NEAR/1 algorithm*) OR balanc*) AND (manuf* OR assembl* OR production* OR industr* OR factory* OR factori* OR design* OR develop* OR productiv*)

This search resulted in 935 results for Scopus and 427 results for Web of Science, which was considered an acceptable amount to start a literature review in the field of research of this research proposal.

2.3 THE RESEARCH DOMAIN

This research proposal requires knowledge of several terminologies. Given the ergonomic factors, it is necessary to know how to evaluate ergonomics. This includes knowing which ergonomic exposure factors that are relevant to consider in respect to the application domain of this research, and to know relevant ergonomics evaluation methods that can be applied in order to assess these exposure factors. It is also necessary to know how production is optimized nowadays so that ergonomic factors can be included in optimizations. In addition to this, it is necessary to know different types of optimizations, such as multi-objective optimizations and multi-level optimizations. These terms were studied, and are explained in a condensed manner in the following sections.
2.3.1 Ergonomic Evaluations

In the field of ergonomics, evaluation methods can be used to assess the risk of WMSDs. These ergonomic evaluation methods can be classified into three different types (David, 2005):

- Self-reports.
- Observational methods.
- Direct measurement.

Self-reports are based on the worker notifying his/her own opinion on how strenuous the job is, their experienced level of comfort and other factors. The self-report method is considered not applicable in this research due to the need of workers assessing real work situations.

Observational methods are based on ergonomists observing workers when they perform job tasks, and based on that the ergonomists make evaluations of the work. This is done by assessing aspects such as work postures and physical efforts, taking notes of the most critical postures (such as joint angles far from neutral positions) or high forces, and the consequential possible risks of WMSDs. These observational methods are typically based on the ergonomist doing annotations in evaluation tables and sheets, which after completing the input fields offer a numerical result that represents the risk of WMSDs. Often the input fields correspond to postural measurements. For example, in RULA (McAtamney and Nigel Corlett, 1993) the posture is measured by numerical threshold of upper arms (Figure 2), lower arms and wrists angles and other conditions.

![Figure 2. RULA upper arm thresholds (McAtamney and Nigel Corlett, 1993)](image)

Examples of other observational evaluation methods are: OWAS (Karhu et al., 1977), NIOSH Lifting Equation (Waters et al., 1993), Strain Index (Moore and Garg, 1995), OCRA (Occhipinti, 1998), QEC (Li and Buckle, 2000), REBA (Hignett and McAtamney, 2000), LUBA (Kee and Karwowski, 2001), PERA (Chander and Cavatorta, 2017) and ErgoSAM (Laring et al., 2005).
Performing these observational evaluations is time consuming and repetitive work for ergonomists, since they must measure the worker's postures by observations, usually spending many hours watching real work situations or videos of workers performing their work, and make measurements of forces exerted by workers while performing the work tasks. Another drawback is that the observational methods typically assess ergonomic conditions at specific instances, e.g. static posture during specific tasks, rather than full work sequences, which would be more valid to characterise the risks for WMSDs (Berlin and Kajaks, 2010). The observational method is also subjective, and recent research has shown that different ergonomists often come to different results when assessing the same work (Eliasson et al., 2017). Its original form, the observational method is considered not applicable in this research due to the need of ergonomists assessing real work situations.

Direct measurement methods refers to the case where ergonomic exposure factors, such as body postures or muscular activity, are measured by some technical device on real humans while they perform work. The measured data is then assessed using ergonomics evaluation methods. Thanks to advancements in technology, and the objective to overcome drawbacks of self-reports and observational methods (e.g. subjectivity, reliability, validity, time consumption), there has been an increase in recent years in the development of solutions for direct measurements. These solutions contain technical devices to measure exposure factors, e.g. digital goniometers (Hansson et al., 2009), IMU:s (inertial measurement units) (Robert-Lachaine et al., 2017; Vega-Barbas et al., 2019) or EMG (electromyography) sensors (Hansson et al., 2009). The solutions can also be based on different kinds of image recognition technologies to capture postures (Plantard et al., 2017; Sandoval et al., 2020) and motions. The direct measurements methods also contain solutions that more or less automate calculation and presentation of the results from the ergonomic evaluations, e.g. to an ergonomist or an engineer.

Using direct measurement methods to assess that workers have low risks for WMSDs matches the modern production trends, such as Industry 4.0 (Lasi et al., 2014) and Smart Factories, where through the use of sensors the factories are digitized, adding in this case the humans to the digital factories. It also matches the UN 2030 Agenda for Sustainable Development within target 3D: “Strengthen the capacity...for early warning, risk reduction and management of...health risks”, and target 8.2: “Achieve higher levels of economic productivity through...technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors” (United Nations, 2016).
Often the evaluation methods utilised in direct measurement solutions were originally developed as observational methods, which pose challenges both related to validity and reliability (these aspects are however not considered in this research). Examples of concerns are that the methods where typically meant to support a skilled ergonomist, having the ability to make judgements, rather than treated as firm rules by a software. Another concern is that the observational methods often were developed to assess static instances rather than work sequences, which is typically in focus for direct measurements. In addition, programming ergonomic evaluation methods can become complicated. The first problem is that among the three types of ergonomic evaluations, only direct measurements can be automated. In addition to this, not all measurement factors can be automated since in some cases they correspond to subjective definitions as if the task is very frequent or infrequent without giving a definition of what is frequent or infrequent. Ergonomic evaluation methods consider different exposure factors for their risk assessments, such as posture, forces, frequencies, duration, recovery time, vibration and other factors, which can sometimes be difficult to automate by programming due to the lack of data. Therefore, the programming of ergonomic evaluation methods is limited by the available data and the complexity of the methods themselves.

In addition to direct measurements of exposure factors on real humans, the corresponding data can be obtained from human models in DHM tools (Scataglini and Paul, 2019). These simulated humans, commonly called digital manikins or just manikins, can also be analysed in terms of ergonomics, replicating the direct measurement method but here in a virtual world. The essential benefits from DHM tools are that workstations can be analysed while they are designed in a digital tool, to be able to iterate designs to find the most suitable design for workers. DHM tools also facilitates testing designs for different manikins, e.g. related nationality, gender, anthropometry and other kinds of diversity. Hence, there is no need for real test persons, or of physical prototypes or real workstations in order to analyse the risk of WMSDs of workers. There are numerous DHM software to perform human simulations and evaluate ergonomics, for example Siemens Jack (Boros and Hercegfi, 2020), Santos (Pitarch et al., 2005) and IPS IMMA (Högberg et al., 2016) (Figure 3).
Simulations performed in DHM tools are usually based on a user-defined operation sequence that, when executed, results in a continuous simulation, meaning that it is simulated for the entire defined time interval and not based on events and states. Depending on the software, static, kinematic, quasi-static or dynamic simulations can be done. Being a simulation in a controlled environment, data is available to be able to perform most ergonomic evaluations. Since this research is about finding optimal design solutions in simulated environments, it will utilise ergonomics evaluation done by direct measurements on manikins in DHM tools as the way to assess risks for WMSDs.

Despite the possibilities of DHM software, ergonomic evaluation methods have their own limitations since each one is dedicated to evaluating a type of task. Moreover, these methods are not continuous or discrete, they usually offer a single value for an entire work day. In addition, often the methods need manual input from the user. Hence, the consideration of all exposure factors can often not be automated. This means that these ergonomic evaluation methods can currently not be used directly to optimize ergonomics and productivity of workstations without first adapting them to be used in optimization algorithms.

2.3.2 OPTIMIZATION IN PRODUCTION

There are many ways to set up a factory, either by creating new stations, changing the order of assembly operations, balancing the tasks of each workstation, increasing or decreasing the buffers etc. (Siregar et al., 2019). All these possible combinations give rise to endless configuration possibilities, so testing them all in the real factory is impossible, given the time taken by these changes and the associated costs. This is why digital tools were developed to simulate production in a factory, so that different configurations can be tested without the need to change the actual factory and analyse its behaviour. These tools are therefore useful to redesign a factory and can simulate the behaviour of the new configuration, allowing
production engineers to optimize the configuration through several iterations, testing and observing main production factors such as throughput, work in process and lead time (Górnicka et al., 2020).

In addition to this, many of these tools include optimization algorithms, which, by different methods, seek the best combination for an objective function, so that the production engineer can define objectives to maximize or minimize and the algorithm will try to find the better configurations without the need to design each configuration manually. There are many production simulation tools to simulate production and optimize the factory configurations such as FlexSim (Shi and Wang, 2011), Siemens Tecnomatix Plant Simulation (Siderska, 2016) and FACTS Analyzer (Ng et al., 2007) (Figure 4).

![Figure 4. FACTS Production Simulation Software](image)

The most common method used to simulate the flow of factories is the discrete event simulation, which instead of continuously simulating the model defines events and states, which are located on a timeline that defines the sequence of events (Negahban and Smith, 2014).

### 2.3.3 Complexity of Optimization in Production

There are systems of different complexities when it comes to optimization problems. Depending on the type of problem, analytical solutions can be obtained, which offer the most optimal result and this in turn is easily testable. An example would be to obtain the maximum of a polynomial function, which is known as a P-type problem. However, sometimes the problem cannot be described as a polynomial function, so it would be classified as an NP-type problem. This distinction is based on the problem being solved in a relatively fast time, in a polynomial time. Solving an NP problem takes longer than solving a P problem, however you can quickly check if the result is correct. When, in addition to needing a long time to solve it, a long time is also needed to verify it, the problem is known as NP-hard. An example of NP-hard problems...
would be the problem of traveling salesmen, where you must define a route for a seller to travel a number of cities in the shortest possible time (Cormen et al., 2009; Vavasis, 2009).

The optimization of a factory is also considered an NP-hard problem (Lamar, 2009). Due to the number of combinations and the complexity of the interactions between the parameters that make up a factory it is difficult to obtain the perfect configuration and it would be difficult to verify that the chosen configuration would be the perfect one. This is why factory optimization problems are usually solved by heuristic algorithms, which do not ensure obtaining the optimal result, but a near-optimal result in a realistic calculation time, reducing the complexity of the problem (Shi and Olafsson, 2009).

2.3.4 MULTI-OBJECTIVE OPTIMIZATION

When trying to optimize an objective there is always an absolute maximum and an absolute minimum provided that the function exists in the defined domain, this belongs to the Bolzano–Weierstrass theorem (Rusnock and Kerr-Lawson, 2005). This is why whenever the problem exists within these limits, it can always be solved with an optimal result, even though this problem corresponds to a problem of NP-Hard complexity (Rai and Vairaktarakis, 2009). However, when trying to optimize two or more objectives at the same time, the problem ceases to have a single optimal solution to have an optimal solution for each objective (Sayin, 2009). This means that in the absence of a single solution, the result is a space of solutions with as many dimensions as objectives. For example, if you want to optimize two objectives, the result will be the function of a line, and for three objectives it would be a 3D surface. This space of solutions is called the Pareto front (Figure 5) (Sayin, 2009), and is one of the main tools when facing a multi-objective optimization problem, since it allows you to make a decision when choosing the desired result by choosing among the solutions that have been proven to be optimal. Solutions that are not found in the Pareto front are called dominated solutions, since in the Pareto front there will be a dominant solution that will be better in all objectives to a dominated solution.
The optimization of a factory is in most of the times a case of multi-objective optimization, since at the same time that it is sought to increase productivity, it also seeks to reduce costs and delivery times. This is why the optimization of a factory is a problem of multi-objective optimization with a NP-Hard complexity.

2.3.5 Multi-level optimization

In some optimization problems there is the possibility of dividing a case with a large number of variables into smaller cases with fewer variables, calling these new cases sub-problems (Figure 6). This significantly reduces the optimization time, especially in cases related to large processing time such as NP-Hard cases (Alexandrov, 2009). In the case of factories, cases such as the optimization of a production line can be reduced to the optimization of each workstation. However, this method of dividing an optimization problem into sub-problems also creates the possibility of not being able to obtain the optimal solution and only reach suboptimal results. This is because the variables can be related to each other, and in some cases a sub-problem will have to have a non-optimal solution so that the entire system (or main problem) can reach the optimal value. This can be observed in factories where resources must sometimes be relocated, making a workstation less productive but making the entire production line more productive. There are currently several studies trying to obtain the benefits of dividing problems into sub-problems to perform a multi-level optimization without the disadvantage of not being able to achieve optimal results for the main problem (Gunawan et al., 2003).
FIGURE 6 DIVISION OF A PROBLEM INTO SUB-PROBLEMS (GUNAWAN ET AL., 2003)
3 RESEARCH QUESTIONS AND PROPOSED APPROACH

This section first sets out the main research questions on which the research proposal is based.

3.1 RESEARCH QUESTIONS

The main research question of this research proposal is:

- How can ergonomics and productivity be optimized at the same time by using a multi-objective optimization approach?

This main research question has been divided into three sub-questions. The sub-questions are:

1. What are the critical ergonomic and productivity factors and what variables do affect them?
2. Which multi-objective optimization method is most suitable to optimize ergonomics and productivity?
3. How can this new method be implemented in a digital tool to meet the needs of potential users?

The first question is related to the study of the ergonomic and productivity factors and the variables that can affect them. It is important to know exactly what to optimize and how, before starting to find the method to adapt and implement, because if the optimization objectives are wrong the optimization will be built on a wrong base.

The second question is related to adapting a simulation based multi-objective optimization method in order to optimize ergonomics and productivity. To answer this question, a study of the existing simulation based multi-objective optimization methods will be done, and later the method will be adapted to handle the variables that are related to improvements in ergonomics and productivity.

The third and final question focuses on the development of the tool. This tool will be based on the adapted method and will be implemented into a simulation software.

3.2 OBJECTIVES

Once the research questions have been defined, the objectives of this research proposal can be defined:

- Study the factors of productivity and ergonomics that indicate both the productivity of the workstations and the ergonomics of the worker.
• Study the variables that have an impact on the aforementioned factors in order to optimize ergonomics and productivity, and adapt a simulation based multi-objective optimization method in order to improve ergonomics and productivity by optimizing the variables.
• Develop a tool to perform this optimization, based on the simulations generated in a simulation software and by implementing the previously adapted method.

3.3 PROPOSED APPROACH

The proposed approach for this research proposal is to create a method for optimization of ergonomic and productivity factors. This method will be created as an algorithm so it can be tested by optimizing simulation models in both productivity and ergonomics at the same time, and it will be iterated until both productivity and ergonomics are improved. The optimization will be performed by using a multi-objective optimization evolutionary algorithm, and different configurations will be tested, such as single level or multi-level optimization approaches.

3.4 EXPECTED RESULTS

The expected result for this research proposal is a method and a tool that includes ergonomic evaluations together with the production optimizations that are done nowadays by the industry. The main focus is to add the ergonomics evaluations into the process of optimizing factories so ergonomics of the workers can be optimized at the same time that productivity is optimized. This method will be implemented by the creation of an tool that will communicate with simulation tools, obtain data from the simulations, evaluate both the productivity factors and the ergonomic factors of the simulation and optimize them by using optimization algorithms (Figure 7).
An example of the communication between the developed tool and the simulation tool is shown in Figure 8.

The theory contribution of this research proposal is the creation of a method for simulation based multi-objective optimization of ergonomics and productivity. The tool generated by implementing this method
will include ergonomic evaluation, productivity evaluation and optimization tools so it can apply the new method.

3.5 MOTIVATION

The motivation of this research proposal has been broken down into three parts: the knowledge gap and the lack of tools for this purpose.

3.5.1 KNOWLEDGE GAP

Simulation software is used in industry to simulate production as it allows predicting behaviours, calculate times and plan production already at initial stages of the production development process. There are also DHM tools to simulate humans at work. When humans are simulated, ergonomics evaluations can be carried out in order to assess whether workstation designs offer appropriate ergonomic conditions for the worker (Fritzsche, 2010). However, these human simulations are usually carried out by human factors engineers or ergonomists, with the purpose of validating workstations, without integrating these simulations with those performed in production by production engineers (Neumann et al., 2009). Due to this, simulations performed to predict production are usually done separately from human simulations performed to evaluate ergonomics (Wells et al., 2007). This can generate problems such as miscommunication between departments and suboptimal solutions for the workstations and production lines.

There have been previous studies in the development of a complete digital factory where humans and the associated ergonomic conditions have been tried to be included in the process, but they mention the need of integrating it without offering a complete methodology and digital solution for the integration (Neumann et al., 2009). For example, some authors mention the need of adding the information from 3D human models, however they consider humans as 3D virtual models that can be analysed independently instead of considering them a complete model in their virtual factory framework, integrating human simulation data with production flow simulation data (Kuhn, 2006). There are organizational issues due to isolating ergonomic studies in industry and there are previous studies offering solutions of how to integrate ergonomics (Neumann et al., 2009). However, these studies only mention the possibility of new initiatives by using system flow and digital human modelling without actually offering a methodology based on digital technologies. It is also known from long time ago that there is a need of adding ergonomics into the standard operating procedures in the manufacturing departments in industry due to the influence that design and production engineers have on ergonomics (Broberg, 1997). Some authors try to offer a
solution, offering in some cases a methodology based on product lifecycle management (PLM) solutions together with human simulations and ergonomic analysis in order to integrate human simulation into the industry development processes (Annarumma et al., 2008). Although PLM systems integrate different data from the factory, they also produce information silos, hindering optimization processes and other processes that require data to be closely linked, and the existing studies do not offer a solution that can be used for optimization, neither a methodology for production data to be linked to ergonomic data. There are also studies that offer a methodological framework to consider ergonomics and productivity, which mention the need of better ergonomic evaluation methods due to limitations of known methods like RULA, however, the improvements are based on traditional balancing and sequencing techniques but no new method for optimization is proposed (Battini et al., 2011).

In the most recent studies, there are some proposed methods for multi-objective optimization of ergonomics and productivity. There are examples of line balancing using energy expenditure models that propose analytical and numerical approaches for line balancing (Battini et al., 2016). There are also studies based on ergonomics risk indexes that try to reduce risk injuries without increasing production time too much (Bortolini et al., 2017). In the last few years the use of evolutionary algorithms for multi-objective optimization of ergonomics and productivity have started to appear as a solution (Harari et al., 2019), also compared to other approaches, showing that evolutionary algorithms outperform other types of approaches when it comes to obtaining more optimal solutions and reducing processing time (Harari et al., 2017). However, these studies consider a single approach at the same time, either balancing or changing the design of a workstation, but they do not offer a solution that considers all the approaches at the same time. Also, these studies are punctual experiments, which do not offer a digital tool that implements these methodologies integrating the solutions with DHM tools or production simulation tools.

3.5.2 NEED OF A TOOL FOR OPTIMIZATION OF ERGONOMICS AND PRODUCTIVITY

When production and human simulations are combined, manikins can be analysed individually at the level of a workstation, but the available tools do not offer ergonomic information at higher levels such as ergonomics of the entire production line. There exist numerous production optimization tools such as FACTS Analyzer (Ng and Bernedixen, 2018) and Siemens Tecnomatix Plant Simulation (Siderska, 2016), however, DHM tools nowadays do not offer any optimization tools for the optimization of the ergonomics of the workers. However, both DHM and production simulation tools do offer the possibility to make scripts and, in this way, develop your own methods for these optimizations. For example, IPS IMMA (Högberg et al., 2016) offers LUA script programming language (Ierusalimschy, 2006) for implementation
of scripts in the IPS IMMA simulations, however, when included in the simulation environment, the scripts are limited if they are compared with the capabilities of usual programming. There is therefore a problem in the access and exchange of data and this problem is accentuated in the case of human simulation data. There are previous studies (Joung et al., 2016) that have indicated and tried to solve this problem, however nowadays there is no standard communication that allows to communicate in a simple way with both human and production simulation programs. That is why it is necessary to develop a tool that interacts with human simulation and production programs, but which allows the free development of optimization methods to be able to implement new methods without the limitations of developing them within the simulation software.
4 PHILOSOPHICAL PARADIGM AND RESEARCH METHODOLOGY

This section defines the philosophical bases and research methodologies of this research proposal. This will define both the type of analysis that will be performed and the knowledge generated. In addition to this, it allows the use of different frameworks to facilitate the process of answering research questions.

4.1 PHILOSOPHICAL PARADIGM

In this research proposal it is wanted to show a relation between ergonomic factors and productivity factors, and optimize them by understanding these relations. Therefore, in this research relationships and causality between variables and factors will be studied. Hence, positivism doctrine will be taken as a philosophical paradigm. In this doctrine the world must be observed in an objective way to demonstrate causalities and laws formulating hypotheses and testing them.

Also, for this research, a deductive methodology will be used to solve the philosophical paradigm. A deductive research starts with a hypothesis, is based on demonstrating causality and it is normally a quantitative research.

4.2 RESEARCH METHODOLOGY

The main research strategy that will be used for this thesis is Design and Creation, and this methodology is within the Design Science (Hevner et al., 2004). This strategy is based on creating an artifact, either software or a physical product through some steps. Comparing to other research strategies, Design and Creation studies a problem or a case and designs an artifact to solve it, while other strategies are based on studying the nature or different cases to generate general knowledge. In this case, the problem is the need of a method to concurrently optimize productivity and ergonomic factors in simulations, and the artifact that is going to be created is a digital tool to implement the created method.

As the research strategy is Design and Creation, a Design and Creation framework will be used. This framework should help to understand the iterative process that this methodology has, by developing and evaluating a method or an artifact. This development must take into account the knowledge gap and industry needs in order to be implemented properly by using data collection and analysis techniques and by basing the work in existing theories, methods and frameworks. For this purpose, the information systems (IS) research framework (Hevner et al., 2004) shown in Figure 9 has been used.
**Figure 9. Design and Creation Framework (Hevner et al., 2004)**
5 METHOD

This research must provide knowledge to the scientific world. Therefore, it must be demonstrated that the knowledge generated does not currently exist. Apart from this, the knowledge generated must be useful, in this case to the industry, so that this knowledge has an impact on the real world. This leads to the conclusion that the methodology created during this research must be implemented in a tool so that the industry can verify its effectiveness and thus be a proven methodology in practice. For this, a prior knowledge of the needs of the industry is initially required. This is why interviews with industrial collaborators will be conducted initially to meet these needs. In addition to this, cases will be needed to develop and evaluate the methodology, so that use cases will be constructed to be used during the research. In this way, with the information collected and with the use cases, the multi-objective optimization method of ergonomics and productivity and the tool that represents this method can be developed in parallel.

5.1 INTERVIEWS

Being a research based on the improvement of the industry both in productivity and ergonomics of the workers, the research must be relevant for people involved in the industry so that the knowledge generated can be applied in the real world and generate changes. For this, the first step is to understand the needs of the industry, since generating a method that is not needed will have little acceptance. Therefore, during the thesis, interviews will be conducted in the industry so that the thesis is based not only on the generation of a new method, but also on the adaptation of the method to integrate it more easily into the industry. This will help to exert a change in how the industry treats ergonomics of the workers, and in addition to this, to obtain a validation of the method through the tool created to instantiate the method. Since this thesis has been initiated in the MOSIM project environment (MOSIM, 2019), the companies belonging to this project have been consulted to obtain an initial knowledge in the topic.

5.2 USE CASES

Subsequently, the method and the tool will be developed in parallel so that the method can be continuously tested and validated. For this, a defined case of a production line is needed to optimize both its productivity and ergonomics for its workers. It has been proposed to make three different cases: 1) an initial case to demonstrate that the initial proposal of this method can improve a production line, 2) a more
complex and detailed case to be able to develop the method and the tool during the thesis, and 3) a final real case to be able to validate the methodology and the effectiveness of the tool.

For the initial case it has been decided to use a simple fictional case that can be reproduced quickly. Given the collaborating industries, it has been decided to use the pedal car assembly at Scania Smart Factory as a case to develop the methodology and the tool. Scania Smart Factory is a sandbox that replicates an industry without being a real production line, so it can be used as a production line and apply changes to it without the restrictions of a real production line. In the case of validation, an attempt will be made to validate the method through the use of the tool by engineers and ergonomists at collaborating companies.

5.3 DEVELOPMENT OF THE METHOD OF MULTI-OBJECTIVE OPTIMIZATION OF ERGONOMICS AND PRODUCTIVITY

The development of the method is a process of Design and Creation, a methodology that is in the context of Design Science (Hevner et al., 2004) further explained in chapter 4.2. Design and Creation is based on developing an initial method and iterating to develop the appropriate method to optimize ergonomics and productivity at the same time. The development of this method includes adequately evaluating the ergonomics of the workers, the creation of an information structure to place the worker within the production and the method of optimizing ergonomics and productivity. For this process the use cases mentioned above will be used.

5.4 DEVELOPMENT OF THE TOOL

The tool will be developed with the main focus of being easily distributed and adapted to several simulation software, both for several DHM tools and for several production simulation software. The main language for the development will be C++ due to its generality and performance for heavy computing, which will be required for multi-objective optimization algorithms and manikin posture processing. In addition to this, the libraries used for the developed tool will be open source, so the code, and therefore the method, can be distributed easily.

The development of the simulation software, both production software and DHM tools, is out of scope in this research. As the developed tool requires simulation software for both production and ergonomic factors, it is critical to enable a connection to existing software. As each software offer different input and output communications, such as scripting, standard communication protocols or file transferences, it will be necessary to create a link to each simulation software that will be connected to the developed tool.
These links will need to be written in the native code or protocol of the simulation software, being unique to a specific simulation software most of the times. The development of these links will enable the generality and cross-platform capability of the developed tool.

As an initial case, and due to the existing collaboration with the developers, IPS IMMA (Högberg et al., 2016) and FACTS Analyzer (Ng et al., 2007) will be used as DHM tool and production simulation software for this thesis. This collaboration allows easier input and output communication between the simulation software and the developed tool, being possible to integrate the developed tool together with the simulation software for a better user interaction. However, this does not risk the independence of the method and the developed tool, since it will be possible to use the developed tool as a standalone software and to create new links to other simulation software.

5.5 TIMELINE OF THE THESIS

The interviews, use cases and development of the method and the tool are represented in the timeline of the thesis (Figure 10).

![Figure 10. Thesis Timeline](image-url)
6 PROCESS DIAGRAM OF THE DEVELOPMENT OF THE METHOD

The process of creating a method and a tool for multi-objective optimization of ergonomic and productivity is a Design and Creation process which considers initial input from organizations, such as industry partners, and follows an iterative process in order to create the method and the tool. For this purpose, the framework (Vilarinho et al., 2018) shown in Figure 11 has been used as a base.

![Example Process Diagram](image)

This base framework (Figure 11) has been adapted for this thesis in order to consider the data collection techniques, industry partners and the study of the ergonomic and productivity factors. In the process diagram (Figure 12) the first step is to collect initial data and study the existing methods and tools (Figure 12, blue) to develop a method and a tool (Figure 12, green) using Design and Creation and case studies methodologies (Figure 12, orange). These methodologies include data generation and collection techniques (Figure 12, purple) such as simulations, interviews and software testing, which will generate data for the thesis (Figure 12, red) and will help to develop the method and the tool (green). This process diagram will provide the steps to answer the research questions.
**FIGURE 12. PROCESS DIAGRAM OF THE THESIS**
7 CHALLENGES

After studying the possible difficulties, it has been concluded that there are three main difficulties. These difficulties are: 1) the complexity of the interaction between ergonomic and productivity factors, 2) the lack of an ergonomic method that can be used for optimizations, and 3) the complexity of optimizing multi-level models. These problems have been analysed individually to consider their difficulty and specify them as much as possible before starting the investigation.

7.1 COMPLEXITY OF THE INTERACTION BETWEEN ERGONOMICS AND PRODUCTIVITY

The first challenge arises with the thought of comparing and balancing two completely different factors from each other, such as ergonomics and productivity. This task is complicated since, while productivity evaluations are easily quantifiable, ergonomic evaluations offer qualitative information in many cases, and are evaluated with some subjective criteria. In addition to this, ergonomic evaluation methods are most often applicable to certain cases, being dedicated to a specific type of task or to specific parts of the body, without having a single factor that measures the worker's complete ergonomics and represents it with a number. Considering ergonomic and productivity factors at the same level and at the same time requires rethinking typical industrial processes where production engineers design the workstations focused on the productivity, and ergonomists validate them from an ergonomic point of view. Performing this research will require rethinking this methodology and consider that ergonomists and production engineers will have to synchronize their work during the design and / or redesign of the stations.

7.2 LACK OF ERGONOMIC EVALUATION METHODS TO MEASURE ERGONOMIC IMPROVEMENTS IN OPTIMIZATIONS

The second challenge is related to the first challenge, ergonomic factors cannot be treated as if they were productivity factors. Making optimizations in production is something known and that is carried out every day in the industry, however in ergonomics it cannot be applied in the same way. There are ergonomic optimization studies (Butlewska et al., 2018), however, it is not so straightforward to define what it is to improve ergonomics as it is in production, where increasing production and reducing times or costs is always positive. There are some studies that tried to solve this problem by analysing different ergonomic evaluation methods (Berlin and Kajaks, 2010), however, the common approach when using ergonomics in optimization is to look at results from different ergonomic evaluation methods and optimize for decimals of the score (Bortolini et al., 2017). This approach does not fit this thesis since static posture ergonomic
evaluation methods are not representative of the risk of WMSDs in time-based simulations, and therefore cannot be used as they are in optimizations. That is why another difficulty will be adapting or creating a suitable method to evaluate improvements in ergonomics.

7.3 COMPLEXITY OF MULTI-LEVEL MULTI-OBJECTIVE OPTIMIZATIONS

The third challenge lies in the technical part of applying the method. As mentioned above, factory optimization is usually a multi-objective optimization of NP-Hard complexity level. If the ergonomic factors of the factory workers are added to the productivity optimization objectives in a factory, the optimization becomes more complex and therefore more complicated to obtain the optimal result. For the creation of the tool it will be important to select the optimization algorithm that best fits this complexity, comparing different algorithms and multi-objective optimization methods to choose the most appropriate one.
These tasks, and the steps for the development of the method are included in the planning (Table 3), where dark blue is a main activity and light blue a secondary task for that period.

**Table 3. Planning of the Thesis**

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9 ETHICAL DIFFICULTIES

The greatest ethical dilemma of this research is based on the fact that the method itself speaks of the optimization of productivity and ergonomics of workers. Therefore, the use of this method can lead to the confrontation of these factors, in which the dilemma of selecting solutions that may be prejudicial to the worker in pursuit of productivity improvements. The objective of this research is not to face ergonomics and productivity, but to find optimal solutions in which both are improved, therefore it should be ensured that the final solutions do not worsen the physical well-being of the workers.

In addition to this, in some cases when the method is applied in real industry, measurements will be made and motion capture systems will be used on workers. The data obtained by these collection methods must be treated in an appropriate manner respecting the protection of data since it is data that could compromise the people involved in it.

Finally, as this research is in the context of human factors and ergonomics, the research ethics code that will be followed is the one provided by the Human Factors and Ergonomics Association ("Code of Ethics - The Human Factors and Ergonomics Society," n.d.).
10 INTERNAL AND EXTERNAL VALIDATION

In order to validate this research internally, realistic models should be available for the simulations. This can be done through the use cases that will be carried out in collaboration with industry partners. In addition to this, it will be important to carry out an adequate simulation manipulation, isolating the variables and studying each of them individually to see the impact they have on ergonomics and productivity factors. Finally, multiple models must be used to demonstrate that the method is not dependent on a single model and that it can optimize models with different characteristics, which is why at least three use cases will be carried out during the research.

To validate the research externally, the industries participating in the associated project will be allowed to test the method through the use of the tool. Based on feedback from industry partners, it will be possible to demonstrate that the method created during this project is effective and that it improves both ergonomic and productivity factors.
REFERENCES


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