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STUDY PROJECT

Human Factors and Ergonomics Study of an Assembly Process

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14/02/2020

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NOMENCLATURE

3D SSPP	3D Static strength prediction program
CAD	Computer aided design
COBOT	Collaborative robot
DHM	Digital human modelling
DMH	Distributed moment histogram
DOF	Degrees of freedom
EFTA	European free trade association
EMS	Engine management system
EN	European standard
ESMERA	European SMEs robotics applications
FABLAB	Fabrication laboratory
HRI	Human robot interaction
HSA	Health and safety authority
HSE	Health and safety executive
ISO	International organization for standardization
.jt	Jupiter tessellation format
LMS	Laboratory for manufacturing systems & automation
M.1	1st Manufacturing challenge
MSD	Musculoskeletal disorder
NIOSH	National institute for occupational safety and health
OWAS	Ovako working posture analyzing system
PLM	Product lifecycle management
QOC	Question option criteria
PS	Process Simulate
ROBCAD	Robotic computer aided design
ROI	Return on investment
RULA	Rapid upper limb assessment

Rx	Rotation around x-axis
Ry	Rotation around y-axis
Rz	Rotation around z-axis
SME	Small and medium-sized enterprises
SMF	Smart mini factory lab
SYSROOT	System root
TS	Technical specification
TSB	Task simulation builder
U. O. P.	University of Patras
UNI	Italian national unification
UR	Universal robot
XLS	Microsoft Excel spreadsheet

Chapter 1

INTRODUCTION

This study project represents a fundamental contribution to the 'ESMERA-M.1' manufacturing challenge. An industrial company located in Slovenia defined the challenge. Specifically, it requires the development of a solution to a 'wire harness assembly process' problem involving human-robot collaboration applications. [1]

1.1 Objectives of the work

The current wire harness assembly process is performed manually at two workstations and is very time consuming. The company that proposed this challenge is looking for a semi-automated assembly process to replace the manual one. The essential requirements are based on standardization and lean manufacturing adaptability. In particular, to evaluate the compatibility and efficiency of the solution, the following metrics will be considered. [2]

1) Ergonomics: the new process should put less strain on the worker;
2) Cycle time: the new cycle time should be the same as or shorter than the current manual process (which is 22.5 seconds on two workstations).

To show the importance of this challenge, it is worth noting that good ergonomics helps to increase comfort and productivity. Moreover, as regards the cycle time, it should be noted that 1 second costs 1€ in wire harness processes. [3]

A further objective of this study project was the autonomous learning of new simulation software called 'Process Simulate', which was developed by Siemens PLM Software. The software was chosen from among different solutions in order to simulate the new assembly process. The writer independently learned the functionality of this software through reading of self-paced courses. [4]

All in all, thanks to this study project, the writer had the opportunity to integrate and put into practice different concepts learned during different courses within the Master program in Industrial and Mechanical Engineering. The most useful courses for the objectives of this study project were the following. [5]

1) Simulation in production and logistics;
2) Industrial automation and mechatronics;
3) Project economics and management;
4) Planning of logistics systems.

Indeed, the competences acquired during the above-mentioned Master courses have been applied in different areas of the study project. For example, they were useful for choosing and working with the most appropriate simulation software and with the most suitable robot. Moreover, they helped with integrating the various operations and evaluating the results of the chosen solution.

In addition to academic skills, the writer was also able to apply his professional skills gained as a technical labor inspector. Indeed, for this study project, he consulted and exploited various ergonomics and safety standards and methods.

1.2 Work plan

As mentioned in the previous paragraph, the goal of this study project was to propose a new collaborative, ergonomic and efficient assembly workstation for wire harnesses. The improvement was meant to reduce the operator's workload and improve his ergonomics, while maintaining or reducing the current cycle time and using a single workstation instead of two. The desired result was a shared process able to exploit human abilities and robot speed and strength. [6]

A large part of this study project was developed at the 'Smart Mini Factory (SMF) Lab' at the Free University of Bolzano. The lab is used for studying advanced concepts of production processes within Industry 4.0. [7] The work plan developed to achieve the objectives of this study project was as follows:

1) Choosing the most appropriate simulation software;
2) Independent learning of the selected simulation software;
3) Ergonomic analysis of the current workstation;
4) Simulation of a new wire harnesses assembly process;
5) Ergonomic evaluation of the new workstation;
6) Analysis of the results obtained in terms of ergonomics and cycle time.

It was necessary to work with different simulation software (e.g. 'Tecnomatix Jack') before choosing 'Process Simulate' by Siemens PLM Software as the most appropriate for this project. The Siemens Italy group then kindly offered a collection of courses designed to teach one how to work with the software. As for the analysis of the current process, it was necessary to reproduce the current workstation in the SMF Lab using its technologies. The reason for this is that, unfortunately, the industrial end-user did not provide enough material for a detailed analysis of the current process.

Chapter 2

STATE OF THE ART AND THEORETICAL BACKGROUND

This section of the study project aims at providing a complete overview of human factors and ergonomics, ergonomic risk assessment methods and standards, and simulation software, as well as collaborative robotics for improved ergonomic processes. It considers mainly the most current research concerning these areas of interest.

2.1 Human factors and ergonomics

Human factors or ergonomics refers to the study of the interaction that exists between people and machines as well as the factors that affect this interaction. It is a scientific discipline which deals with understanding how people and other elements within a system interact. Ergonomics involves the use of various design methods to maximize overall human well-being and system performance. The purpose is to improve a system's performance by improving the interaction between humans and machines. Ergonomics is concerned about social behaviors and safe environments for productive, effective and comfortable human use. It addresses certain factors such as movement (pushing, pulling, lifting, standing and sitting) as well as environmental factors (humidity, temperature, lighting, and noise). The ergonomic concept is determined by metrics such as work done beyond human capabilities. [8]

The use of ergonomics principles in the workplace increases the chances of performing the job with no apparent injury. Primarily, ergonomics refers to designing work activities that fit individuals, as it takes into account their various work limitations and their capabilities. Systems can thus be improved by changing the work environment or designing the user interface and tasks to be more compatible with the worker. The concept aims to match job requirements with worker capabilities. Ergonomics helps minimize the overall risk of injuries which may result due to physical handling. Musculoskeletal disorders can be prevented by employing proactive ergonomics through reduction, anticipation, and recognition of risk factors at an early stage, and the planning of new systems of work or workplaces. The whole process aims at designing operations which are enhanced by the best possible tool selection, materials, workstation layouts, and job methods, ensuring that the worker does not endure too much strain and stress. Work modification and redesigning working methods and spaces can lead to extra costs; hence, it is cost-effective to ensure minimal risk factors during the design stage. [9]

2.1.1 Importance of ergonomics in the workplace

Conditions such as poor posture and repeated body movements may stress the body, leading to musculoskeletal disorders. The primary symptoms of such infections include pain, discomfort, and fatigue. [10] Ergonomics serves a significant role in safeguarding workers against such injuries. The main reasons why it is fundamental to use ergonomics within an organization are listed below. [11]

Fewer employees experiencing pain - discomfort caused by the working environment can be minimized by the use of ergonomic improvements.

Increased output and throughput within the workplace – the primary risks resulting from MSDs are reduced as a result of ergonomic improvements, leading the employees to be more productive, efficient and increasing workers' general job satisfaction.

Increased worker morale – paying closer attention to ergonomic development can increase employees' interest levels as they feel more valued since their safety in the workplace is well catered for.

Reduced employee absenteeism – workers experience pain-free working conditions; hence, their fear of potential risks decreases significantly as the likelihood of an injury occurring is minimal.

Increase in savings – both the direct and indirect costs of MSDs are reduced. Direct costs include, for example, legal expenses and medical payments. Indirect costs include accident investigation, training of new employees, damaged machinery and materials.

Ergonomics involves solutions to various barriers occurring in an organization. The main restrictions may include the following aspects. [12]

High costs - ergonomics does not focus on high price returns, hence ways of saving extra costs. The programs generated are generally comprehensive, allowing focus on different areas. Employing risk reduction techniques implies that the extra cost which could have been generated by employee compensation is completely reduced.

Lack of employee morale regarding new inventions – ergonomics employs various measures which convince employees to be interested in their jobs. Ergonomics can achieve this by personalizing their working areas for job satisfaction, and health. Ergonomics helps employees to develop techniques for making work more comfortable. It also serves as a constant reminder to healthy workers on the importance of being patient.

Lack of management interest in employees' safety and comfort – investment values are presented as a return. This encourages use of the safety committee, setting a defined price on the service delivered, and documenting any changes made.

Some basic examples of ergonomic applications include the following cases.

Stress	Improvement
Awkward posture	Maintain neutral posture
Working at danger zone	Work at comfort zone: hand-shake zone
Working for long time in static position	Allow for stretching and movements
Using excessive force	Minimize high force loads
Repetitive motion	Reduce unnecessary motion
Contact stress	Avoid sharp or hard contact surfaces
Frequent vibration exposure	Minimize vibration exposure
Poor lighting	Provide adequate lighting

Table 1: Basic examples of stresses and related ergonomic improvements [13]

2.1.2 Impacts of poor ergonomics

Exposing workers to poor ergonomic working surroundings can easily predispose them to long-term health issues as well as injuries that are preventable. Maintaining a confident posture reflects the specific structural framework an individual carries over a lifetime. Keeping the right attitude can be beneficial to both health and personal wellness. If this approach is reduced, the general structure may decline, especially if the design used is wrong. Poor design will reduce the effectiveness of human performance because humans dominate the relationship. [14] Sometimes poor posture causes no pain, but gradually leads to long-term health issues, putting employees at risk. The main long-term effects related to poor ergonomics include the following. [15]

Productivity plummets – overall output and efficiency within a working environment may drop drastically, especially when the worker cannot work anymore.

Increased spinal degeneration – the workers slowly get used to the same posture with minimal strain, which may eventually lead to weakening of the spinal cord.

Heightened injury risk – working long shifts such as 10 hours or more may raise injury risks among workers.

Irreversible damage – working under poor ergonomic conditions may result in irreparable damage to one’s health, or permanent health deformity.

Posture aging – maintaining specific postures may lead to aging. A worker gets used to them, and eventually, physical signs can be seen, reflecting certain working behaviors.

Respiratory issues – most workers get breathing complications due to diseases such as blood pressure and heart infections. Poor ergonomics may directly affect breathing mechanisms, especially when a position is maintained during breathing.

In conclusion to this paragraph, maintaining correct ergonomics may be the best solution to minimize long-term effects resulting from poor posture in working environments.

2.2 Ergonomic risk assessment methods and standards

Risk assessment in ergonomics focuses on when, how and who should perform what. Risk assessment involves a series of stages. Ergonomics has increasingly developed to be the main component for maintaining safety measures within an organization. Various techniques used to assess and define the ergonomic risk present within the workplace are essential elements of ergonomic progression. Every organization should focus on ergonomics and the various procedures for implementing an active process. [16]

The basic analysis point defines how a company will approach the analysis and reduce the ergonomics risk. The process involves identification of ergonomics stressors that are related to developing musculoskeletal disorders, which is the main aim of ergonomic activity. The main stressors, in most cases, are realized through check-list driven methods and observation. Detecting risks related to ergonomics does not necessarily involve or require the use of advanced techniques or tools. [17]

Use of the observational method is considered the most effective and efficient technique for data gathering on ergonomic stressors in working environments. However, during observation, data density is not emphasized. The observation technique does not produce measurable results such as data, so it becomes difficult to track impacts. The main limitation of observation is therefore that one cannot give an overview of changes in the workplace, such as the general improvement, when this method is used. [18] Positive impacts of the stressor identifying technique are based on which method is used. This technique is associated with quick turnaround time and low assessment cost. There is a need for re-organization of companies, new forms of work organization, workforce diversity and also communication technology in the work system to be properly aligned. Conducting a simple observation method can be useful to achieve a quick fix of an obvious ergonomic stressor. If costly or intricate complications are occurring in the current situation there may be a need for a more sophisticated method. Similarly, if the situation becomes more complicated, elaborate, or expensive, the need for a more advanced approach may present itself. [19]

Making use of risk assessment tools is the next ergonomic assessment technique in situations where the organization is interested in improving its ergonomics job assessment method. The main types of equipment used are not complicated (except for a force gauge in some cases). Before using an ergonomics risk assessment tool, the company may raise the following questions.

1) Why is the company considering using a risk assessment tool?
2) Which body will be responsible for implementing the assessment?
3) How can the ergonomic risk assessment tool be used effectively?
4) Which conditions necessitate using specific ergonomic risk assessment tools?

These are the four main pillars for how an ergonomic risk assessment tool should be applied to programs or safety issues. [20]

2.2.1 When and why ergonomic risk assessment should be conducted

While considering the correct time to carry out a risk assessment process and the reasons for doing so, the following questions should be addressed. [20]

1) Which are the main jobs with high potential risks?
2) How much is too much?
3) How can it be shown that significant improvements were made?

Identifying the main stressors present within a working environment is evaluated as the first step in any ergonomic action. Subjective evaluation helps accomplish the identification process. The primary assessment involves identifying things such as extreme posture or high force and frequent repetition as present in a working environment, without any apparent metrics. The above method is only suitable for determining the various jobs which may require further investigation, since identifying stressor severity is quite challenging to document and express. Comparing diverse jobs and various functions to determine where to focus ergonomics efforts is a difficult task.

Questions such as "which jobs pose the greatest risk?" may arise when this comparison between various jobs is made. Ergonomics intervention may not eliminate working stressors; the main stressors may only be reduced rather than removed. The fact remains that, since humans are involved in working environments, stressors will always be present. Due to such human factors, questions such as "how much is too much?" are asked.

Some intrusions may refer to the stressors observed in the initial evaluation, which may result in other stressors. In cases where interventions have been put in place, a thorough assessment should be carried out to ensure stressors are eliminated or reduced as compared to the original observation. This may help to avoid the creation of secondary stressors in the process. By addressing such issues, the organization is urged to ask, “how can improvement be evaluated and shown?”. This question leads to different answers through the use of ergonomic risk analysis tools. Numerical outputs can be provided through the use of quantitative evaluation tools which can eventually be utilized as the primary metrics for evaluation of MSD development for a given task. [19]

2.2.2 RULA method

Rapid Upper Limb Assessment (RULA) is a method developed to evaluate the ergonomic conditions of workers. An evaluation is done on a single worksheet page in which certain body conditions such as posture, repetition, and force are examined. Scores are then entered based on both the two central regions: section A for wrist and arm and section B for trunk and neck. When data for each section has been obtained, tables are created to assess risk using variable factors to produce a single outcome that represents the MSD risk level. [21]

The motive behind RULA was to ease use, enabling ergonomics assessment without requiring a higher degree in ergonomics or even the need for expensive equipment. An evaluator assigns scores for the various body parts using a RULA worksheet. The body parts evaluated include legs, trunk, neck, wrist, lower arm, and upper arm. When data has been collected for the various components, the next step involves creating tables for compilation of the risk factors. Eventually, a single score is obtained as shown in the table below.

Score	Level of MSD Risk
1 - 2	Negligible risk, no action required
3 – 4	Low risk, change may be needed
5 – 6	Medium risk, further investigation, change soon
6+	Very high risk, implement change now

Table 2: RULA levels of MSD risk [22]

2.2.3 Using RULA simulation software

The ergonomics data obtained through simulation software is more reliable and accurate. RULA assessment can be conducted using simulation software instead of PDFs, spreadsheets, and paper methods. [23] The workers are first interviewed by the evaluator to gain an understanding of the job and what is required. Before the use of simulation software, the worker's movements are first observed, as well as the postures adopted during working periods. Choosing the positions depends on the following criterion:

1) The most challenging work tasks and posture (dependent on the employee interview and the prior observation);
2) The longest maintained position in the working environment;
3) Positions in which the highest force load takes place.

Multiple poses can be evaluated by assuming several positions and numerous jobs in a working cycle. After observation and interviewing of the worker, the evaluator can determine the correct arm to evaluate, or if both arms should be evaluated. [22]

2.2.4 ISO 14738:2002 standard

'ISO 14738:2002' refers to an international standard that governs machinery safety. The rule highlights the various principles which designers must put in place to be held accountable for ergonomic factors. The measure describes the use of anthropometric specifications for designing a workstation in a piece of machinery. It also recommends the posture which a particular machine imposes by referring to 'ISO 11226:2019' and 'UNI EN 1005-4'. The creation of the 'ISO 14738:2002' standard was formulated to control machinery directives as well as EFTA rules. [24]

The measure laid down several rules which govern a worker's overall posture. For the case in this project, the main concern is seating posture. The standard states that the seat should offer stable and comfortable support, which allows for psychological worker satisfaction. The seat should be appropriate for the job being executed as well as remaining comfortable within the span of service delivery. The location should allow for rotation and changes in position. Moreover, the area should embrace the following psychological characteristics. [25]

1) Allowance of proper posture which requires little muscular strain;
2) Minimized spinal loading through maintenance of a minimum moderate lordosis with low muscular tension;
3) The intended users should be well accommodated by a diverse range of adjustability as well as different sizes available;
4) The working seat should allow for adjustments according to specific user requirements.

2.3 Simulation software in industry

Simulation software is the safe, efficient solution to the majority of real-world problems. The application of the same helps to provide a critical method of analysis which can be easily verified, communicated and understood. [26]

The program allows the users to make observations on the operations that they have read about theoretically and gives the opportunity to perform them to obtain better professional knowledge. In general, the use of simulation software is for the broad design of equipment so that the final product is closer to the design specs. Software is important for use in manufacturing companies and in logistics companies as well. The imitative process enables one to see how operators in the different areas behave when subjected to different conditions, which include testing for new theories. One major goal and useful trick that manufacturing and logistics companies need to use is the development of useful simulations which will determine the most important factors that affect fulfilment of their general objectives. [27]

2.3.1 Simulation of the real-world environment

When there is the creation of a theory on causal relationships, the theorist can quantify the relationship in the form of a computer program that can be useful for other operations. In that case, if there is the same behavior portrayed in the process, it means that there is a great chance that the proposed relationship is correct. Simulation software includes modelling of real phenomena using mathematical formulas, which is the key content (especially in the field of industrial engineering) that ensures that operators are aware of theoretical models and how to apply them in real life. [28]

Different processes involved in modelling a real phenomenon with various sets of formulas are strictly applied in simulation software. They are widely used to ensure the design of equipment results in a final product that is as close to the design specs as possible, without any high costs being incurred by modification processes. Penalties for improper operation of this simulation software are always very high. Moreover, the software is usually an essential program allowing simulation without necessarily performing that specified operation. [29]

However, it is also a computerized model of an imagined or real scenario that is used to educate different individuals concerning the performance of systems. Simulating something usually entails representing the critical behaviors or characteristics of any selected abstract or physical system. Its primary importance is to ensure that every individual clearly knows how conceptual and physical systems perform their work.

The characteristics of simulation software mostly depend on the type of tutorial software used. Menu procedural simulations provide instruction in the appropriate steps to ensure excellent performance in specific procedures. [30]

2.3.2 Application of ergonomics simulation software

Several industries often face the same challenge: the human element is not considered during the earliest stages of assembling, designing, or indeed the maintenance of different products. Several simulations can however, be applied to ensure that the above challenge is fully addressed by industry. This is done through the utilization of applied integration between Digital Human Modelling (DHM) and Product Lifecycle Management (PLM) solution packages. DHM usually use digitalized humans as representations of the number of workers who are inserted into a vitalized environment to ensure applicable predictions of performance or safety. It, however, includes visualizations of humans, with science and mathematics remaining in the background. [31]

Software employed in industry, known as industry 4.0 DHM, provides help with designing safer and ultimately efficient products while also ensuring optimal costs and productivity. However, applications using DHM software always have the potential and ability to create a space in which engineers can incorporate human factor principles and ergonomics at the earliest design stages. Ergonomic analysis has great importance, which includes:

Firstly, reduction of costs, through the systematic reduction of ergonomic risk factors by preventing costly MSDs.

Secondly, ergonomics helps by ensuring an improvement in productivity centers. Ergonomics can be implemented through job designation to create easier working conditions, less exertion, good posture, better heights and reaches and fewer motions, thus helping a workstation to become more efficient.

Thirdly, ergonomics helps in quality improvement while, on the other hand, poor ergonomics result in fatigued and frustrated workers that never do their best at work.

Fourthly, ergonomics ensures an increase in employee engagement. This is achieved when employees note that a company is putting maximum effort into ensuring that they are always safe and healthy. [32]

In this way, industries also reduce employee absenteeism and turnover, improve their morale, and increase employee involvement at work. Finally, ergonomics creates a better safety culture and usually shows the company's commitment to making health and safety core values. Healthy employees are always valuable assets that most industries like and appreciate. Simulation is in many ways used as a cognitive tool to understand how to achieve this. Through a recreation of assembly in a three-dimensional virtual environment, an animation allows one to see what human models performing acts need to do during a work process. [33]

2.3.3 'Process Simulate' software by Siemens Tecnomatix

Siemens' Tecnomatix's software 'Process Simulate' is defined as a digitalized manufacturing simulation tool applied to making development and verification plans for plant manufacturing systems. It is an add-on application extending the above functionality by enabling one to realistically simulate human tasks and create effective and efficient economic studies. In today's economy, simulation plays an ever greater role in the new automation industry where it usually saves costs and time. [34]

Within ‘Process Simulate’, the robot was firstly reproduced as a sequence-based model, but later it was converted to the final event-based model. Simulation is preferred to a robot since it is easier to make modifications and debug. Modifying real robots is costly and expensive compared to simulation. Human-Robot Interaction (HRI) is, however, a promising concept that helps increase the reconfigurability and flexibility of hybrid production working cells. [35]

Furthermore, in human-robot collaborative assembly, the presence of robots is important to inject dynamic change into pre-planned tasks and provide collaboration with human operators in a shared workspace. Robots that are in use today are usually controlled by pre-generated rigid codes that cannot provide support for human-robot collaboration. Deep learning is generally appropriate for enhancing recognition, classification and context-awareness identification. [36]

Proposed methods that are applied in HRI are usually expected to provide support to engineers, designers and also operators within production lines. HRI workplace automatic and design task allocation can result in a significant decrease in time needed for cell reconfiguration. A decision-making framework is, however, used to present a number of alternatives and evaluate those alternatives against sets of criteria. Complex tasks are simplified through recent developments and designs using robots. [35]

Coordination of robots’ and humans’ tasks always requires timely feedback and the awareness of situations from the perspective of both robot and human resources. Human resource station controllers provide room for the execution of human resources tasks that are later stored in the external databases. To enable safe human resources cooperation and coexistence, one should apply multiple-layer fenceless safety approaches. The above tools and methods are involved in very different industrial cases present within automotive industry assembly lines, which later proves the viability of the proposed concept for industrial settings. [37]

2.4 Collaborative robots for enhanced ergonomics

A robot refers to an electro-mechanical structure which follows a specific set of instructions given to complete a job. The class of so-called fixed robots is the most used in today’s world, however mobile robots (wheeled or tracked) are also available on the market. Automation in industrial robotics is a widely used aspect of industrial processes, hence the name industrial robots. In robotics, a simple task is done repetitively since the robots are used to carry out simple precision jobs. The programming of industrial robots also enables switching between different applications. The main design goals are keeping track of multiple positions and orientations. Designers are concerned about the various objects that form a robot, such as the joints, links and tools which surround the manipulators and their interactions. For effective and sustainable designs, the position and orientation of concerned objects are required to be presented in a mathematical way to ensure the manipulators move in the required direction. [38]

2.4.1 Advantages of Co-bots

Collaborative robots are easy to program within a short period, unlike traditional robots, which needs much greater knowledge of specific programming concepts. User-friendly software can be used (including mobile apps) to allow new concept learning. Collaborative robots provide for a manual setting to do certain tasks. Due to their easily programmable nature, they are easy to implement and assign different tasks.

Easy installation – unlike the cumbersome and tedious installation processes for traditional robots, collaborative robots are easy to set up and assign tasks, even on the day of installation. Depending on how they are set up, collaborative robots can serve as assistant employees in several departments doing various jobs.

Flexible – adding functionalities in collaborative robots is quite an easy task; hence, these robots can be used in various departments. Flexibility allows the robot to execute the maximum number of functions.

More accurate and consistent than humans – collaborative robots show more consistent and precise results than humans. Since the collaborative robots perform the same tasks with the same power and intelligence, the outcomes have no apparent deviation and are therefore reliable. Improved quality in the products made using collaborative robots ensures increased productivity and general outcomes for the product or service to be made. [39]

2.4.2 Universal UR5 robot

A UR5 robot is a highly advanced robot, which is produced by Universal Robots. It consists of a robot arm which is flexible and suitable for repetitive and dangerous tasks. The robot helps free workers from time wastage, thus adding significant value to the whole production process. [40]

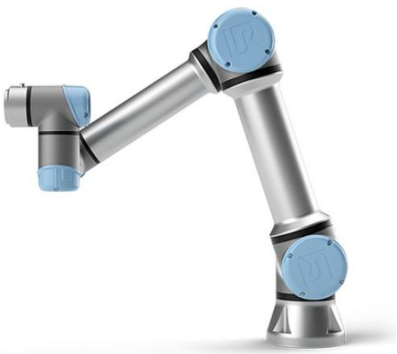

Figure 1: UR5 robot arm [41]

The UR5 arm is easy to implement within an organization and usually offers a fast response time to industry. Use of UR5 can automate processes by carrying out tedious tasks within a short period. Unskilled personnel can efficiently work with the robot since most technical aspects are already catered for. UR5 robots are the most suitable for assembling electrical wires since there is consistency in their work output and the quality of the products. Here is a list of the main technical specifications for the UR5 robot. [41]

Degrees of freedom DOF: 6 rotating joints

Joints range: +/- 360°

Speed: 180°/s for all joints

Working radius: 850 mm

Weight: 18.4 kg

Payload: 5 kg

Repeatability: +/- 0.1 mm

2.4.3 Application of Universal Robot arms in electronic assembly

Collaborative robots help increase precision and reduce costs in electrical assembly points. UR5 robots assist with quickening processes and mounting with an accuracy of 0.1 mm. Robot arms originating from Universal Robots are easy to deploy, space-saving and lightweight, fitting multiple applications such as the electronic industries. [42] Technology-based and electronic industries rely most on robot arms due to their agility, which is needed when automating manual duties. In general, a collaborative robot is useful for adding value to electronic industries. The cost of the robot arm can be paid back within a short period since the global production is increased. Electronic companies are growing at a faster rate; therefore, industries require robot arms which are easy to implement in a variety of technological and electronic production contexts. Moreover, Universal Robots arms reduce injury risks for employees. The robots ensure the correct movement and interaction of electronic components at a closer range to sensitive machinery. [43]

Chapter 3

IMPLEMENTATION OF THE WORK IN THE SMF LAB

The core part of the study project is presented in the third chapter. This section of the final report describes the work that was implemented, mainly at the Smart Mini Factory (SMF) Lab at the Free University of Bolzano. The purpose was to replicate, analyze and especially optimize the current wire harness assembly process in use at an industrial company located in Slovenia. The SMF laboratory is a great space used for research and inventing in the context of industry 4.0. [7]

3.1 Replication of the current assembly process

Unfortunately, the material provided by the end-user was not sufficient to enable detailed analysis of the current process. As shown in the following figure, the only video that was provided did not show all the movements of the operator's upper limbs during the positioning and taping phases of the wire harness assembly process.

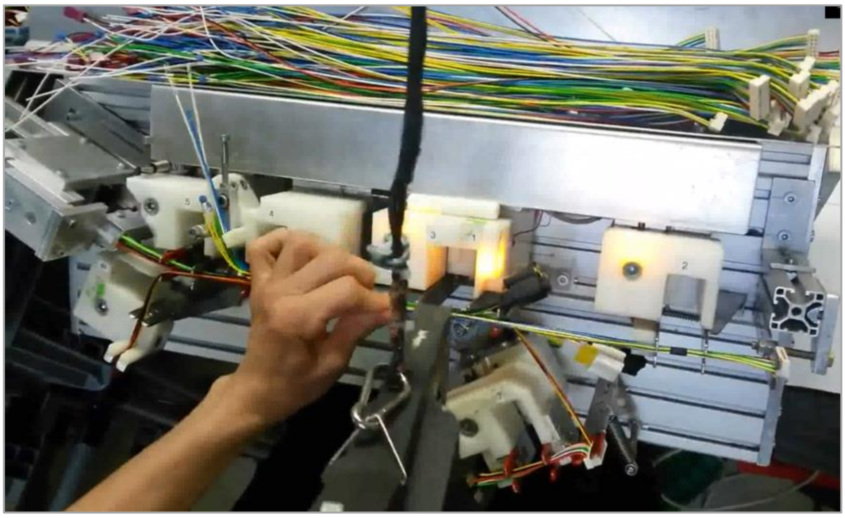

Figure 2: Video frame of the current assembly process

Instead, as indicated in paragraph '2.2.2 RULA method', in order to perform a correct ergonomic analysis, it is necessary to carefully observe and evaluate all the movements of the operator. For this reason, it was decided to replicate the current process in the laboratory. For this purpose, electrical wires of different colors were used. To represent the taping pistol, a similar-sized scanning pistol was used at first. The assembly panel and the supports for the wire harnesses were designed with AutoCAD software. The generated CAD file was used to cut a wooden panel on the FabLab laser machine 'Epilog Laser CO2 M2 Serie Fusion'. This machine can be used for cutting and engraving wood and other materials in a simple and reliable way. [44]

Below is the CAD drawing of the assembly panel, which was created as described above. The drawing shows a representation of the three wire harnesses with an indication of the mounting order, and the supports used for performing the taping operations, as well as the isolating tapes.

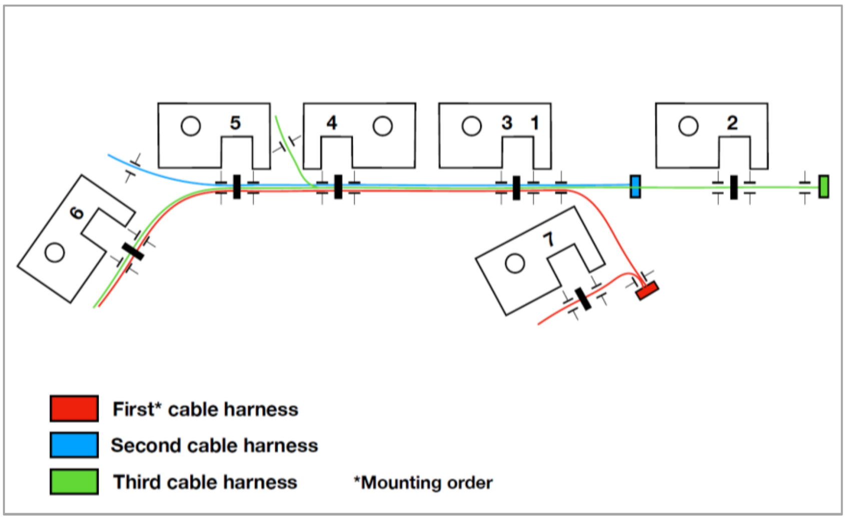

Figure 3: Assembly panel CAD drawing

With the purpose of accurately replicating the current wire harness assembly process, the times required for the various work operations were taken from the video and reported in the following table. The table shows the partial times for each working activity, as well as the progress duration.

Nr.	Activity	Time [sec]	Progress duration [sec]
1	Storing previous wire harnesses	4	4
2	Taking 1st wire harness	2	6
3	Positioning 1st wire harness	1	7
4	Taking 2nd wire harness	3	10
5	Positioning 2nd wire harness	3	13
6	Adjusting 1st wire harness	2	15
7	Taking taping pistol	2	17
8	Performing 1st taping	1	18
9	Depositing taping pistol	1	19
10	Taking 3rd wire harness	3	22
11	Positioning 3rd wire harness	5	27
12	Taking taping pistol	2	29
13	Performing 5 taping operations	10	39
14	Depositing taping pistol	1	40
15	Manual taping	5	45

Table 3: Operation times for the current assembly process

The table above shows that the total cycle time is 45 seconds. Considering that there are now 2 identical workstations in the company, the cycle time for assembling a wire harness turns out to be equal to 45/2 = 22.5 seconds. It is worth remembering that one of the purposes of the manufacturing challenge was to maintain or reduce the current cycle time. [2]

Furthermore, the timing and repetitiveness of operations is an important parameter to be considered within the ergonomic analysis. It must, however, be specified that the terms used in the table above are quite generic. The reason is that, as mentioned before, the video provided by the company did not show all the details of the various operations. The times taken from the video were, however, very useful for recreating the assembly process in the SMF laboratory. As will be shown in the following paragraphs, the tables related to the replicated process are more specific, in order to carry out a detailed temporal and ergonomic analysis of each individual working operation.

3.2 Ergonomic analysis of the current assembly process

After recreating the workstation and learning the various assembly operations, the entire process was replicated in the SMF lab. In order to conduct the required RULA ergonomic analysis, an operator was asked to perform the wire harness assembly process several times. The writer, a technical labor inspector, recorded the operator from different angles, together with an expert on accident prevention.

In fact, the so-called ‘Rapid Upper Limb Assessment’ (RULA) requires that an evaluator assigns scores for the various body parts during the different working activities using a RULA worksheet. The body parts evaluated should include the neck, trunk, legs, left upper arm, left lower arm, left wrist, and left wrist twist as well as right upper arm, right lower arm, right wrist, and right wrist twist. In addition to this, scores should be added regarding muscle use, required force and the repetitiveness of each operation. When data has been recorded for the various components, the next step involves drawing up tables for risk factors. In particular, the tables resulting from the RULA assessment method are the following. [22]

- Table A: combined upper arm, lower arm, wrist and wrist twist scores;
- Table B: combined neck posture, trunk posture and legs scores;
- Table C: combined total wrist/arm scores and neck/trunk/leg scores.

While table B is created only once, table A must be created twice, for the left and for the right sides of the body. Finally, table C will be given by combining the resulting scores of table A and table B. Table C contains the final score for the work operation being analyzed. The final score shows whether the posture is acceptable or requires further investigation and change. Moreover, it shows whether any changes are urgent.

To develop an accurate ergonomic analysis following the RULA assessment method, the various video frames and work operations were ergonomically evaluated. Below is an example showing the fifth taping, which will turn out to be one of the ergonomically most critical postures.

Figure 4: Operator performing the 5th taping

According to the previous mentioned RULA method [22], the scores obtained for the various parts of the body, regarding this particular work operation were the following:

- Neck: > 20° and twisted, score 4;
- Trunk: < 20° and twisted and side-bent, score 4;
- Legs: well supported and evenly balanced, score 1;
- Muscle use and Force: repetitiveness < 4times/min and weights < 2kg, score 0.

- Left upper arm: < 45°, score 2;
- Left lower arm: 60°-100°, score 1;
- Left wrist: < 15° and bent away from midline, score 3;
- Left wrist twist: twisted away from hand-shake position, score 2.

- Right upper arm: > 90° and raised shoulder and abducted shoulder, score 6;
- Right lower arm: 60°-100° and working across the midline of the body, score 2;
- Right wrist: > 15° and bent away from midline, score 4;
- Right wrist twist: mainly in hand-shake position, score 1.

In the next step, each score must be highlighted in tables A and B. Then, the two scores obtained are reported in table C, resulting in a single final score representing the MSD risk level for the specific work operation. Below is the example for the left side of the body.

Table A		Wrist score							
		1		2		**3**		4	
Upper Arm	Lower Arm	Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
		1	2	1	2	1	**2**	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	**1**	2	3	3	3	3	**4**	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table 4: 'RULA table A' for 5th taping, left side of body

Table B	Trunk Posture Score											
	1		2		3		**4**		5		6	
Neck	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	**1**	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	**7**	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Table 5: 'RULA table B' for 5th taping, left side of body

Table C		Neck, Trunk, Leg Score						
		1	2	3	4	5	6	**7+**
Wrist, Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	**6**
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Table 6: 'RULA table C' for 5th taping, left side of body

The MSD risk level obtained above is related to the 5th taping and to the left side of the body. The procedure must be repeated in order to determine the final score for the right side of the body, as follows.

Table A		Wrist score							
		1		2		3		**4**	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	**1**	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	6	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	**9**	9
	3	9	9	9	9	9	9	9	9

Table 7: 'RULA table A' for 5th taping, right side of body

Table B	Trunk Posture Score											
	1		2		3		**4**		5		6	
Neck	Legs		Legs		Legs		Legs		Legs		Legs	
	1	2	1	2	1	2	**1**	2	1	2	1	2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	**7**	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Table 8: 'RULA table B' for 5th taping, right side of body

Table C		Neck, Trunk, Leg Score						
		1	2	3	4	5	6	**7+**
Wrist, Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	**7**

Table 9: 'RULA table C' for 5th taping, right side of body

From the above method, the following risk levels regarding the 5th taping are obtained. [22]

- Left side of body: level 6 (medium risk, changes are required soon);
- Right side of body: level 7 (very high risk, changes are required immediately).

The procedure was repeated in detail for each working operation. The resulting tables A and B can be found in appendices 1 and 2 of this report. The final table C is shown below.

Working operations	Current	
	Left	Right
Taking 1st wire harness from box	5	4
Inserting 1st wire harness into frame	3	3
Taking 2nd wire harness from box	5	6
Blocking 2nd wire harness upper extremity	6	7
Inserting 2nd wire harness into frame	6	7
Adjusting first wire harness along the frame	6	7
Taking taping pistol (1)	5	5
Performing 1st taping	6	7
Depositing taping pistol (1)	6	5
Taking 3rd wire harness from box	4	4
Inserting 3rd wire harness into frame	6	7
Taking taping pistol (2)	5	5
Performing 2nd taping	6	7
Performing 3rd taping	6	7
Performing 4th taping	6	7
Performing 5th taping	6	7
Performing 6th taping	6	7
Performing 7th taping	5	7
Depositing taping pistol (2)	3	3
Removing and storing complete wire harness	6	7
Max values	6	7

Table 10: 'RULA table C' for the current assembly process

The results of the above final table will be analyzed in the following paragraph, in order to propose an ergonomically optimized workstation.

3.3 Proposal for an ergonomically optimized assembly process

The RULA ergonomic analysis of the current process showed high criticality levels. In particular, 'very high risk' levels (6-7) were obtained for the following work operations.

1) Positioning of 2nd and 3rd wire harnesses;
2) Performing of taping operations;
3) Removal and storage of the complete wire harness.

It can be stated that the current workstation is potentially dangerous in terms of biomechanical overload of the workers' upper limbs. The solution is the implementation of a new workstation, keeping MSD risk levels lower or equal to 4 (low risk). [22]

Observing the current panel layout, we note that the working operations are mostly carried out in the upper part. Only the first wire harness is positioned in the lower part. Instead, the positioning of both the second and third wire harnesses, as well as the removal of the complete wire harness, take place in the upper part of the panel. This means that the operator must continuously stretch his arms and often raise his shoulders. A possible solution would be the definition of a new panel layout. The new panel should include upturned wire positioning. In this way, most of the work activities would be carried out in the lower part of the panel, resulting in a lower stress on the worker's upper limbs.

As for awkward positions during the performing of taping operations, a possible solution would be to leave this operation to the robot. It should be recalled that the main purpose of the study project is to propose a new ergonomic assembly workstation with the use of a collaborative robot. [2] The robot could perform the taping operations on a second panel in order to increase the safety and productivity of the process. Moreover, after making sure that the quality offered by this new process is acceptable, the final removal of the wires could also be left to the collaborative robot. In this way, the operator's workload and the cycle time would be reduced even further.

The solutions to the main problems that were listed on the previous page are as follows.

1) New panel layout (2nd and 3rd wires at the bottom);
2) Assigning the taping process to a collaborative robot on a second panel;
3) New panel layout (wire removal from bottom) and/or assigning the removal task to the robot.

However, in general, all the analyzed activities presented unsuitable and high MSD risk levels. For this reason, in addition to the main improvements listed above, it is advisable to provide for further improvements in order to obtain better indexes for the other work operations as well. Using simulation software 'Process Simulate' on EMS (which will be discussed in detail in the next paragraph) the optimal panel inclination angle was calculated by the writer. According to the software results, an inclination of the panel above 45 degrees would cause an excessive bending of the wrists. Instead, an inclination of less than 30 degrees would cause an unnatural bending of the neck and trunk as well as repetitive abduction of the upper arm. Thanks to these simulated results, it was decided to maintain a panel inclination equal to 30 degrees for the design of the new workstation. The panel used thus far in the company is in contrast inclined at about 45 degrees.

Another improvement concerns the definition of chair and panel height relative to the floor, as well as the position of the boxes from which the wires are taken. In fact, from the video of the current process we see that a box is placed above the panel and the other two boxes are placed at the operator's sides, requiring him to execute multiple body rotations. Furthermore, the box containing the complete wire harnesses is located very far from the workstation.

The standard ‘ISO 14738:2002’ defines the ideal chair and worktable height, as well as the optimal horizontal working area, as shown in figure 5 and figure 6 (the arc-shaped area) respectively. [25] The optimal horizontal working area should include at least the two panels and, if feasible, the boxes containing the wire harnesses too (above the two panels). The collaborative robot could be positioned in the middle of the two assembly panels.

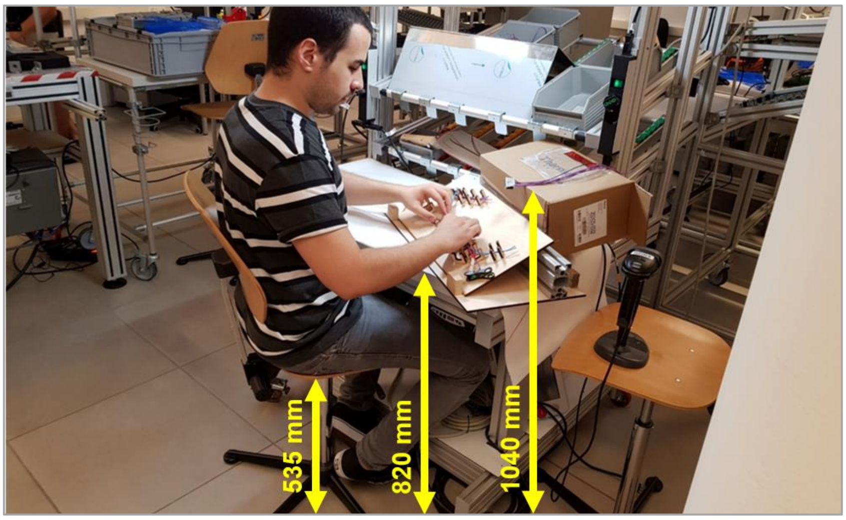

Figure 5: Chair and work plan height, according to ‘ISO 14738’

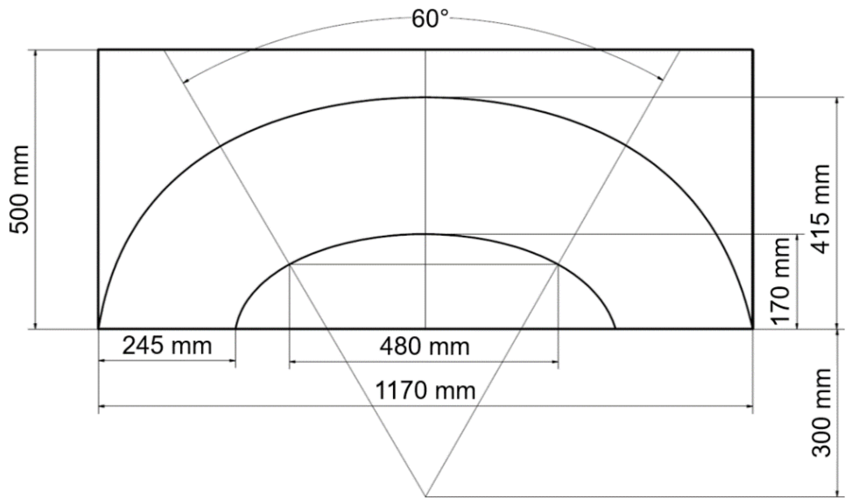

Figure 6: Optimal horizontal working area, according to ‘ISO 14738’

3.4 Simulation of the ergonomically optimized assembly process

One of the objectives of this study project was to independently learn a simulation software program in order to simulate a new wire harness assembly process. After testing different software, it was decided to work with 'Process Simulate (PS)', which was developed by Siemens PLM. This modern software enables simulation of manufacturing processes involving humans and robots working together within so-called 'RobCad' studies. [45]

3.4.1 Human modelling

The first resource that needs to be created is the human. Humans generated in this software have real anthropometric, ergonomic and biomechanical characteristics. It is possible to create humans of any stature based on validated databases and to scale human figures in order to evaluate workstations designs for a variety of people sizes. The human figures can move, balance, lift weights and they have the same limits as humans in the real world. Moreover, it is possible to define body and hand postures, force and weight loading as well as create tasks. All these operations are performed in the so-called 'Task Simulation Builder (TSB)'. [46] The human created in our study has average height and weight, respectively 1750 mm and 79 kg. Furthermore, his posture must be defined as 'seated straight'.

3.4.2 Working panel modelling

The 'Modelling menu' enables the creation of geometries that can be used in the study. Of course, it is also possible to insert an existing object that has been designed using other software (e.g. SolidWorks, AutoCAD 3D, Inventor). [47] The first geometry to be created is the working panel. As for the design of the current working panel, the dimensions of the new panel are 500 mm * 250 mm. This surface must then be extruded to obtain a height of 30 mm. All generated objects must be saved into the desired sysroot in order to modify or reuse them at a later time (e.g. for creating the second panel). The next step is the definition of the position and orientation of the panel. In order to have a reference for the panel, it is convenient to first set the posture of the human as seated within the TSB. After that, by opening the 'Placement manipulator' it is possible to translate the panel with respect to the principal axes x, y, z as well as rotate it in Rx, Ry, Rz. As explained in the previous paragraph, the ideal ergonomic panel inclination is 30 degrees and the panel should be positioned within the optimal horizontal working area represented in figure 6. In order to increase the productivity of the process and exploit the collaborative robot, a second panel should be inserted in the study. In fact, the human could position the wire harnesses on one panel while the robot tapes the wire harnesses that were previously placed on the other panel. The previously saved file of the first panel can be re-imported into the study and positioned and rotated with the procedure just described. Obviously, in the real model, the work table and the operator's chair must be adjustable in height.

3.4.3 Box modelling

The next objects to be created are the boxes in which the three wire harnesses are contained. To minimize the movements of the operator's body, it was decided to create three boxes above each of the two panels. To do this, a single box can be modelled following the same procedure described in the previous paragraph and using the additional 'subtract' function, in order to obtain the internal volume of the box. The box length is equal to the panel length (500 mm) so that there is enough space for all the wire harnesses. The box width is equal to 1/3 of the panel length (167 mm), in order to place three boxes above each panel. The height of the boxes is equal to 140 mm, which is a typical value used for Kanban picking containers. [48] The file thus created must be saved into the sysroot and re-imported into the study in order to create the other five boxes. All the boxes must then be positioned above the two working panels. During the positioning and orientation phase, it is necessary to place the boxes as much as possible into the ideal horizontal working area of figure 6. Eventually, the final box for storing the complete wire harnesses could be modelled in the same way. Obviously, the final box must be bigger than the other six boxes and could be placed near the workstation, as now there is more free space around the operator. It is worth remembering that, in the current assembly process, the final box is far from the workstation because the operator is surrounded by boxes containing the three initial wire harnesses.

3.4.4 Wire harness modelling

The next step consists in the creation of the three wire harnesses. In the current assembly process, the wire harnesses are positioned at the top of the working panel. Instead, the RULA method states that it is better to avoid stretching the arms too much. [21] Therefore, in the new assembly process, the wire harnesses will be positioned in the lower part of the panel. This is possible by almost mirroring the current layout.

An important limitation of PS is the impossibility of bending solid objects. To overcome this limitation, it was decided to create the wire harnesses already bent. During the simulation, the operator will position them on the two panels and then touch them exactly where he would touch them, if he were to bend them. This solution is valid because the weight of the harnesses is negligible (< 2kg). [22]

In order to model the wire harness within 'Process Simulate', the modelling menu allows a polyline to be drawn by defining the coordinates of the various points directly on the working panel. After that, the 'swept to circle' function enables the extrusion of the solid form of the wire harnesses starting from the previously defined polyline. [49] Moreover, it is convenient to use different colors for each of the three wire harnesses, as done for the replication of the current assembly process in the SMF laboratory. The wire harnesses thus created must finally be positioned inside the respective boxes.

3.4.5 Robot modelling

In order to compute the robot size, the minimum radius of the operative space was calculated as 589 mm. Moreover, the taping gun weights 3 kg, so the robot payload must be at least 3 kg. [3] Although different robots meet the requirements in terms of both reach and payload, the UR5 was chosen, since it is already available at the University of Bolzano. UR5 robots are widely used in assembly processes. [50] The '.jt' models of different robots can be downloaded from the Siemens website. [51] Very often the robot models are offered in other formats, and it is then necessary to convert them using the 'Upgrade CO' program within the PS package.

In order to ensure its operability, the base of the robot should be placed in front of the operator, in the middle of the two panels and above a cubic plate, as shown in figure 7. Moreover, robots downloaded from the library do not have tools attached to them. It is necessary to create a geometry representing the taping pistol and mount it on the last frame of the robot using the 'mount tool' function. [52] If in future applications the removal of the complete wire harness will be left to the UR5, an additional tool change should be provided.

Robot kinematics is another aspect that has to be defined by the user. The dependencies of the robot joints and links are defined within the 'Kinematic editor'. [53] The maximum speed and acceleration can be defined in the robot 'motionparameters.e' file, by changing the parameters 'cart_max_lin_speed' and 'cart_max_lin_acc'. The reference standard for these parameters is the 'ISO TS 15066:2016'. This standard provides specifications for operations where a robot and humans share the same workplace. [54] Specifically, if the robot could hit the hands and arms of the operator, the maximum speed would be 300 mm/s and the maximum acceleration 200-250 mm/s^2. All the resources generated in the model are shown in the following figure.

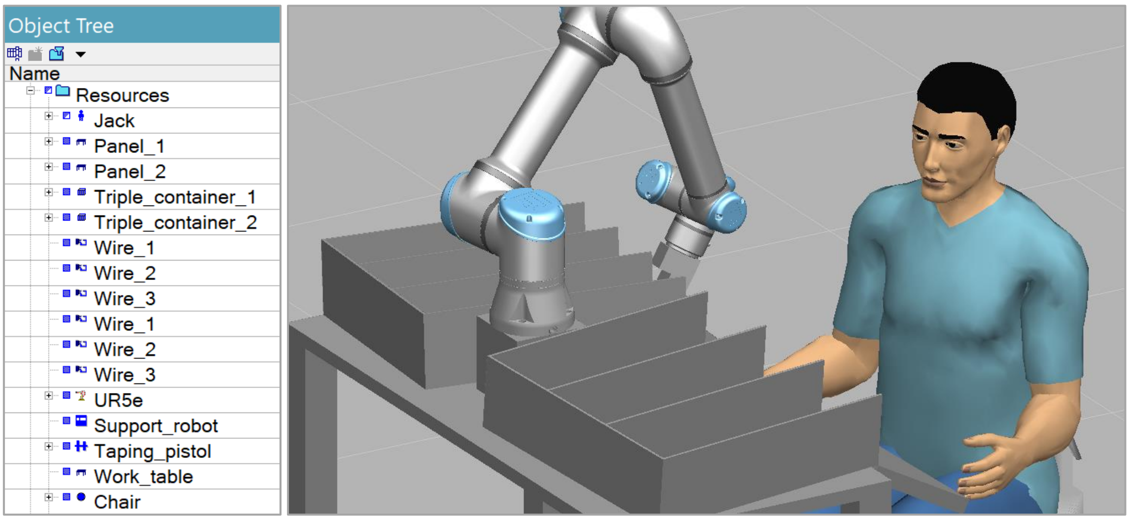

Figure 7: Resources within the simulation study

3.4.6 Human tasks

Before starting the definition of human tasks, the human grasp as well as vision envelopes should be checked by clicking on the respective buttons within the 'Human menu'. [55] After that, human postures and activities can be managed within the 'Task Simulation Builder (TSB)'. The TSB uses commands to create simulations with human models. First, the type of activity should be selected from the task list. Then, the selected activity must be defined by selecting 'who, what and where'. Finally, the operator's movements can be improved, for example by editing the final posture. [56]

The first required operation is called 'Sit'. This simple operation allows the human to remain seated during the entire simulation. The second operation is called 'Get'. For this operation it is necessary to indicate at which points the hands of the human will grasp each wire harness. The third operation is called 'Position' and requires indicating in which position on the panel the human will place the wire harness. The next operation is called 'Put' and is used to fix the wire harness on the panel. The last operation is called 'Touch' and can be used to touch the wiring harnesses where they should be bent. In fact, to solve the impossibility of bending wires in 'Process Simulate', it was decided to create them already bent. During the simulation, the human will touch them exactly where he would touch them, if he were to bend them. As mentioned above, this solution is valid because the weight of the wire harnesses is negligible. Indeed, according to the RULA method, all weights less than 2kg are negligible. [22]

Obviously, all the operations described above must be performed for all three wire harnesses. The operations thus created will appear on the 'Operation tree'. It is advisable to create different groups of operations, since it will then be necessary to reorganize them in sequence or in parallel with the robot operations.

3.4.7 Robot operations

Within PS, many different types of robotics applications can be defined. Some typical examples are discrete robotic applications (e.g. spot-welding applications), material handling (e.g. assembly operations) and continuous robotic applications (e.g. arc-welding applications). [57]

Robotic operations are defined by clicking on 'New generic robotic operation' within the 'Operation menu'. Here the frame of reference must be identified, which usually corresponds to the frame of the robot tool. After that, it is possible to program the robot path by defining the specific coordinates to be reached. [58] In our case, it is necessary to indicate the coordinates of the points where the wire harnesses must be taped by the robot, as well as the starting and end points of the robot path. The configuration of the robot can also be defined for each location, in order to avoid collisions with other objects or people.

3.4.8 Combining human and robot activities

After having defined all human tasks and robot operations, these can be combined in sequence or in parallel within the ‘Sequence editor’. First, activities that are linked together should be grouped within the ‘Operation tree’. After that, the sequence editor will automatically put in sequence the various groups of operations. [59] It will then be possible to set the right sequence of operations, as well as to define which operations must be carried out in parallel by clicking on ‘Link operation’. [60]

In our case, the human tasks of taking and positioning the first two wire harnesses on one panel occur in parallel with the six taping operations that are performed by the robot on the opposite panel. When the human finishes positioning the first two wire harnesses, the robot will perform the first taping on the same panel (in sequence). Finally, the human will take and position the third wire harness, then move to the opposite panel to remove the complete wire harness, and the process starts again.

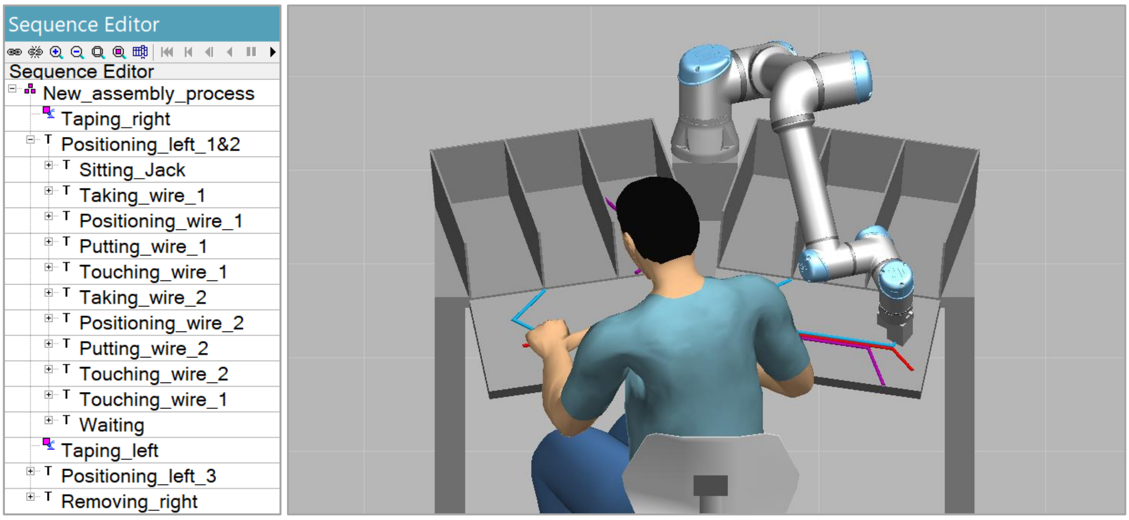

Figure 8: Human-Robot collaboration within the simulation study

Chapter 4

RESULTS AND VALIDATION OF THE WORK

The fourth chapter of the report is devoted to the results and validation of the simulation study. The ergonomic results obtained by the new wire harness assembly process will be analyzed in detail and compared with those of the current process. The results were automatically generated by the software ‘Process Simulate’, which was used to create the simulation of the new workstation.

In addition, the cycle time of the new wire harnesses assembly process will be compared with the cycle time of the current process. One of the purposes of the study project was to maintain or reduce the current cycle time, which is equal to 22.5 seconds. [2]

4.1 Ergonomic scores for the optimized assembly process

Process Simulate supports several ergonomic standards, such as OWAS, NIOSH, 3D SSPP, DMH and RULA. [61] Due to its completeness and ease of use, the RULA method has been selected for the ergonomic analysis of this project. From the ‘Human menu’, the box next to the ergonomics report RULA must be checked. It will then be possible to see the final RULA results for each posture in real-time during the simulation, as well as to generate a detailed RULA report at the end of the simulation. [62]

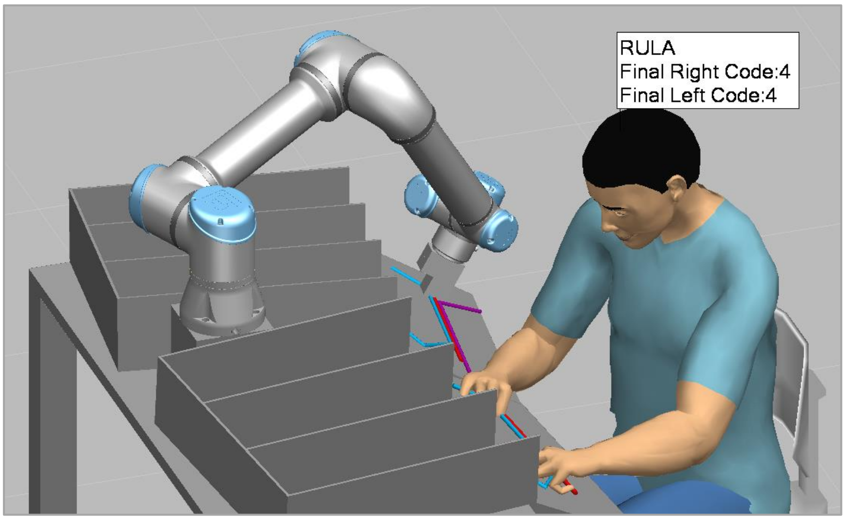

Figure 9: Real-time RULA scores

The final report contains pictures of the study and all the RULA tables for the human postures. In addition to the standard report, custom ergonomic reports can be created. Customizable .xls sheets allow results to be displayed according to a specific company’s standards, by introducing intermediate steps and limit values. [63]

For the purposes of this study project, the standard worksheet for RULA has been generated. In this way, it is possible to compare the results with those obtained from the ergonomic analysis of the current wire harness assembly process and evaluate the improvements made to the process. All the scores obtained for the different postures related to the optimized wire harness assembly process are reported in appendices 3 and 4 of this report. Below are the final results from table C, for both the left and right sides of the operator's body.

Working operations	Optimized	
	Left	Right
Taking 1st wire harness from box	3	2
Inserting 1st wire harness into frame	3	3
Taking 2nd wire harness from box	3	4
Blocking 2nd wire harness upper extremity	4	4
Inserting 2nd wire harness into frame	3	4
Adjusting first wire harness along the frame	4	4
Taking taping pistol (1)		
Performing 1st taping		
Depositing taping pistol (1)		
Taking 3rd wire harness from box	3	3
Inserting 3rd wire harness into frame	4	4
Taking taping pistol (2)		
Performing 2nd taping		
Performing 3rd taping		
Performing 4th taping		
Performing 5th taping		
Performing 6th taping		
Performing 7th taping		
Depositing taping pistol (2)		
Removing and storing complete wire harness	4	4
Max values	4	4

Table 11: 'RULA table C' for the optimized assembly process

In the table, the taping operations cells have been greyed out. In fact, in paragraph '3.3 Proposal for an ergonomically optimized assembly process', it was decided to leave this type of operation to the robot. The reason was that taping operations had 'very high MSD risk' level (6-7). From a first glance at table 11, we notice that the new assembly process has a level of risk that ranges from 'negligible MSD risk' (score 2) to 'very low MSD risk' (scores 3 and 4).

The next section is dedicated to comparing these results with those obtained from the ergonomic analysis of the current process, in order to measure and evaluate the improvements obtained.

4.2 Ergonomic improvements obtained with the optimized process

The RULA method requires recording the worst scores among those obtained for each operation performed by the operator. For example, the operation 'inserting 3rd wire harness into frame' involves different postures by the operator, and only the posture that obtained the worst scores must be recorded in the RULA worksheet. [22] Despite this rule, the RULA table related to the optimized wire harness assembly process showed successful results. These results can be compared with those related to the current process, as follows.

Working operations	Current		Optimized		Improvements	
	Left	Right	Left	Right	Left	Right
Taking 1st wire harness from box	5	4	3	2	-40%	-50%
Inserting 1st wire harness into frame	3	3	3	3	0%	0%
Taking 2nd wire harness from box	5	6	3	4	-40%	-33%
Blocking 2nd wire harness upper extremity	6	7	4	4	-33%	-43%
Inserting 2nd wire harness into frame	6	7	3	4	-50%	-43%
Adjusting first wire harness along the frame	6	7	4	4	-33%	-43%
Taking taping pistol (1)	5	5			-100%	-100%
Performing 1st taping	6	7			-100%	-100%
Depositing taping pistol (1)	6	5			-100%	-100%
Taking 3rd wire harness from box	4	4	3	3	-25%	-25%
Inserting 3rd wire harness into frame	6	7	4	4	-33%	-43%
Taking taping pistol (2)	5	5			-100%	-100%
Performing 2nd taping	6	7			-100%	-100%
Performing 3rd taping	6	7			-100%	-100%
Performing 4th taping	6	7			-100%	-100%
Performing 5th taping	6	7			-100%	-100%
Performing 6th taping	6	7			-100%	-100%
Performing 7th taping	5	7			-100%	-100%
Depositing taping pistol (2)	3	3			-100%	-100%
Removing and storing complete wire harness	6	7	4	4	-33%	-43%
Max values	6	7	4	4	-33%	-43%

Table 12: Ergonomic improvements in %

Obviously, the ergonomic improvements related to the taping operations and handling of the taping pistol are equal to 100%. In fact, these operations have now been left to the collaborative robot. The various operations related to the positioning and removal of wire harnesses have been improved between 33-50%. This is thanks to the new layout that concentrates the work in the lower part of the panel. Finally, the postures assumed when taking the various wire harnesses from the boxes have been improved between 25-50%, thanks to the design of the new workstation according to ISO 14738:2002. [25]

All in all, the current workstation had maximum RULA scores equal to 6 for the left side of the body and 7 for the right, amounting to 'very high risk level'. The optimized workstation has a maximum RULA score of 4 for both the left and the right sides of the body, so a 'negligible risk level'. If we refer to the maximum values obtained from the two workstations, the overall ergonomic improvement for the left side of the body is about 33% and the overall improvement for the right side of the body is about 43%.

4.3 Further improvements obtained: cycle time and related economic savings

The 'Sequence editor' displays all the operations included in a simulation. In particular, it consists of an 'Operation tree' window on the left and a 'Gantt Chart' window on the right. The 'Operation tree' shows the hierarchical structure of the current simulation, while the 'Gantt chart' shows the duration and sequential relationship of each operation. [64]

The 'Sequence editor' below shows the following operations that are performed in parallel:

- Taping on right panel (done by the robot, 7.90 seconds);
- Positioning wires 1 & 2 on left panel (done by the operator, 10.26 seconds).

When the operator has finished positioning the first two wires, the robot will move to the left panel and the following operations will be performed in sequence:

- Taping on left panel (done by the robot, 2.20 seconds);
- Positioning wire 3 on left panel (done by the operator, 7.82 seconds);
- Removing and storing wires from right panel (done by the operator, 1.02 seconds).

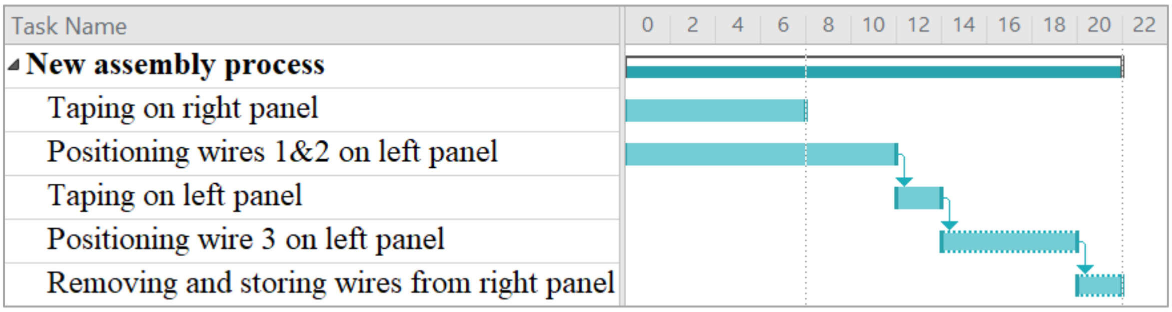

Figure 10: Gantt chart for the new assembly process

The total cycle time for the new assembly process is therefore equal to 21.3 seconds, whereas the cycle time of the current assembly process is equal to 22.5 seconds. As a result, the cycle time has been reduced by 1.2 seconds. The company production for the year 2018 was 1˙200˙000 units/year, with good growth prospects. [3] Therefore, it can be stated that the annual savings will be equal to:

Annual saving (cycle time) = 1˙200˙000 units/year * 1.2sec/unit = 400 hours/year

It should be noted that for the optimized process it was agreed to no longer consider the final manual taping. This operation lasts 5 seconds in the current process. However, it would have had no effect on the total cycle time of the optimized process, since the robot would have time to perform it in parallel with the human operations.

Furthermore, the current process is performed on two workstations by two operators, while the new process requires the use of a single worker. Based on market research, the cost for an employee in Slovenia would be 21˙845 €/year. [65]

Obviously, we must also consider the costs for the construction of the new workstation and training of the worker. From a web search, the highest cost is for the purchase and programming of the UR5 robot, totalling 45˙500 €. [66] Based on a comparison with similar assembly stations, the cost for the construction of the new workstation and the training of the worker can be approximated to 3˙000 €. [67]

The total investment is therefore equal to 48˙500 €. If we consider the savings of 21˙845 €/year due to the use of only one worker, the initial expense will be covered in just 2.2 years, resulting in a worthwhile investment.

Chapter 5

CONCLUSIONS AND OUTLOOK

The fifth and last chapter of this study project is devoted to the conclusions and recommendations that have been reached. In addition to this, some suggestions for additional improvements will be proposed, both for the ergonomic aspects and also for further reducing the cycle time.

5.1 Summary of the work

The main objective of this study project was to propose a new wire harness assembly process in order to improve the ergonomic conditions and reduce the cycle time of the current process.

As explained in the fourth chapter, ergonomic improvements have been achieved thanks to identification of the ergonomically most critical postures using the RULA method. These postures have been improved by introducing a new layout for the workstation, according to ISO14738:2002 ‘Safety of machinery - Anthropometric requirements for the design of workstations at machinery’. Furthermore, some of the working operations have been fully reassigned to a UR5 collaborative robot. The new workstation and the new assembly process were modelled within the software 'Process Simulate'. As a result, the MSD risk level for the wire harnesses assembly process changed from ‘very high risk level’ to ‘low risk level’. It is difficult to quantify this improvement in terms of money and time saved. However, better ergonomics in the workplace leads to improved productivity, employee engagement and quality as well as a better safety culture and therefore reduced costs. [68]

The re-design of the workstation and the introduction of the UR5 collaborative robot also contributed to reducing the current cycle time. In fact, the current process takes 45 seconds and is performed on two workstations by two operators, resulting in a cycle time equal to 22.5 seconds for the output of an assembled wire harness. By using only one workstation specifically designed for this type of process and by passing the taping operations to the collaborative robot, the cycle time has been reduced by 1.2 seconds. Finally, considering that the company production for the year 2018 was 1˙200˙000 units/year, the annual saving would be equal to 400 hours/year.

Of course, the costs for the implementation of the new workstation and the operator's training must be considered as well. Based on market research, this investment amounts to 48˙500 €. [66] [67] Considering that employing a second worker would cost 21˙845 €/year in Slovenia [65], the initial investment will be covered in just 2.2 years.

5.2 Possible further improvements

The layout of the new workstation could be further improved by reducing the size of the two assembly panels. In fact, the size of each panel could be limited to the area occupied by the wire harnesses. In this way, it would be possible to create more space for the boxes containing the wire harnesses within the optimal horizontal working area. Furthermore, the right panel could be mirrored with respect to the left. By doing so, the right and the left sides of the body would be stressed evenly.

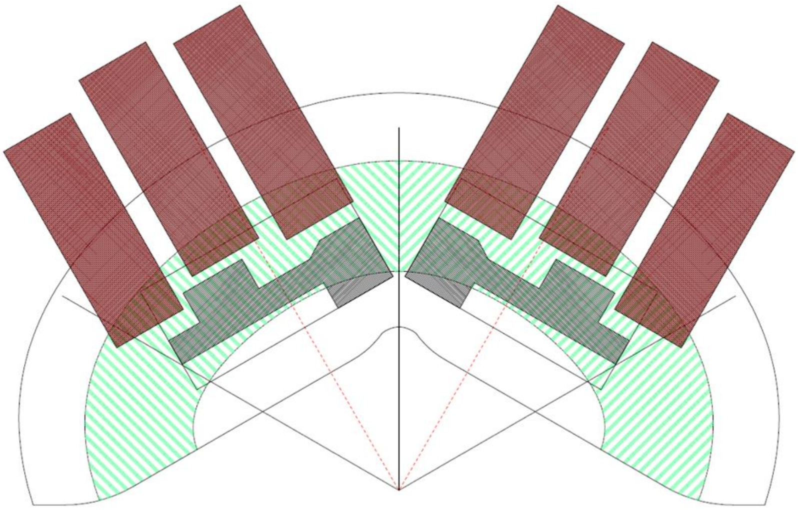

Figure 11: Panel size reduction and mirrored left panel

Another interesting solution would be the design of a workstation in which the operator remains standing and the robot works behind the panel. In this way, the operator would work in safer conditions. [69] Moreover, the cycle time would be even shorter because the robot could perform the last taping without the operator needing to stop.

As already mentioned in previous paragraphs, a final improvement would be to leave the removal and storage of the complete wire harness to the collaborative robot. For now, this operation is still performed by the operator, in order to perform a quality check of the final product. After making sure that the quality provided by this new process is acceptable, the final removal and storage of the wire harnesses could be completely handed over to the collaborative robot. It would be necessary to add a hook to the taping pistol or provide for a robot tool change in order to remove and store the complete wire harness. [70] In this way the operator's workload and the cycle time would be reduced even further.

To validate these solutions and improve understanding of the system, the 'Process Simulate' software program would also allow the use of modern virtual reality technology in order to increase the reliability of simulations. Moreover, the company 'Xsens' offers accurate sensory measurement systems that are compatible with 'Process Simulate' software for capturing human motion and for virtual validation of workplaces. [71]

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Appendix 1

'RULA TABLE A' FOR THE CURRENT ASSEMBLY PROCESS

	A - Arm and Wrist ergonomic anaysis															
	1. Upper arm scores		**2. Lower arm scores**		**3. Wrist scores**		**4. Wrist twist**		**5. Index in table A**		**6. Muscle use scores**		**7. Force use scores**		**8. Find row in table C**	
Working operations	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Taking 1st wire harness from box	4	3	3	1	2	3	2	2	5	4	0	0	0	0	5	4
Inserting 1st wire harness into frame	1	1	2	2	3	2	2	2	3	2	0	0	0	0	3	2
Taking 2nd wire harness from box	1	2	2	3	1	3	2	2	3	4	0	0	0	0	3	4
Blocking 2nd wire harness upper extremity	3	4	1	2	3	3	2	2	4	5	0	0	0	0	4	5
Inserting 2nd wire harness into frame	3	3	2	2	3	4	2	2	4	5	0	0	0	0	4	5
Adjusting first wire harness along the frame	3	4	1	2	3	3	2	2	4	5	0	0	0	0	4	5
Taking taping pistol (1)	2	2	2	1	2	2	2	1	3	3	0	0	0	0	3	3
Performing 1st taping	3	6	1	1	3	4	2	1	4	8	0	0	0	0	4	8
Depositing taping pistol (1)	2	2	2	1	3	2	2	1	4	3	0	0	0	0	4	3
Taking 3rd wire harness from box	4	4	1	2	3	3	2	2	5	5	0	0	0	0	5	5
Inserting 3rd wire harness into frame	3	3	2	2	3	4	2	2	4	5	0	0	0	0	4	5
Taking taping pistol (2)	2	2	2	1	2	2	2	1	3	3	0	0	0	0	3	3
Performing 2nd taping	3	5	2	2	3	3	2	1	4	6	0	0	0	0	4	6
Performing 3rd taping	3	6	1	1	3	3	2	1	4	7	0	0	0	0	4	7
Performing 4th taping	2	6	1	2	3	4	2	1	4	9	0	0	0	0	4	9
Performing 5th taping	2	6	1	2	3	4	2	1	4	9	0	0	0	0	4	9
Performing 6th taping	2	6	1	2	3	3	2	2	4	9	0	0	0	0	4	9
Performing 7th taping	1	6	2	1	3	4	2	2	3	9	0	0	0	0	3	9
Depositing taping pistol (2)	2	2	1	1	2	2	2	1	3	3	0	0	0	0	3	3
Removing and storing complete wire harness	3	3	2	3	3	4	2	2	4	5	0	0	0	0	4	5
Max values	4	6	3	3	3	4	2	2	5	9	0	0	0	0	5	9

Appendix 2

'RULA TABLES B AND C' FOR THE CURRENT ASSEMBLY PROCESS

	B - Neck, Trunk and Leg analysis							**C - Final values**				
	9. Neck scores	**10. Trunk scores**	**11. Legs scores**	**12. Index in table B**	**13. Muscle use scores**	**14. Force use scores**	**15. Find column table C**	**16. Find row table C**		**17. Find column table C**	**18. Final values from table C**	
Working operations								**Left**	**Right**		**Left**	**Right**
Taking 1st wire harness from box	3	3	1	4	0	0	4	5	4	4	5	4
Inserting 1st wire harness into frame	3	1	1	3	0	0	3	3	2	3	3	3
Taking 2nd wire harness from box	4	3	1	6	0	0	6	3	4	6	5	6
Blocking 2nd wire harness upper extremity	4	3	1	6	0	0	6	4	5	6	6	7
Inserting 2nd wire harness into frame	4	3	1	6	0	0	6	4	5	6	6	7
Adjusting first wire harness along the frame	4	3	1	6	0	0	6	4	5	6	6	7
Taking taping pistol (1)	4	3	1	6	0	0	6	3	3	6	5	5
Performing 1st taping	4	4	1	7	0	0	7	4	8	7	6	7
Depositing taping pistol (1)	4	3	1	6	0	0	6	4	3	6	6	5
Taking 3rd wire harness from box	3	2	1	3	0	0	3	5	5	3	4	4
Inserting 3rd wire harness into frame	4	3	1	6	0	0	6	4	5	6	6	7
Taking taping pistol (2)	4	3	1	6	0	0	6	3	3	6	5	5
Performing 2nd taping	4	3	1	6	0	0	6	4	6	6	6	7
Performing 3rd taping	4	4	1	7	0	0	7	4	7	7	6	7
Performing 4th taping	4	4	1	7	0	0	7	4	9	7	6	7
Performing 5th taping	4	4	1	7	0	0	7	4	9	7	6	7
Performing 6th taping	4	4	1	7	0	0	7	4	9	7	6	7
Performing 7th taping	4	3	1	6	0	0	6	3	9	6	5	7
Depositing taping pistol (2)	3	2	1	3	0	0	3	3	3	3	3	3
Removing and storing complete wire harness	4	3	1	6	0	0	6	4	5	6	6	7
Max values	4	4	1	7	0	0	7	5	9	7	6	7

Appendix 3

'RULA TABLE A' FOR THE OPTIMIZED ASSEMBLY PROCESS

	A - Arm and Wrist ergonomic anaysis															
	1. Upper arm scores		**2. Lower arm scores**		**3. Wrist scores**		**4. Wrist twist**		**5. Index in table A**		**6. Muscle use scores**		**7. Force use scores**		**8. Find row in table C**	
Working operations	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Taking 1st wire harness from box	3	1	2	1	2	3	1	1	3	2	0	0	0	0	3	2
Inserting 1st wire harness into frame	2	2	1	2	3	2	2	2	3	3	0	0	0	0	3	3
Taking 2nd wire harness from box	2	3	1	1	3	4	2	2	3	5	0	0	0	0	3	5
Blocking 2nd wire harness upper extremity	2	2	1	1	2	3	2	2	3	3	0	0	0	0	3	3
Inserting 2nd wire harness into frame	2	2	1	2	3	4	2	2	3	5	0	0	0	0	3	5
Adjusting first wire harness along the frame	2	2	2	1	3	3	2	2	3	3	0	0	0	0	3	3
Taking taping pistol (1)																
Performing 1st taping																
Depositing taping pistol (1)																
Taking 3rd wire harness from box	1	2	1	1	1	2	1	1	1	2	0	0	0	0	1	2
Inserting 3rd wire harness into frame	2	3	1	2	2	2	1	2	2	3	0	0	0	0	2	3
Taking taping pistol (2)																
Performing 2nd taping																
Performing 3rd taping																
Performing 4th taping																
Performing 5th taping																
Performing 6th taping																
Performing 7th taping																
Depositing taping pistol (2)																
Removing and storing complete wire harness	2	1	1	1	1	4	2	2	2	3	0	0	0	0	2	3
Max values	3	3	2	2	3	4	2	2	3	5	0	0	0	0	3	5

Appendix 4

'RULA TABLES B AND C' FOR THE OPTIMIZED ASSEMBLY PROCESS

	B - Neck, Trunk and Leg analysis							C - Final values				
	9. Neck scores	10. Trunk scores	11. Legs scores	12. Index in table B	13. Muscle use scores	14. Force use scores	15. Find column table C	16. Find row table C		17. Find column table C	18. Final values from table C	
Working operations								Left	Right		Left	Right
Taking 1st wire harness from box	2	1	1	2	0	0	2	3	2	2	3	2
Inserting 1st wire harness into frame	2	1	1	2	0	0	2	3	3	2	3	3
Taking 2nd wire harness from box	1	1	1	1	0	0	1	3	5	1	3	4
Blocking 2nd wire harness upper extremity	4	1	1	5	0	0	5	3	3	5	4	4
Inserting 2nd wire harness into frame	3	1	1	3	0	0	3	3	5	3	3	4
Adjusting first wire harness along the frame	4	1	1	5	0	0	5	3	3	5	4	4
Taking taping pistol (1)												
Performing 1st taping												
Depositing taping pistol (1)												
Taking 3rd wire harness from box	3	1	1	3	0	0	3	1	2	3	3	3
Inserting 3rd wire harness into frame	4	1	1	3	0	0	5	2	3	5	4	4
Taking taping pistol (2)												
Performing 2nd taping												
Performing 3rd taping												
Performing 4th taping												
Performing 5th taping												
Performing 6th taping												
Performing 7th taping												
Depositing taping pistol (2)												
Removing and storing complete wire harness	4	1	1	3	0	0	5	2	3	5	4	4
Max values	4	1	1	5	0	0	5	3	5	5	4	4