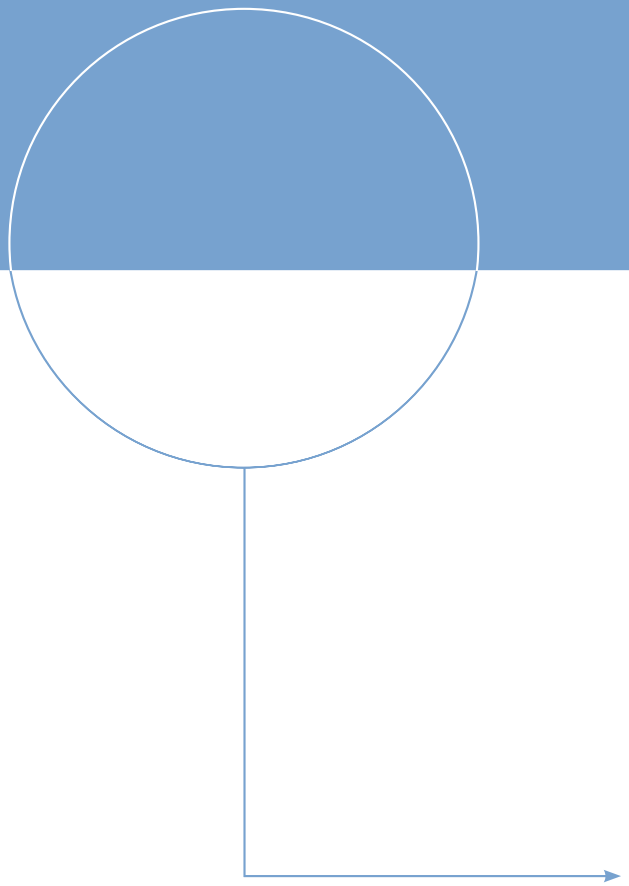
Christian Vig

The use of ergonomic and production KPIs to evaluate workstation performance

How human variation affects the performance and how Industry 4.0 technology can improve it

June 2020



Master's thesis

2020

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How human variation affects the performance and how Industry 4.0 technology can improve it

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Global Manufacturing Management
Submission date: June 2020
Supervisor: Fabio Sgarbossa
Co-supervisor: Marco Simonetto and Mirco Peron

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Preface

This Master's thesis is the ending thesis for the Master of Science degree in Global Manufacturing Management at the Department of Mechanical and Industrial Engineering at NTNU: the Norwegian University of Science and Technology. The degree is in the field of Production Management and was conducted in the spring semester of 2020.

Trondheim, June 10th, 2020

C Vig

Christian Vig

Acknowledgement

I would like to thank my supervisors Professor Fabio Sgarbossa, Marco Simonetto, and Mirco Peron for the help and guidance. I would also like to thank Professor Jan Ola Strandhagen, Guiseppe Fragapane, and Jo Wessel Strandhagen for feedback from the preliminary presentations. Thanks to the staff of the Department of Mechanical and Industrial Engineering for a great learning environment.

I would like to thank my family for the support, and especially my father, Jens Christian Vig, for helping by reading the thesis to find logical errors and missing information. I would also like to thank my girlfriend and home office colleague Marielle Taalesen Hagengen for company, support and proofreading of the thesis.

C.V.

Abstract

The manual workstation is seeing a renaissance due to growing market trends of consumers wanting customized products, and the product life cycles decreasing as new products are introduced more frequently. Mass production solutions with fully automated production lines are not flexible enough to keep up with the constant changes in the product mix of companies. In order to stay competitive in rapidly changing markets, the use of human operators is preferred in some production stages.

For companies to stay competitive, managers should strive for state-of-the-art production facilities and processes, increasing quality and cutting costs and processing times. To enable this, the human operators need workstations that are playing to their strengths and limiting their weaknesses. By having a set of key performance indicators, it is more apparent when a workstation is performing satisfactorily and when it needs improvements. These KPIs can be useful in the designing phase, as well as when evaluating a current workstation setup. A prominent difference between the use of human operators compared to machines in production, is how human performance is susceptible to variation due to how individuals differ. Human variation is the reason why one-size-fits-all solutions are no better solutions for workstations than it is for shoes. Knowing how human variation affects the KPIs in this thesis can be used to reduce the impact it has, through the design of the workstations. Some factors are not possible to alter to an acceptable level through design alone. In some of those cases, there are Industry 4.0 technologies available and emerging to make smarter workers and workstations.

The research in this thesis was conducted through three research questions: 1) Which ergonomic and production KPIs found in literature can be used to evaluate the performance of a workstation, and how? 2) Which forms of human variation can influence the KPIs? And how will the variations influence the score of the KPIs? 3) Which Industry 4.0 technologies can improve workstation performance, and how can it assist the human operator?

The research in this thesis is based on the perspective of production management, with focus on workstation evaluation which is within the field of facility planning. The scope is workstation performance evaluation with focus on productional and ergonomic performance. The objective of the thesis is to suggest a set of performance indicators that can be used to evaluate workstation performance, present how human variation can affect the indicators and present Industry 4.0 technologies to improve production performance and operator well-being.

By conducting a literature study, an academic gap was discovered. The gap was used to find a scope for the thesis. The gap was the lack of key performance indicators to use for evaluating workstation performance. Through the literature study, relevant performance indicators were found in studies of other industrial aspects.

In this thesis, by answering the research questions, a set of KPIs for workstation evaluation was suggested, the human variation parameters most influential on workstation performance were presented, along with some ways they impact each of the KPIs. In the end, Industry 4.0 technologies useful for improving the performance was presented.

Sammendrag

Manuelle arbeidsstasjoner har fått nytt liv som et resultat av en økende markedstrend der forbrukere ønsker spesialtilpassede produkter, og livssyklusen til produkter blir kortere på grunn av at nye produkter oftere blir sluppet på markedet. Masseproduksjonsløsninger som helautomatiserte produksjonslinjer er ikke fleksible nok til å holde tritt med konstant endring i produktsortimentet en bedrift tilbyr. For å være konkurransedyktige i marked som endres raskt, er menneskelige operatører foretrukket i visse produksjonssteg.

For at bedrifter skal være konkurransedyktige bør ledelsen streve etter å ha «state-of-the-art» anlegg og prosesser, for å forbedre kvaliteten, samt for å redusere produksjonstid og kostnader. For å muliggjøre dette må operatørene ha arbeidsstasjoner som spiller på deres styrker, og reduserer ulempene. Ved å ha et bestemt sett med nøkkelindikatorer er det tydeligere å skjønne når en arbeidsstasjon fungerer som ønsket, og når det trengs forbedring. Disse nøkkelindikatorene kan være nyttige å bruke i designfasen av arbeidsstasjoner, så vel som når arbeidsstasjonene som brukes i produksjonen skal testes. En av de større forskjellene mellom menneskelige operatører og maskiner i en produskjonssetting er hvordan menneskelig prestasjon er utsatt for variasjon på grunn individuelle forskjeller. Menneskelig variasjon er grunnen til at "en størrelse passer alle" løsninger er like lite fornuftig for arbeidsstasjoner som for sko. Gjennom å vite hvilken innvirkning menneskelig variasjon har på nøkkelindikatorene som er satt kan påvirkningen det har på prestasjonen bli redusert gjennom design av arbeidsstasjonene. Noen av faktorene er ikke mulig å forandre til et akseptabelt nivå gjennom kun design. I noen av de tilfellene er det Industry 4.0 teknologi tilgjengelig, eller under utvikling, som kan bidra til smartere operatører og arbeidsstasjoner.

I forskningen foretatt i denne studien har 3 forskningsspørsmål blitt brukt: 1) Hvilke produksjons og ergonomiske nøkkelindikatorer funnet fra litteraturen kan brukes til å evaluere ytelsen til arbeidsstasjoner, og hvordan? 2) Hvilke former for menneskelig variasjon kan påvirke nøkkelindikatorene. Hvordan vil de påvirke skåren på indikatorene 3) Hvilke Industry 4.0 teknologier kan øke arbeidsstasjonsytelsen, og hvordan kan de assistere den menneskelige operatøren?

Forskningen i denne studien er basert på et produksjonsledelsesperspektiv, med fokus på arbeidsstasjonsevaluering som er et undertema innen anleggsplanlegging. Omfanget av oppgaven er på evaluering av arbeidsstasjonsytelsese med fokus på produksjon og ergonomisk ytelse. Målet med studien er på foreslå et sett med nøkkelindikatorer som kan

som kan brukes til å bedømme arbeidsstasjonsytelse, presenter hvordan menneskelig variasjon påvirker disse indikatorene, og presentere Industry 4.0 teknologi som kan forbedre ytelse i form av produksjon og operatørers trivsel.

Gjennom å svare på forskningsspørsmålene i denne studien har et sett med nøkkelindikatorer for evaluering av arbeidsstasjonsytelse blitt foreslått, menneskelige variasjoner som påvirker arbeidsstasjonsytelse har blitt presentert sammen med hvilken innvirkning de har på nøkkelindikatorene. Tilslutt ble Industry 4.0 teknologi for å forbedre ytelse presentert med hvordan ytelsen forbedres.

Table of Contents

List of Tables

List of Figures

1. Introduction

Due to the outbreak of the COVID-19 pandemic, the thesis needed considerable changes from the original outline. NTNU closed its doors to students and faculty March 12th. Conducting lab experiments for the thesis was no longer an option.

Before the university closed its doors, the aim of the thesis was to develop a framework for using a motion capture system to evaluate the production and ergonomic performance of existing workstations and workstations in the design process, by using virtual reality. These experiments were planned to be conducted in the Logistics 4.0 Laboratory at NTNU Valgrinda. With the laboratory closed, the main research questions were not possible to answer, so there was a need for a change in the topic. In cooperation with the supervisors, the research questions were altered to be possible to answer without gathering empirical data through experiments, but still within the same topic. This led to a thesis based on previously conducted research on the topic, instead of new experiments and testing.

1.1. Background

In the industrial situation of today, with automated production lines and robots in many stages in production, there is still a need for the human operator. In many processes, human operators are preferred to machines and automation due to flexibility and less changeover time (Gorecky et al., 2017).

For the commercial producers of workstations, ergonomics and human-centered design are fundamental concepts used in their designs (Rexroth, 2017, Item, 2014). Workplace design and ergonomics are strongly correlated. Workstations are often designed based on basic guidelines using trial and error. This approach to design can be very time-consuming, and in extension- expensive. Reducing the arbitrariness of the design procedure can be achieved by knowing what to look for when testing and understanding which factors influence the performance.

For companies, it is vital to ensure good production performance. In flexible productions, focus on ergonomics is essential, as improvement in this area has proven to increase production rate and lower product defects (Das et al., 2007, Neumann et al., 2016), as well as the health and well-being of the operator. The ergonomic level of a workstation varies between the individual operators, especially if it is not adjustable to their specific needs. Detecting differences in performance due to individual differences, and knowing which differences cause them can help the design team remove or reduce the differences when updating the design.

Some performance differences are not possible to remove by through design by changing workstation layout or including generic workstation features. For these differences, assistive Industry 4.0 technologies can be used to lessen the stress and strain on operators and improve the performance of the workstation. With musculoskeletal disorders related to the workplace being the main reason for absenteeism in Norway (STAMI, 2018), more emphasis on ergonomics is necessary to keep employees healthy and a part of the workforce for as long as needed, without unnecessary injuries.

1.2. Motivation and Problem Formulation

In this thesis, the influence human variability has on the performance of operators using workstations will be studied. The results can be used to discover if the design needs changes for the workstation to fit most operators and their differences. The thesis will highlight which human variabilities affect the operator's performance at the workstation and how the performance can be increased.

In the specialization project conducted prior to this thesis, the author presented an updated procedure to design ergonomic workstations, depicted in Figure 1.1 (Vig, 2019). Step 6.3 and 6.4 are testing with end-users and assessing the performance of the workstation. Without having set performance indicators for the testing phase, the evaluation can be arbitrary and more time-consuming. It is also possible that this will lead to workstations optimized to other standards than what the company needs. When conducting the specialization project, there were many papers about the importance of ergonomics/human factors in facility design and using advanced technologies in the process, but few papers about how to evaluate the performance of the facilities. Battini et al. (2018) listed some time-measured key performance indicators (KPI) relevant to workstation evaluation without going into detail about them. The thesis is influenced by the work and the KPIs mentioned in Battini et al. (2018). From the literature search for performance indicators, no specific sets for use in workstation design were found. No set of how human variation influences the workstation performance was found either. These topics are the gap in literature being studied in this thesis.

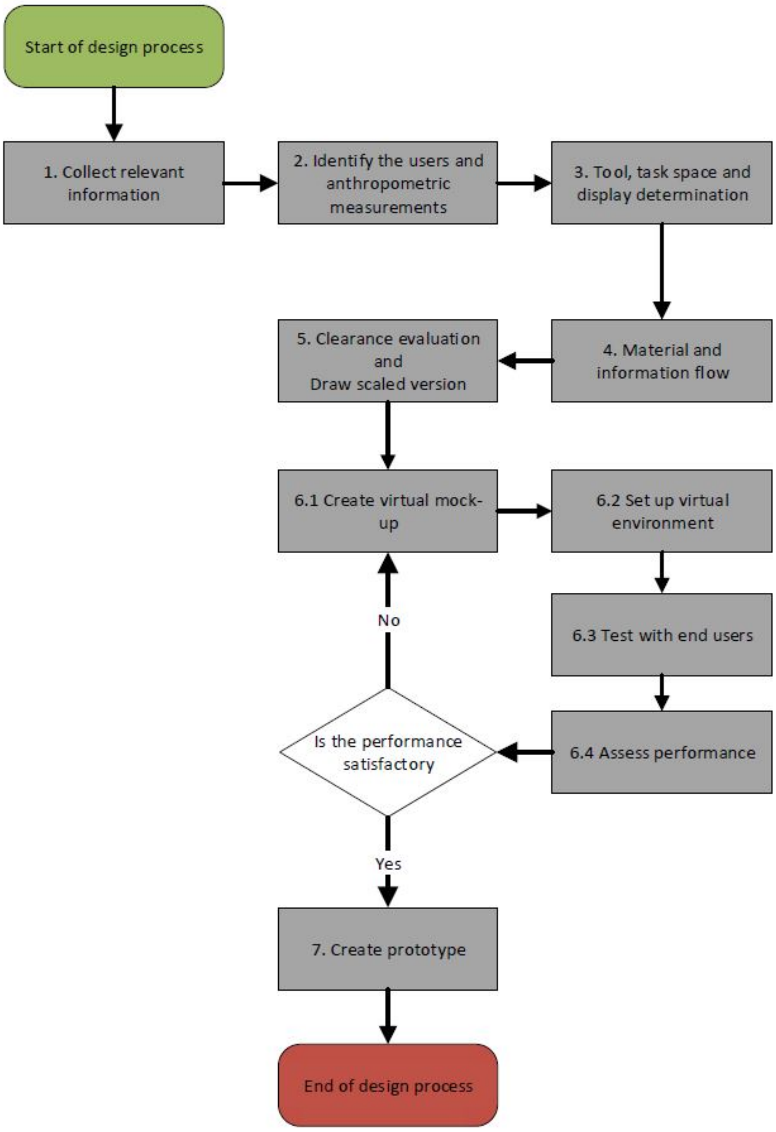


Figure 1.1 Updated workstation design procedure based on Das and Sengupta (1996) from (Vig, 2019)

Industry 4.0 is considered to be the 4th industrial revolution with *"intelligent networking of machines and processes for industry with the help of information and communication technology"* (BMWi, 2020). It brings the human-machine interface closer together and has introduced many new technologies. Some of them are assistive technologies that can help workers to be more productive and reduce the load as collaborative robots. By combining assistive Industry 4.0 technologies with personalized workstations, operators with different performance due to human variation, can be able to perform at the same level as their other coworkers, and overall performance can be increased..

1.3. Related Work

In the author of this thesis' specialization project, the procedure of workstation design was the main topic. The project work led to an updated procedure for designing new workstations to be used by researchers, manufacturing companies, and workstation manufacturers. The procedure can be seen in Figure 1.1. Some parts of this project are useful for this thesis.

The research of Battini et al. (2018) is related since it mentions the need for performance indicators to evaluate the workstations properly, and inspired the topic of the thesis.

Other related work is presented in chapter 4 Findings and Observations.

1.4. Research Questions

To be able to evaluate the performance of a workstation, suitable KPIs for knowing the desired performance level when testing is needed. Performance indicators related to production performance are needed to convince the managers that the design fulfills the needs of the company, and ergonomic performance indicators are needed for both the well-being of the operators and the positive impact it has on production. This leads to research question 1:

Which ergonomic and production KPIs found in literature can be used to evaluate the performance of a workstation, and how?

The diversity of operators influences how to make ergonomic workplaces and how well solutions work. These variations are the reason why one-size-fits-all workstations are not suitable and can potentially be harmful to both the operator and the productivity. Knowing how human variation can influence the performance of a workstation can contribute to tests that reveal designs that cannot accommodate the variation span. This leads to research question 2:

Which forms of human variation can influence the KPIs? And how will the variations influence the score of the KPIs?

The performance of the workstations is dependent on the operator using it. With that in mind, research question 3 was formed to evaluate the potential of Industry 4.0 technologies to provide support for the operators. The research question will look into which and how the technologies can improve the performance. Research question 3:

Which Industry 4.0 technologies can improve workstation performance, and how can it assist the human operator?

Figure 1.2 illustrates how the research questions are connected. Having the right performance indicators, and knowing what influences them, is needed to continue the design procedure shown in Figure 1.1. Is the performance satisfactory? Multiple factors influence the answer to this question. How well the workstation is suited for the operators will differ due to human variation. Knowing how it influences the performance can be used to reduce the differences through design. Although, in some cases, the differences in performance cannot be removed by design alone. The cases where differences cannot be resolved by design is where the results of research question 3 can be used to remove or reduce the differences. The workstation is tested using the key performance indicators to evaluate the performance of the workstation. The scores of the KPIs will vary due to human variation (2), and the assistive technologies (3) can be used to reduce the differences. Using this information, the design team or the testers can reveal whether the performance is satisfactory or not.

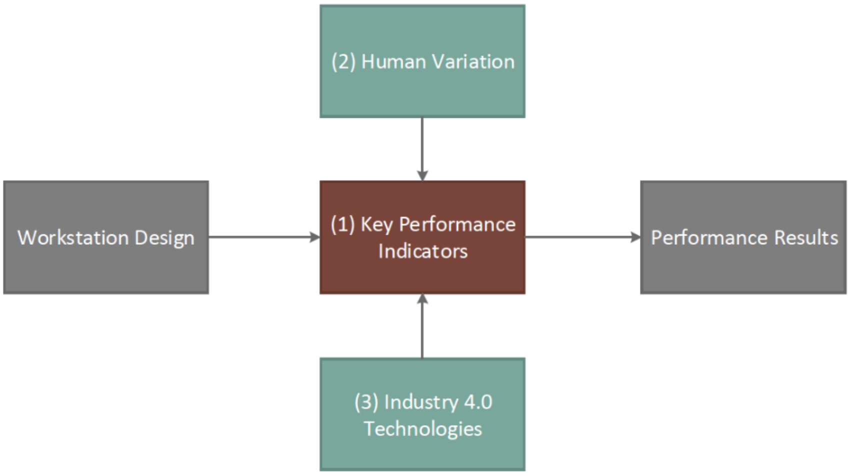


Figure 1.2 Relations between research questions

The objective of the thesis is to suggest a set of performance indicators that can be used to evaluate workstation performance, present how human variation can affect the indicators and present Industry 4.0 technologies to improve productional performance and operator well-being.

1.5. Contributions

In this thesis, the contribution will be by providing a set of tools to evaluate workstations. The use of these tools can be valuable for producers of workstations to evaluate their workstations, and be an aid when producing new models. It is also beneficial for manufacturing businesses to investigate if they need to invest in new workstations for their operators.

In literature, some have mentioned KPIs that can be relevant for the evaluation of the performance of the design. However, through a literature study, no research on which KPIs suited for evaluating the performance of workstations were found. The contribution of this thesis is to present a set of KPIs that are relevant for the evaluation of workstations, and research how these KPIs change due to human variation. The thesis will also present Industry 4.0 technologies that can help meet the goal of the KPIs by aiding and assisting the operators.

1.6. Scope

It is essential to acknowledge that ergonomic performance is not subjected to the physical attributes of a workplace alone. Psychosocial factors are also very influential in matters as absenteeism and musculoskeletal disorders. This thesis will not include the impact psychosocial factors have on workstation performance but focus on the physical environment.

The thesis will focus on workstations being used mainly for manual work. This includes assembly work, packing tasks and other manual workstation tasks. Automatic feeding systems of parts are not a disqualifying factor in this regard.

The workstation considered in the thesis is defined as a tabletop used by the operator for conducting his/her assembly or packing tasks, the storage bins and racks for frequently used parts, and the tool storage systems. Frequently used storage systems in the immediate area, meaning not only on the tabletop, are also within the scope of the thesis.

The operators are within the scope of the thesis. Knowing how human variability influences the fit of the operator to the workstation can be used to determine features that can be universal and which should be personalizable. These differences need to be acknowledged to make workstations with high ergonomic performance, to prevent work-related musculoskeletal disorders among the workers.

Industry 4.0 technologies that can improve the performance of operators are part of the thesis and will be in the scope of the thesis.

1.7. Outline of the project

In the first part of the thesis, the thesis has been introduced. The next part will cover the research methodology used to answer the research questions. After that, the theoretical background will be presented. Then the findings and results will be presented before being discussed in the 5th part. In the end, there is a conclusion, and future work will be recommended.

2. Research Methodology

2.1. Literature Methodology

In this thesis, research conducted by others, in the form of papers, books, and assumptions made by the author are the only sources of information. These aspects lead to many literature searches to find relevant information. In the following sub-chapters, the methodology and the ways the searches were performed are presented.

2.1.1. Literature Search

A literature search was conducted for most of the topics in this thesis. The search engines used for finding relevant academic papers and books were mainly Scopus, Web of Science, and Oria. Web of Science and Scopus were used when a thorough search with multiple topics was needed, while Oria was used when the aim was to find a specific paper.

The literature searches were conducted by searching Scopus or Web of Science, using multiple blocks of key-words to narrow the search down. If the search gave a manageable number of papers, both headlines and abstracts were read. With too many results, only the headlines were read for the first screening. If the paper then seemed relevant or partly relevant, it was put in a group for a second, more thorough screening. If the number of papers was still too high, a second screening was conducted by also reading the abstract, headlines, and studying figures and tables. The remaining papers were downloaded, skimmed, read, and then summarized.

KPI Literature Search

Relevant key performance indicators (KPIs) were needed to evaluate the performance of workstations. The KPIs can be used to compare the performance of different designs, or to evaluate the performance of the current workstation to decide if there is a need for a new one. As shown in Table 2.1, the blocks of key-words are “KPI,” “workstation”, and “Industry”, and synonyms of the words. Using Web of Science led to 35 papers from this search, which were narrowed down to 13 after the initial screening.

Table 2.1 Literature search for workstation KPIs

Block 1		**Block 2**		**Block 3**
KPI	AND	Workstation	AND	Industry
OR		OR		OR
"Performance indicators"		Workbench		Industrial
OR		OR		OR
"Performance measurement"		"Assembly station"		Produce
OR		OR		OR
"Indicator of performance		"Assembly system"		Production
				OR
				Manufacture
				OR
				Manufacturing

From this search, no KPIs for evaluating ergonomic performance were found. This lead to another literature search specifically for ergonomic KPIs, as described in the next subchapter.

Ergonomic KPIs Literature Search

The process of finding production KPIs relevant to evaluate workstation design was less complicated than finding ergonomic KPIs. The first iteration of the literature search for ergonomic KPIs gave little to no suitable performance measures to use when using KPI and synonyms for it, like in Block 1 of search words in Table 2.1. Therefore, a new literature search had to be conducted using different key-words. The second iteration of search words is shown in *Table 2.2*. The search was limited to English articles, books, and book chapters.

Table 2.2 Literature search for ergonomic KPIs

Block 1		Block 2
"Ergonom* assessment tool"		Industry
OR		OR
"Ergonom* assessment method"		Industrial
OR		OR
"Ergonom* evaluation tool"		Produce
OR		OR
"Ergonom* evaluation method"		Production
OR		OR
"Human Factor* assessment tool"	AND	Manufacture
OR		OR
"Human Factor* assessment method"		Manufacturing
OR		
"Human Factor* evaluation tool"		
OR		
"Human Factor* evaluation method"		

The search resulted in 37 papers and book chapters. By screening them through reading the title, 10 papers were excluded, leaving 27 papers. After reading the abstract, another ten papers and book chapters were excluded, leaving 17.

Finding Human Variation Factors Relevant For Inclusion

Of the many ways humans can vary, some are relevant for evaluation in industry, others are not. In order to evaluate how human variation influences workstation performance, the relevant factors that differentiate the performance of individuals in an industrial setting needed to be found. The factors used in the thesis were found by searching for literature, either listing factors that can influence performance or papers testing performance differences. Using the "human variability" and synonyms to variability and key-words for "workplace", as shown in Table 2.3 originally, 69 papers were found using Scopus. After removing unrelated topics from the search and exclude all non-English publications, there were 41 papers left. After reading the abstracts of these papers, 16 papers were deemed relevant. Out of these papers, relevant human variability factors were found in 7 papers. Snowball sampling and other papers found through another literature search, including relevant information on the topic were also used.

Table 2.3 Key-words used in literature search for human variability

Block 1		Block 2
"human varia*"		workplace
OR		OR
"human diversity"		industry
OR	AND	OR
"human differences"		manufacturing
		OR
		assembly

2.1.2. Snowball Sampling

Some papers used in the thesis were found by snowball sampling. It is when an interesting statement in one paper is referencing another paper, so the second paper is checked. If the second paper then is included, it is by the use of snowball sampling, resembling a snowball rolling down a hill growing in size as more is sticking to it.

2.2. Limitations

2.2.1. No Laboratory Tests

The plan for this thesis was to test the performance of the workstations in the Logistics 4.0 Laboratory at NTNU, by using a motion capture system and potentially virtual reality. Due to the outbreak of COVID-19, the university restricted access to campus for students and faculty and closed the laboratory. The closed laboratories made it not possible to conduct experiments for workstation, making the thesis being solely based on literature and previously conducted research.

2.2.2. Closed Libraries

Due to COVID-19, the NTNU libraries closed down alongside the rest of the campuses. With the libraries closed, relevant books on the topics of the thesis were no longer available for a loan, making papers and online books the only available sources of information. In some cases, like finding human variability factors, using reference books and encyclopedias would have saved much time and possibly given a better overview and understanding of the topic.

2.2.3. Problem limiting search scope

Within the research field of what happens to aging workers' performance and the difference skill makes on operator performance, there has been done very much research. The task of scoping down the number of articles to a manageable number was not possible with the author's knowledge of the subjects without excluding relevant papers. This lead to the choice of papers used on the topic being chosen more arbitrarily than it would have otherwise.

3. Theoretical Background and Literature Study

In this chapter, the theoretical background of the thesis will be presented. Firstly, the theory of workstation design will be presented before human factors/ergonomics, human variation, KPIs, and Industry 4.0 technologies for manual operators.

3.1. Workstation Design

Workstations for manual work are commonly used in flexible production facilities producing many variants of products, or products with a short product life cycle. Workstation design has traditionally been done with the primary goal of increasing productivity, with little regard to human factors (Golabchi et al., 2015). In later years, there has been an increased focus on ergonomics, and human factors due to regulations as well as realizing the negative impacts poor ergonomics have on productivity and the society as a whole (Peruzzini et al., 2017).

Workstation design is part of lower-level facility design. According to Kovacs (2019) definition of facilities layout design, the workstation is considered a facility (about facilities layout design): "*optimum arrangement of facilities in a manufacturing site and optimum flow of materials from one facility to another, which minimizes material handling costs. A facility may be a department, workstation, machine, equipment, etc.*"

3.2. Human Factors and Ergonomics

According to The IEA (2019) ergonomics/human factors is defined as:

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

According to STAMI (2018), 38% of absenteeism in Norway relates to musculoskeletal disorders, where half of it is wholly or partly due to their work. Musculoskeletal disorders are strongly correlated to poor ergonomics, so being aware of this when designing workplaces can contribute to reducing the negative impact.

Ergonomists/human factors specialists are a profession with the primary objective of evaluating or designing with the needs, abilities, and limitations of people in focus (IEA, 2019). The goal of human factors specialists is to make systems that are adapted to the need of the users, rather than making the workers adapt to the system (Wickens, 2014). It is their responsibility to ensure human factors criteria is included in the system requirements, and to include features that directly relate to operator safety and performance.

One significant difference between human factors design and regular design, is that in human factors design, the attributes are based on the end-user and not the creative process of the designer (Giacomin, 2014). When implementing ergonomics in the design of systems to be used by more than one user, the process can become complicated.

3.3. Human Variation

Human variation or human variability is about how individuals differ from each other. What makes one person different than another. The characteristics of how one person differs from another can make two seemingly similar operators' performance at a workstation different when using the same setup.

Katiraee et al. (2019) studied how human diversity is incorporated into the way production systems are modeled and designed. This is done by investigating the current literature on how human factors are used in manufacturing systems design. Not all of these diversity factors have a direct impact on how an operator perform their work. Some are correlated that an increase in one variable generally leads to either an increase or decrease in another.

There are many ways humans can differ. Some are physical differences, and others are not visible. In this subchapter, the most relevant human variations to the manufacturing industry found in the literature search will be presented, and how they influence performance will be presented in chapter 4 Findings and Observations.

3.3.1. Age

Age is one of the aspects humans differ. It can be a useful way to group humans based on their age, as statistical similarities are among people in the same age group. In the case of this thesis, old workers will be considered operators in the age group of 55 years and above, as done by the Statistics Norway SSB (2020).

3.3.2. Gender

Humans can be born either male or female. The gender of a human is not affecting the characteristics of a human by itself, but some other characteristics are more common in one or the other gender. This can lead to workplaces being more unaccommodating towards one gender than the other. The author recognizes that there are people not associating with the gender they are born.

3.3.3. Anthropometry

The definition of anthropometric measurements are according to the Oxford dictionary of English (2020) *"relating to the scientific study of the measurement and proportions of the human body"*. Body dimensions in regards to bone dimensions, muscle and fat tissue are considered anthropometric measurements (NCHS, 1988).

Anthropometric variance is among the main factors for designing for adjustability or making products in multiple sizes. Humans can vary in height, standing or sitting, arm length/reach, weight, and those measures are not always directly proportionate within another variable like gender and ethnicity (de Vries and Parkinson, 2014).

Anthropometry can be useful for multiple decision-making processes in the design phase of workstations. Lu (2003) highlights the use of anthropometric measurements for posture evaluation and reaching distance, clearance of the operator from surrounding potential hazards, identifying objects that can limit the operator's freedom of movement, and biomechanical analyses of force on the body.

Weight and Body Mass Index (BMI)

For standing operations, weight can have a significant impact on the accumulated fatigue the operators experience. For standing operations, some sort of relieving feature might be necessary. Weight can be measured by using a standard bathroom scale.

Abdominal Circumference

The abdominal circumference can impact the performance of a workstation if the worker is obese, as the stomach is getting in the way of reaching parts and tools. This makes the operator stand further away from the workstation. The abdominal circumference is measured by using a tape measure and lay it around the waist above the hip bones, as shown in Figure 3.1.

Figure 3.1 Measuring abdominal circumference (NCHS, 1988)

Height

Standing height is a critical anthropometric measure for workstations personalization, as this impacts the recommended height of the working surface and where to place parts in combination with the arm length. This measurement is taken by having the operator stand towards a wall with the shoulder blades, buttocks, and heels touching the wall, as depicted in Figure 3.2a.

Sitting height is how tall an operator measures from sitting position. This anthropometric measure is measured by placing the ruler at the seat of the chair and measuring to the top of the head, as shown in Figure 3.2 a and b.

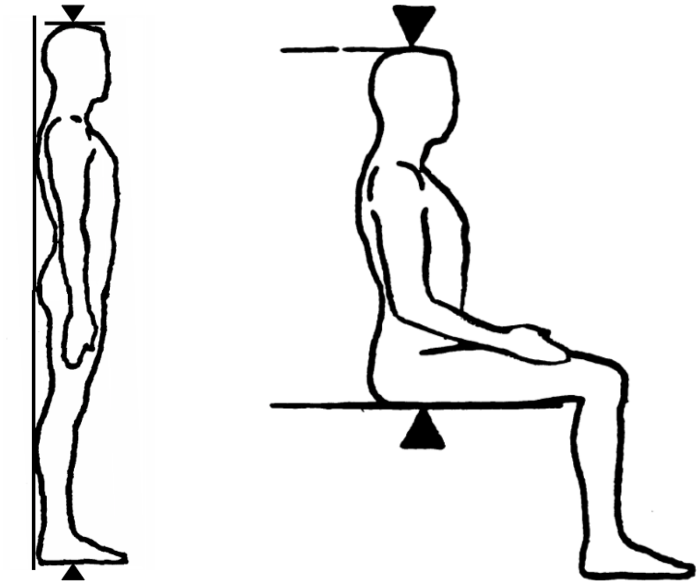


Figure 3.2a and b Measuring standing(a) and sitting(b) height (NCHS, 1988)

Knee Height

The height of the knee is a measurement that can affect the design of a workstation, as the knee has to go clear of beams and other objects under it. It is found by sitting with a 90-degree angle in the knee joint and measured from the floor to the top of the knee, as illustrated in Figure 3.3.

Figure 3.3 Measurement of knee height (NCHS, 1988)

Arm Length

The length of the arms on operators is a deciding factor when it comes to how far they can reach for parts and tools. The upper arm length is also a deciding factor for the best-suited working height, both when seated and standing, as the elbow height is used as a reference. Finding the total arm length/reach of the operator is done by measuring from the back of the shoulder and to the fingertips, as depicted in Figure 3.4a. For the upper arm length, it is measured from the top of the shoulder to the underside of the elbow, as depicted in Figure 3.4b.

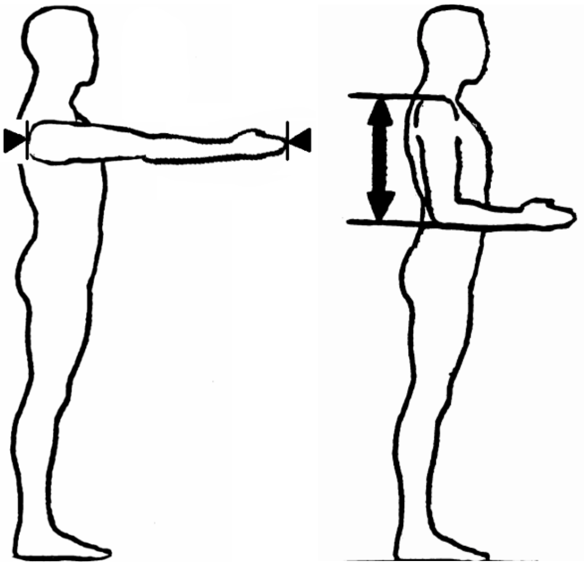


Figure 3.4 Measuring arm length/reach (a) and upper arm length(b) (NCHS, 1988) (3.4 a is modified to reach forward)

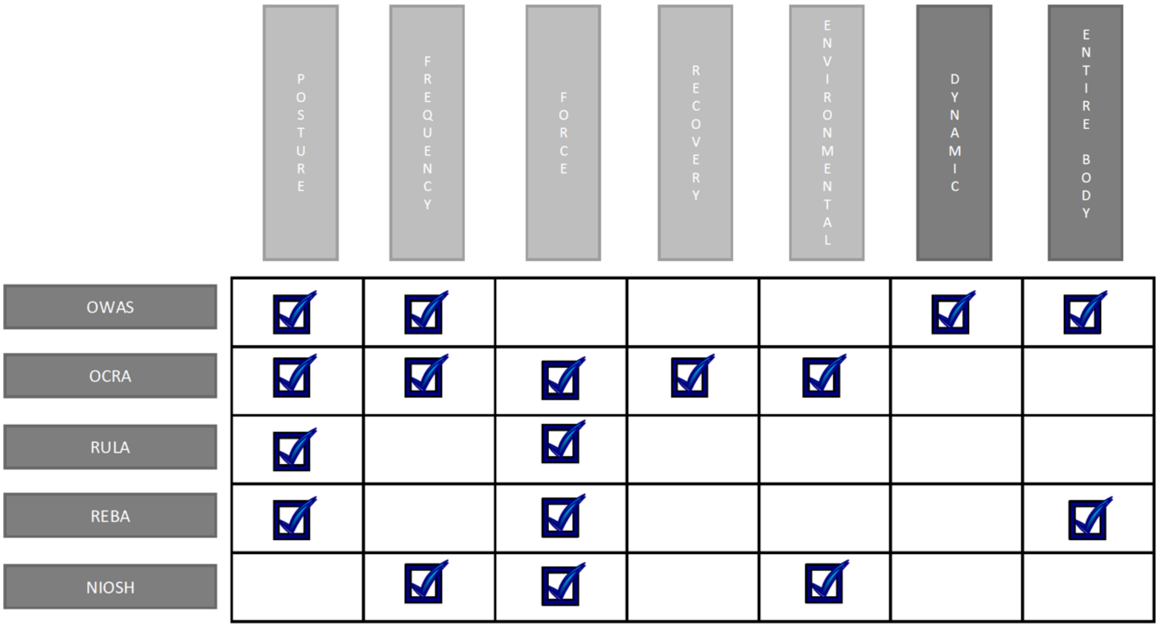
3.3.4. Skills and Experience

The skill level of humans is a parameter influencing how humans perform tasks. Accommodating designs based on both inexperienced workers with little to no previous experience and skilled specialized operators can be demanding, as they might have different needs. The inexperienced and experienced workers often have different procedures for conducting the same tasks (Hussain et al., 2016, Chen et al., 2011).

3.3.5. Strength and endurance

The strength and endurance of operators can vary. Some operators might be able to lift and work with heavy equipment and assemblies, while others are not able to perform the same tasks alone. The endurance of workers can also impact the level of fatigue the operators are experiencing and the recovery time needed after conducting exhausting tasks.

3.4. Ergonomic Evaluation Methods



	POSTURE	FREQUENCY	FORCE	RECOVERY	ENVIRONMENTAL	DYNAMIC	ENTIRE BODY
OWAS	☑	☑				☑	☑
OCRA	☑	☑	☑	☑	☑		
RULA	☑		☑				
REBA	☑		☑				☑
NIOSH		☑	☑		☑		

Figure 3.5 Main ergonomic evaluation methods and characteristics according to Battini et al. (2014)

Battini et al. (2014) made an overview of the leading ergonomic evaluation methods and their characteristics. Figure 3.5 is a copy of the figure they used for their paper. The figure shows 5 conventional ergonomic evaluation methods listed in the row section, and what they evaluate in the line sections.

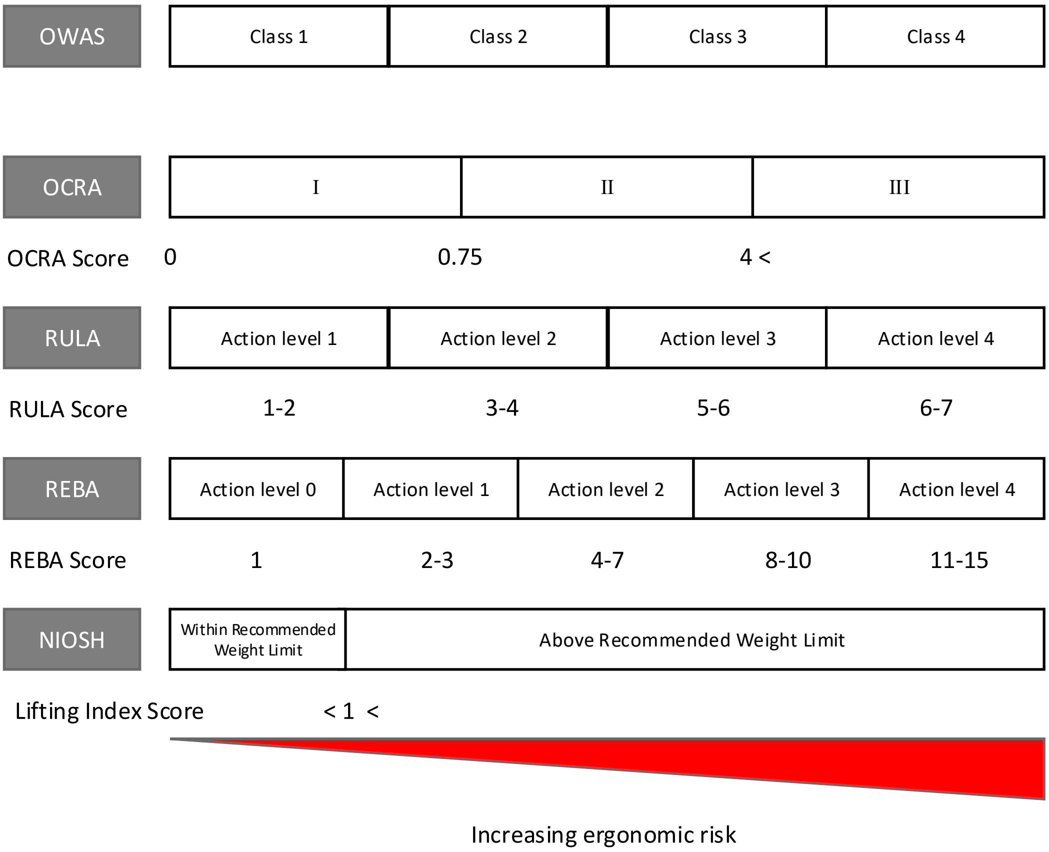


Figure 3.6 Ergonomic assessment methods with grades for the level of ergonomic risk

Figure 3.6 lists the aforementioned ergonomic evaluation methods and illustrates how each is graded. The ergonomic risk increases from left to right and the urgency for reevaluating a task is higher the further to the right on the figure the score is. Although one evaluation method's level is at the same place in the figure as another, does not mean they have the same ergonomic risk.

3.4.1. Ovako Working Posture Analysis System (OWAS)

The analysis tool puts most emphasis on the discomfort caused by working postures (Karhu et al., 1977). The makers of the OWAS had the criteria that it should be possible to conduct by ergonomically untrained personnel, that it must provide unambiguous answers even if it results in over-simplifications, and that it must be possible to correct the over-simplified approach. The method is based on work sampling to find the frequency and time spent in different postures. OWAS also have 4 classes of results, from class 1 being normal postures not needing any special attention, to class 4 requiring immediate attention, as seen in Figure 3.6.

3.4.2. Occupational Repetitive Actions Index (OCRA index)

OCRA is a method for calculating operators' exposure to repetitive movements of the upper limbs (Occhipinti, 1998). The index is based on the difference between the recommended number of actions per day and the number performed. OCRA is an exposure index, comparing the number of technical tasks performed during a shift to the recommended number of technical actions per shift. There are 3 levels to the OCRA index, as seen in Figure 3.6. When the exposure index is less or equal to one, exposure can be assumed to be acceptable. It is significant once it surpasses 1, meaning more technical actions per shift than recommended. A score of less than 0.75 means the condition is acceptable. Scores between 0.75 and 4.00 are uncertain and require more detailed studying, and above 4 indicates that actions should be done to improve working conditions. The value of OCRA lies in its ability to classify scenarios that can expose operators to significant risk factors, and therefore avoid them, and also identify tasks that are not problematic.

3.4.3. Rapid Upper Limb Assessment (RULA)

McAtamney and Nigel Corlett (1993) developed RULA as a method for investigating workplaces where work-related upper limb disorders are present. The method does not require any special tools to conduct the investigations. RULA is based on the OWAS system, as seen in subchapter 3.4.1. The risk factors investigated are numbers of movements, static muscle work, force, work postures determined by the equipment and "furniture", and time worked without a break. Other important factors that vary between individuals are work postures adopted, unnecessary use of static muscle work or force, speed and accuracy of movements, the frequency, and the duration of pauses taken by the worker. RULA is developed to avoid using any specialized equipment and performed without disrupting the work. The result of investigating different tasks performed by the workers is a score between 1 and 7, as illustrated in Figure 3.6. A score of 1-2 the posture is acceptable if not repeated or kept too often over long periods. 3-4 means further investigation should be done, but changes might be necessary. 5-6 means investigation and changing of the procedure to be done soon, and a score of 7 means immediate actions and investigation are required. When conducting a thorough investigation of the workplace, RULA can be used as a screening tool or as part of a more extensive assessment.

3.4.4. Rapid Entire Body Assessment (REBA)

Rapid Entire Body Assessment was developed as a tool for evaluating working postures where the workers are by Hignett and McAtamney (2000). It is designed to review unpredictable working postures as found in lines of work as health care and other service industries requiring minimal equipment. More than 600 postural examples were included in the creation of the tool by Ergonomists, physiotherapists, and other researchers within the field of occupational safety, from an ergonomic point of view. The design of the REBA method aimed to develop an analysis system that is sensitive to musculoskeletal risks in varying tasks, divide the body into segments individually coded using references to movement planes, have a scoring system for the parameters, and result in an action level and indication of urgency. The scoring system is illustrated in Figure 3.6 with 5 action levels, from 0-4. The action level is decided from a score between 1 and 15.

3.4.5. NIOSH Lifting Equation

The NIOSH lifting equation is an ergonomic evaluation method for evaluating the recommended weight limit for a task. This weight limit is within a range so almost all healthy personnel can conduct these lifts regularly over a substantial period, defined as 8 hours (Waters et al., 1994). The recommended weight limit is compared to the actual weight for the task, and the lifting index indicates if the weight is acceptable or not. A lifting index score of above 1, is considered potentially harmful, as shown in Figure 3.6. The more the score exceeds 1 the higher the likelihood of strain and injury. The recommended weight limit is based on a load constant of 23 kg, which is the maximum recommended weight for carrying under ideal conditions. The distance the object is carried from the body both vertically and horizontally, the distance it is carried, the angle it is carried off the centerline of the body, and the frequency of lifting is also included in the equation.

3.5. Key Performance Indicator (KPI)

Performance measures are essential for understanding the state of a system to supervise that standards are made or to take steps to maintain competitiveness (Hon, 2005). For the sake of workstations, this is making sure the current workstations or new designs are performing well.

In Figure 3.7 Meyer (2002) presents the seven purposes of performance measures. It can look back at historical performance data, called a lagging indicator, it can look ahead at forecasted performance, called a leading indicator, it can compensate or motivate. The purposes placed outside the pyramid are common from the smallest to the largest organizations. Roll up, cascade down, and compare purpose is placed within as it becomes more valid to study when a firm is of larger size and complexity. The look back and ahead purposes are at the top, as it is to evaluate the firm as a whole, and Compensate and Motivate are at the bottom as they have the purpose of driving individual workers/operators.

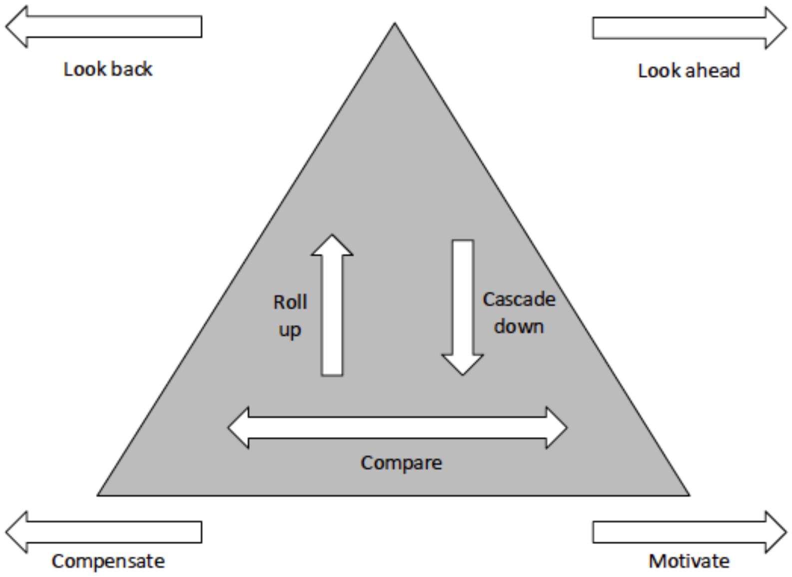


Figure 3.7 The seven purposes of performance measures (Meyer, 2002)

The properties key performance indicators should have are related to how relevant it is to the organization, how usable it is, and its adaptability (Hon, 2005). Hon suggests that the KPIs are practical in the way that they are simple to measure and informative. Leading measures should be predictable, so they can be used for planning. Pervasive measures could be applied throughout the organization and be compared to each other, instead of specific single-purpose measures.

When choosing the right performance measurements to evaluate a business or a system, there can be problems with trying to have few measures that can potentially not give the depth needed or having many that can be hard to manage (Slack et al., 2016).

Performance indicators or performance measurements are data that indicate how a system is performing compared to a set goal. The measurements are usually quantifiable, so the evaluation can be done quickly. If the goal is to have less than 2 scraps per day, a number lower than that is indicating that the system is performing well. If the set goal is to make more than 80 of a product per day, any score above 80 means the system is performing well. It can also be goals and measurements in a percentage of a total.

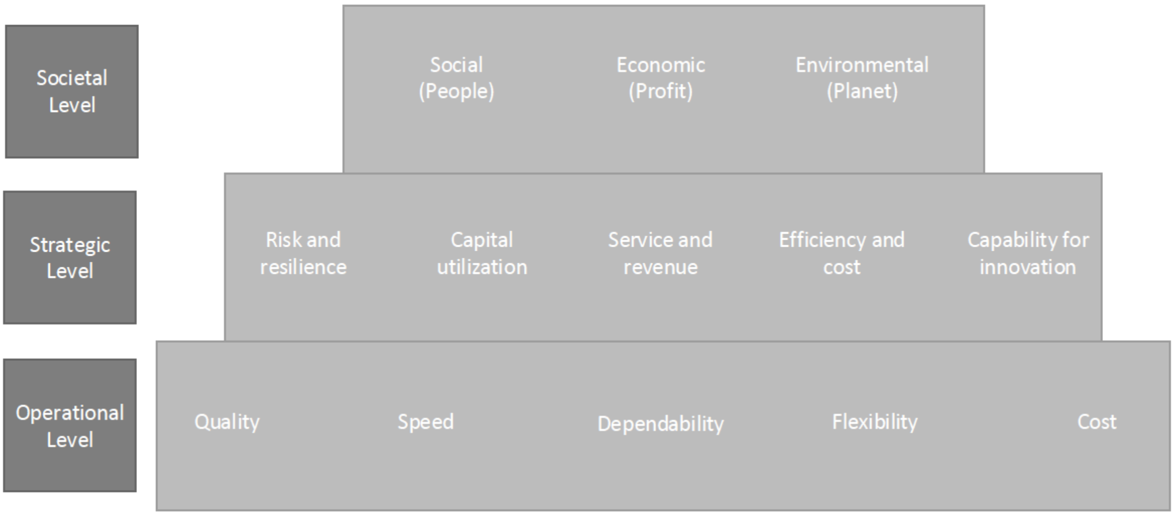


Figure 3.8 Performance measures of three levels (Slack et al., 2016)

Figure 3.8 shows the three levels of performance measures (Slack et al., 2016). In this thesis, the main types of aspects are on different levels of the figure. Production KPIs are mainly at the operational level, while ergonomic KPIs are part of the social measures at the societal level.

3.6. Industry 4.0 Technologies for Manual Operators

For manufacturing companies to develop their workforce in the same direction as the rest of their operation when faced with the changes related to Industry 4.0, the typology of Operator 4.0 was introduced by Romero et al. (2016). The paper includes early tests and future projects of research using Industry 4.0 technologies to aid and assist operators by machines, as well as cooperative work with robots. This is by *"means of human cyber-physical systems, advanced human machine interaction technologies and adaptive automation towards 'human-automation symbiosis work systems'"(Romero et al., 2016).*

4. Findings and Observations

4.1. KPIs for Workstation Evaluation

In this part the production and ergonomic KPIs found for workstation evaluation will be presented.

4.1.1. Production KPIs

From the literature search described in Table 2.1 and some relevant papers, useful production KPIs were found.

In (Battini et al., 2018), many potentially relevant KPIs for workstation evaluation are mentioned. Many of the KPIs mentioned are time monitored indicators, as it is intended for use with a motion capture suit. The paper mentions the time necessary for performing a specific task, and the time spent on value-adding tasks compared to non-value-adding tasks. The percentage of picking errors is also mentioned. Kärcher et al. (2018) are studying the analysis of manual assembly systems using sensors and recognizes the importance of processing time for successful planning and control for manual tasks. Kärcher et al. (2018) describe possibilities to track the time of manual assembly steps. Yoon et al. (2014) use performance indicators as work-in-progress (WIP) level, tardiness, throughput, and due date. The paper investigates bottleneck workstations and the effects of the dispatching rule and bottleneck load order review in a printed circuit board manufacturing line.

Rotaru et al. (2014) are using KPIs to evaluate how the flow is managed, production performance management, and the demand of clients impact the performance indicators. The KPIs used in that paper are work in progress, cost per unit, the systems reactivity to client demand, and throughput. In that paper, the KPIs were applied to simulations. In Schipper et al. (2016), the paper is about the emergence of synchronization and its effects on production performance objectives. The performance indicators included in their paper were throughput time, work-in-progress (WIP), and capacity utilization.

The following three KPIs were considered to be the best suited for evaluating the production performance of a workstation.

Processing time

Processing time is the time it takes to produce a product or provide a service (Stevenson, 2012). When using it as a performance indicator for workstations, it can be narrowed down to the time it takes to complete a process step at the workstation.

Time spent on value-adding tasks

Value-added is the difference between the cost of inputs and the value of outputs. Value-adding tasks are tasks that transform the inputs, in the case of workstations parts, to outputs in the form of products. Assembly processes are value-adding tasks, as they transform the parts into products, while picking the parts is not value-adding, but necessary.

Product quality

Quality is one of the 5 main performance measures at the operational level, according to Slack et al. (2016), and can include error or scrap rate as a measurement for its performance.

4.1.2. Ergonomic KPIs

Ergonomic performance indicators are measurements that show how workstations perform in terms of when considering human factors. These indicators have become more relevant lately, as more businesses are acknowledging the impact ergonomics has on their operators and their production. More regulations have also caused businesses to increase their focus on ergonomics (Peruzzini et al., 2017).

Battini et al. (2018) describe multiple ergonomic performance indicators for the evaluation of workstations. As with the production KPIs highlighted in the paper, the ergonomic KPIs are time monitored. The time spent in what Battini et al. (2018) calls “the golden zone,” which is the area closest to the body where both hands can easily overlap, is one of them. Other types of ergonomic performance measures are the ergonomic evaluation methods presented in Figure 3.5 (Battini et al., 2014, Bortolini et al., 2017).

In the search for ergonomic KPIs, few single measurements were found. The search revealed multiple ergonomic evaluation methods. The methods for evaluation that appeared the most in literature from the search were the same ones presented in Figure 3.5, copied from Battini et al. (2014).

Ergonomic KPIs Literature Search gave 17 papers. The number of papers each ergonomic evaluation methods appeared in is presented in Table 4.1. Most of the papers mentioned more than one method.

Table 4.1 Ergonomic evaluation method appearances in literature search

Ergonomic evaluation method	**Number of papers mentioned in (of 17)**
OWAS	6
OCRA	5
RULA	9
REBA	10
NIOSH Lifting Equation	9

From the literature search for ergonomic KPIs and mentioned consequences of poor ergonomics, the following five ergonomic KPIs were chosen as the performance measurements to use.

Score from ergonomic evaluation method

The common methods for evaluating ergonomic performance in literature are different methods of highlighting potentially harmful positions and operations. According to Battini et al. (2014), the most common evaluation methods are OWAS, OCRA, RULA, REBA, and NIOSH, as depicted in Figure 3.5. These are the same methods that are included in (Bortolini et al., 2017). The evaluation methods are score based on different measures suggested depending on the score.

In subchapter 3.4 some of the most common assessment tools for workplace ergonomics were presented. Most of these assessments are done by evaluating specific postures and grading them according to the score chart.

Time spent in the primary work envelope

The length of the operator's arms is the determining factor for how far they can reach, and how large their reach envelope is. The reach envelope can be divided into sectors, where the overlapping area where both hands can reach without stretching should be reserved for the workpiece. The primary work envelope is the normal reach, and the area that can be reached with bent elbows, and maximum reach with straight arms is the secondary work envelope (Stack, 2016). Outside of the work, envelopes are where the operator has to bend and stretch to reach. Working within the primary work envelope causes less strain on the body and is, therefore the recommended work area. A workstation where the operator spends more time in the primary work envelope will score better on this performance indicator, and also lead to less strain on him/her. Figure 4.1 and Figure 4.2 show Stack (2016) representation of the work envelope horizontally and vertically, respectively.

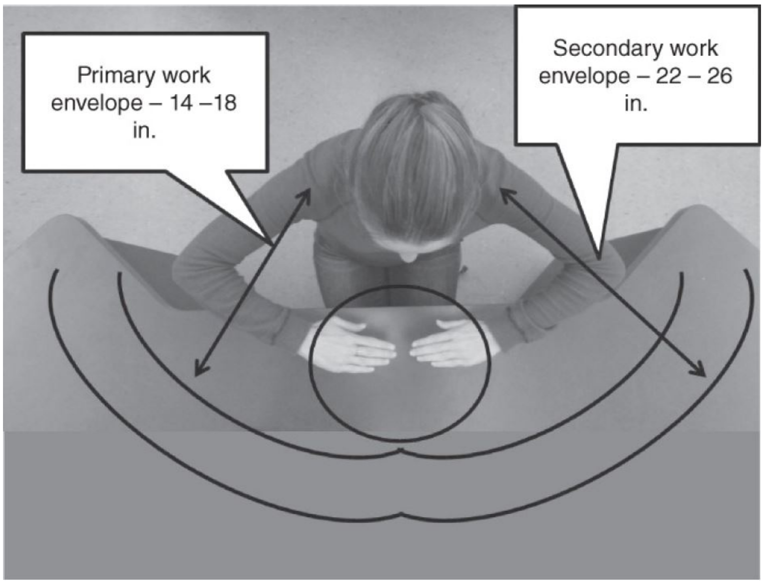


Figure 4.1 Horizontal reach envelope seated (Stack, 2016)

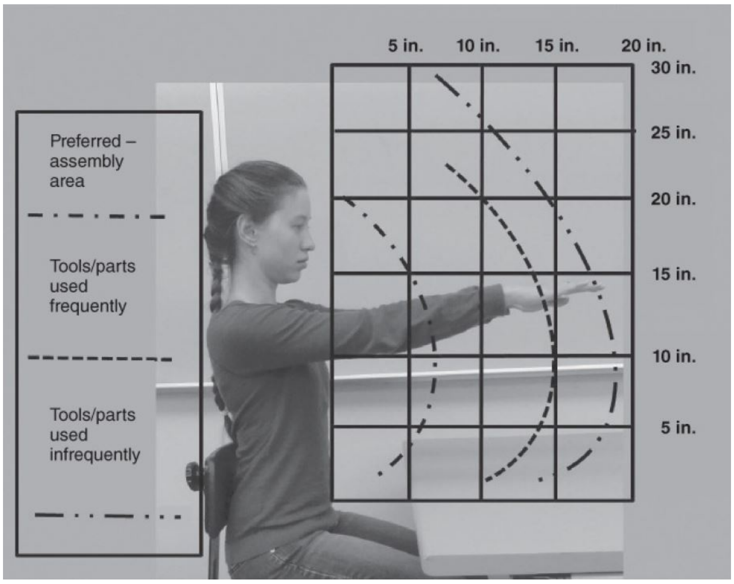


Figure 4.2 Vertical reaching envelope seated (Stack, 2016)

Absenteeism

Absenteeism can be an indicator of poor human factors at the workplace. In Norway, 38% of all absenteeism is due to musculoskeletal disorders (STAMI, 2018). As aforementioned, half of the more severe cases are reportedly partly or completely workplace-related. Because of this, absenteeism can be a good indicator of ergonomic performance in the workplace. If the absenteeism at a facility is reduced after the workstation design has been changed, it can mean the ergonomic performance of the workplace has been improved.

Employee turnover rate

How long operators are staying in their position can be an indicator of the human factors of the company. A low average of time working in the company can be an indicator of poor ergonomics in the company. Early retirements are influencing this measurement, as in Toomingas and Kilbom (2007).

Fatigue

Fatigue is defined as *"extreme tiredness resulting from mental or physical exertion or illness"* by Oxford dictionary of English (2020). It can be measured by operators having increased processing times or needing more or longer breaks.

4.2. Human Variation and How it Affects Workstation Performance

In Katiraee et al. (2019), age, gender, anthropometry, anthropology, skills, personal and professional abilities, and cognitive abilities are mentioned as factors of human diversity in a manufacturing setting. Battini et al. (2018) briefly mention gender, age, anthropometric measurements, and physical capabilities as examples of human variation. Age, gender, level of skill, experience, and background is (Hussain et al., 2016). In (Battini et al., 2011) includes some other ways of variation with anthropometry, grip strength, height, weight, and BMI. Gallwey (1992) uses anthropometry, gender, muscular strength, age, and physical fitness when describing what another study fails to include when researching operator performance. NIOSH (1981) mentions gender, age, anthropometry, lifting technique, attitude, training, and strength aspects where individuals differ.

The ways of human variation included for this thesis is age, gender, anthropometry, skills/experience, and strength/stamina. These human variations were chosen because they were the most mentioned in papers and the most influential.

4.2.1. The Effects of Human Variation on the performance

Through conducting literature searches, a correlation of the decided human variation factors and the KPIs as presented in Table 4.2 and Table 4.3.

Table 4.2 Correlation found between human variation (HV) factor and production KPIs

HV \ KPIs	**Processing time**	**Time spent on value-adding tasks**	**Quality**
Age	In high tempo work the older workers had a hard time keeping the pace (Toomingas and Kilbom, 2007)	From a study of operators, older workers had less value-added than younger workers(Lee et al., 2018)	
Gender			
Anthropometry			
Skills/experience	The learning curve effect contributes to operators reducing the processing time, especially in more complex tasks(Stevenson, 2012)	It was noticed that skilled workers rotated the workpiece fewer times in an assembly than lower skilled workers, as they adapt their own techniques (Hussain et al., 2016)	Own experience and observation from manufacturing tasks have shown an increase in quality as workers get more experience.
Strength			

Table 4.3 Correlation found between human variation (HV) factor and ergonomic KPIs

HV \ KPIs	**Ergonomic evaluation method**	**Time in Primary work envelope**	**Absenteeism**	**Staff turnover rate**	**Fatigue/breaks needed**
Age			Older operators have fewer non-fatal injuries, but need more recovery time if they get injured (Silverstein, 2008)	In heavy assembly jobs there was a problem with early retirements (Toomingas and Kilbom, 2007)	Elderly workers showed increased fatigue resistance than younger, although they also had reduced strength (Yassierli and Nussbaum, 2009)
Gender	Differences in joint angles between males and females (Hamilton et al., 2013)				Females work closer to max strength capacity and show less muscular rest (Nordander et al., 2008)
Anthropometry	Through seeing how the methods are evaluated, with joint angles and positions	Higher BMI gives smaller work envelope (Hamilton et al., 2013)			
Skills/experience			Skilled operators adopt better working positions from experience (Chen et al., 2011)		Experience makes operators adopt work positions causing less fatigue (Chen et al., 2011)
Strength					Weaker subjects showed less fatigue when working within acceptable weights (Fernandez and Marley, 2014)

Hussain et al. (2016) say the human variation can be a source of performance inconsistencies, and (NIOSH, 1981) says that task performance, in that case lifting tasks, varies a lot between individuals, but is also variations for the same individual over time.

Human variation is not only affecting production and ergonomic KPIs, but also related to the other chosen variations. Older operators showed approximately 23% lower maximum voluntary contraction in their muscles with older male operators at almost 25% reduction and older female operators 19.2% (Yassierli and Nussbaum, 2009).

In Neumann et al. (2016), a systematic literature review was conducted to evaluate the effects human factors have on quality performance in workstation design, process design, and product design. The literature review identified 49 different workstation variables related to a drop in quality. It also identified quality risk factors related to process design, product design, and individual factors.

Age

One of the research ways of human variation is their age. Age is different from most of the other human variation, as it is the same operator varying from how he or she was earlier.

Silverstein (2008) says that older workers have less non-fatal injuries than their younger counterparts. However, when they first suffer an injury, it is likely to need more recovery time than with younger workers. Yassierli and Nussbaum (2009) indicate that elderly workers have a reduction in strength, but showed increased fatigue resistance, suggesting it could be taken advantage of by low resistance lifting.

Fritzsche et al. (2014) found that the error rate does not increase as the operators get older, as they benefit from job experience. In small and medium-sized enterprises (SME) within manufacturing, a study showed a negative relationship between increased age and value-added per worker (Lee et al., 2018). Toomingas and Kilbom (2007) also found from one of their case studies that it was hard for aging workers to keep the set production rate at a car assembly plant.

In many case companies studied by Toomingas and Kilbom (2007), early retirement of older workers was reported as a problem, resulting in a loss of competence for the companies. It could also lead to a staff problem if few there were few job seekers at the time.

Gender

Hamilton et al. (2013) found that there are relatively large differences between genders when it comes to elbow extension angles, neck flexion, and lateral neck bending. Women had significantly larger elbow extension angle at max reach during workstation testing. They also had a higher neck lateral flexion angle than men. Men had a more top neck flexion angle than women. The elbow extension angle can put women at a higher risk of musculoskeletal disorders in the upper extremities and was argued to be a contributing factor to why women have statistically higher risks of these types of disorders.

For similar repetitive tasks, women showed higher muscular activity compared to their maximum voluntary contractions than men (Nordander et al., 2008). The female participants of the study showed a muscular activity closer to their maximal capacity than their male counterparts, and a higher occurrence of musculoskeletal disorders. Female participants were exhibiting lower muscular rest than males giving them a lower ability to combat muscular fatigue. Nordander et al. (2008) suggest higher muscular activity compared to the maximal capacity to be an important factor as to why women have a higher occurrence of work-related musculoskeletal disorders.

In a study conducted by Varianou-Mikellidou et al. (2020), female workers scored lower on the workability index. Rotenberg et al. (2008), researching gender differences among nursing personnel, explains this as females have less time to rest due to double work exposure by having more responsibilities in the home with childcare and home keeping.

Anthropometry

The score on ergonomic evaluation methods is very influenced by anthropometry, as most of them are using joint angles to give an ergonomic score. It can be assumed that for operators with shorter reach, stretching is more likely if tools and parts are not placed properly, resulting in a lower score in the ergonomic evaluation method. For taller operators more bending for parts and tools stored at a lower level can be assumed.

Hamilton et al. (2013) found that the maximal forward functional reach of obese subjects was significantly lower than the reach of the normal-weight subjects. Their overall reach envelope was significantly lower due to abdominal circumference.

Overweight operators will probably score lower on the percentage of time spent in the primary work envelope. This results in a poorer ergonomic for overweight operators. It was also found that a higher body mass index often resulted in a slight sway backward (Hamilton et al., 2015).

Skills and Experience

In their case study, Hussain et al. (2016) noticed that the skilled manual operators made fewer rotations to the workpiece, in that case sofas, when assembling it. The fewer rotations resulted in less time spent in awkward and uncomfortable positions as well as less time per assembly. The specialized (skilled) workers made on average 2.25 rotations to the sofa while working on it, while the multiskilled made 1.5 rotations more and the semiskilled 3.5 rotations more than the skilled.

The learning curve is a known effect in production management. When operators conduct a task several times, they get better at conducting this task. The learning effect is more significant, with more complex tasks that take longer to finish than with shorter routine tasks (Stevenson, 2012). The learning effect is not only due to increased worker skills but also because of preproduction factors.

In the study conducted by Chen et al. (2011), there is a positive correlation between work experience/skill and static strength. Experienced workers also had adopted a safer technique for generating lifting strength. They concluded that skilled workers adopt their own techniques to perform their work safely.

Strength/Endurance

According to Fernandez and Marley (2014) weaker operators could work at a higher rate than stronger operators at the same relative force level. Harbin and Olson (2005) had a goal for their study to develop strength profiles that could be used as a tool to determine if a worker were more prone to injury. They realized that this was not possible without linking their strength to the requirements of the job. The use of this was to pre-test workers to assign them to jobs suitable for their needs and showed in case tests lower injury rates and less spent on medical cost.

4.3. Enabling technologies

Romero et al. (2016) present ways INDUSTRY 4.0 technologies can assist operators in becoming what they call “smarter operators” in an Industry 4.0 environment. The technologies presented are for social improvement purposes. In the paper, the technologies are presented to be either single or hybrid types combining the technologies.

4.3.1. Exoskeletons

The ASTM F48 International Technical Committee on Exoskeletons and Exosuits defines them as *“an exoskeleton is defined as a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity”* in the paper by Lowe et al. (2019). Exoskeletons are either classified as active or passive, depending on their use of electric power supply or springs, levers, or other non-electrical means.

Exoskeletons can be used for protection, increased strength, and endurance of the operators. It also helps reduce injuries and accidents related to heavy workload (Romero et al., 2016).

4.3.2. Augmented Reality

Augmented reality (AR) technology can assist the operators in real-time with instructions and thereby reduce human errors (Romero et al., 2016). It can be used to give the operators instructions for the task, or highlight where to find parts or tools required.

4.3.3. Virtual Reality

Immersive virtual reality is technologies where a user can enter an immersive environment with visualizations of digital objects in a three-dimensional space. Peruzzini et al. (2019) describe virtual reality as able to provide immersive working areas where the operators can move around in a virtual environment. When it comes to the execution of virtual reality, there are different types. The type most people associate with virtual reality is the use of a head-mounted display (HMD), as shown in Figure 4.3. This type is a form of mask/glasses covering the eyes of the user, and showing an environment through two screens, one for each eye, for the sense of depth perception. Usually, these HMDs have sensors that make the view follow the head movement of the user. There is also projection-based virtual reality, with the environment being projected on screens covering the field of view of the user.

Virtual reality is useful in training novice operators, especially when it comes to complicated assemblies that can have the potential for being costly if mistakes are made (Romero et al., 2016).

Figure 4.3 Test subject using HMD VR *NASA Goddard Photo and Video / CC BY (https://creativecommons.org/licenses/by/2.0)*

4.3.4. Collaborative robots

What is meant by collaborative robots (cobots) are not entirely agreed upon. There are two main types; collaborative and assistive robots (Schou et al., 2018). While collaborative robots are robots that help the operator directly in solving tasks, the assistive robot is more of an assistant working alongside the human worker. In this thesis, cobot will refer to the collaborative robot directly aiding the operator in solving tasks. Cobots are intended for industrial use and can be used to complete tasks that are repetitive and not ergonomic for the human operator (Romero et al., 2016). The cobots are made to be safe for use in a collaborative manner for the operator, which differs from other industrial robots that need their designated rooms or barriers for operator safety. Cobots are equipped with sensors to detect operators and other objects that can block their movement. Figure 4.4 shows an assembly worker using a cobot to get a better angle for the assembly.

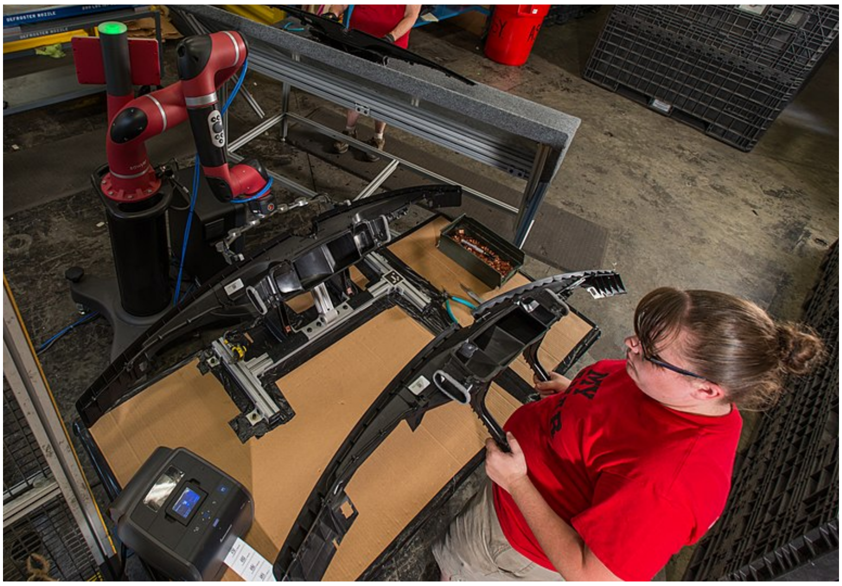


Figure 4.4 Operator aided by cobot Jeff Green/Rethink Robotics / CC BY (https://creativecommons.org/licenses/by/4.0) (cropped image)

4.3.5. Motion capture system

A motion capture system is a type of technology or technique to capture the movements of a subject. The relative movement of the sensors can digitally represent the movements in software or a spreadsheet of relative movements. Motion capture systems have been used in the movie production and entertainment industry, for evaluation of biomechanics in sports and health care patients, and engineering purposes (Corazza et al., 2006).

There are different types of motion capture systems. Optical motion capture systems usually have the subject wearing graphical reference points on their body, which is then recorded with multiple cameras to capture all relative movement of the subject. Another motion capture system is inertial motion capture systems. They are suits with inertial sensors on every major bone, to show relative movement. One advantage of the inertial motion capture system is that the movement data is available in realtime because the system is fully digital.

Literature has shown the benefit of using a motion capture system to test current and potential design alternatives to evaluate the ergonomic performance of the workstations (Peruzzini et al., 2019, Battini et al., 2018). It is helpful in the collection of data for evaluation and leaves less need for personal judgments of the performance. For evaluating workstations inertial motion capture systems are, according to Battini et al. (2018), better than optical alternatives. The reason why it is considered superior is due to more accurate capturing, as well as not needing to video record the process as well. It also provides the possibility for realtime evaluation of the ergonomics in combination with an evaluation software, as the movements are directly recorded in the computer (Battini et al., 2014).

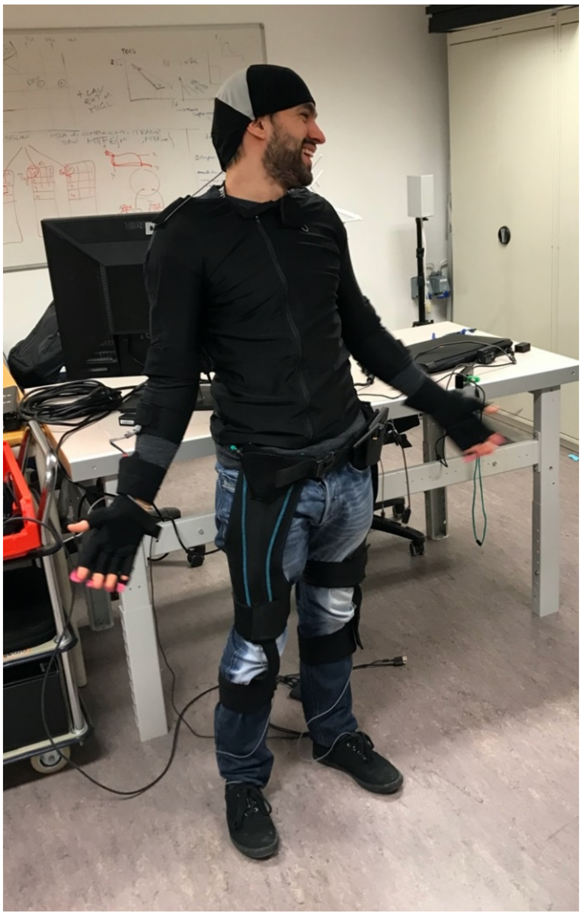


Figure 4.5 Test operator wearing an inertial motion capture suit in the Logistics 4.0 Laboratory at NTNU

5. Discussion

In this part the findings from the research will be presented and discusses. Limitations to the thesis will also be presented and discussed.

5.1. Which ergonomic and production KPIs found in literature can be used to evaluate the performance of a workstation, and how?

In the start of searching for KPIs viable for workstation performance evaluation, it was visible that there was not a given recipe used for assessments. The importance of ergonomics was stressed by most of the recent workstation design papers, as it had positive impact on production performance as well as operator well-being. As part of lower level facilities, workstations are areas operators spend a considerable amount of time, and often most of their workdays in assembly plants. For a long time workstations have been designed from a productional point of view, but managers are starting to realize the positive impacts of designing with human factors in mind.

The performance indicators found in relevant literature could have different uses. As shown in Figure 3.7 there are, according to Meyer (2002), 7 purposes of performance measures. All seven purposes are not equally relevant to workstation performance. For workstation performance evaluation, the primary purpose of the performance measures is to compare. The comparisons are to evaluate the current performance of the workstation setup with what the acceptable or wanted performance. When testing in a design phase, the comparisons are with goal performance levels set in the early stages of the design phase.

The KPIs found and used throughout the thesis have different times where they can be used for evaluating workstation performance. In

Table 5.1, they have been divided into two different uses. KPIs listed in column 1 are appropriate to use as indicators of their workstation not performing at an acceptable level. In column 2, performance indicators usable for testing the workstations are listed.

Table 5.1: The time of use for the KPIs

To indicate the need for further testing	For actual testing workstation
Absenteeism	Ergonomic evaluation methods
Processing time	Time spent in the primary work envelope
Fatigue	Time spent on value-adding tasks
Employee turnover	Processing time
Quality	
Operator feedback*	

Some of the KPIs found are not exclusively related to workstation performance. In those cases, it is necessary to do a root cause analysis to identify if the workstations are part of the problem. If more of the KPIs are pointing to it being workstation related, measures should be taken to fix the problems.

Without proper performance indicators for workstation evaluation, the design process can become arbitrary and result in too much emphasis being put on aspects that are not the most important. When performance goals are set for workstations, it is also possible for the design team to have a clear finish line in the process. If these goals are met, then the workstation is ready for production. This is also applicable for managers responsible for facility planning to decide if the workstations are still performing satisfactory or if new ones are needed.

As aforementioned, musculoskeletal disorders are one of the most common reasons for absenteeism in Norway, and much of this is work-related. Absenteeism statistics for the workplace can be utilized to uncover if there are issues at the workplace that needs to be fixed. Employee turnover can be used in the same regard, but can be unreliable in small businesses. If the turnover is early retirements, it can be related to operators not being able to do their job properly without getting injured. These ways to evaluate workstation performance are not only influenced by the workstation performance itself. It is a very broad measure, that can be influenced by other factors at work as well as personal matters outside work. However, an increase in the average length of absenteeism or the frequency, as well as increased employee turnover, are indicators that an investigation should be conducted.

Fatigue is a useful indicator for evaluating if a task is causing too much strain on the employee. Ways to monitor this can be through breaks needed to recover or increasing processing time after consecutive tasks.

Processing time can be used as a performance measurement in the evaluation if further testing is needed as well as actual testing of existing workstations and designs. It can be used to assess fatigue, optimal layout and indicate if the workstation is functioning well enough for all operators. Inconsistencies in processing time can indicate that the system is not optimal for all operators. Quality differences in terms of scrap and error rates can also be a result of this. If the part quality is consistent, but the assembly quality differing, the assembly process is a likely factor.

The operators are the ones using the workstations on an everyday basis, so if they have feedback regarding the state of the facility, the managers need to listen. If many operators are giving feedback that the workstations are not good enough, they should be tested and/or upgraded.

The ergonomic evaluation methods presented earlier are the most used tools in workplace ergonomics. Most of them are relatively old but still useful. None of the methods are suited for all purposes, as seen in Figure 3.5. E.g. OWAS is the only dynamic method, but it has its limitations in other areas. However, in combination, they can be used to evaluate workstation performance both in the design phase and in an AS-IS investigation. Some of them are not only focused on the production industry but can be just as relevant there. The aid of Industry 4.0 technology can potentially increase the usefulness and the ease of use of the evaluation methods.

The time spent in the primary work envelope is useful to identify if the tasks the operator conducts is fit the workstation he or she works uses. More time spent in the primary working envelope is related to less strain on, e.g., shoulders. If most of the time is spent in the primary working envelope, the tasks are fitting the station.

Time spent on value-adding tasks is useful to identify optimal workstation layout and placement of parts. Picking activities, although necessary, is not contributing to adding value to the product. If this can be reduced the processing time can reduced.

The applicability of the KPIs found through this thesis will differ between companies when testing the performance of their workstations. KPIs can be switched with others to fit the strategy of the company. If the company has rapid changes in the product mix, adaptability and changeover time could be more important than the actual processing time.

5.2. Which forms of human variation can influence the KPIs? And how will the variations influence the score of the KPIs?

In manual operations, the operator is the primary tool for assembling, packing, or other manual tasks. The flexibility this provides is far greater than with the use of machines, as humans require less changeover time to adapt to new tasks. However, operators can vary quite a lot from each other in physical and intellectual ways. These variations can make it more challenging to make tools and tasks to fit everyone. Variations also impact how well workstations function for the operators, and it is essential to be aware of when designing. If the KPIs are very inconsistent between operators with differences but stable among operators with similar traits of human variation, it can be a sign that the workstation is not suitable for the population using it.

In Table 4.2 and Table 4.3, the relationships found between human variations and the KPIs have been presented. This list is not complete, as many researchers have studied some of the correlations, and others have very little research. When more correlations have been studied and proven, they can be added to the table.

Although old age makes the muscular capacity of workers lower, it is interesting that their resistance to fatigue is increasing. Experience is also increasing with age, as they have more often been in similar situations than their younger counterparts. Given that the older operators have been working at the same job, their knowledge and experience can make their processing time lower even if their speed and strength is reduced. Therefore, it is fitting that the error rate is not increasing with age.

With the average age of the working force increasing in Europe, age has become an increasingly researched topic in industry. What is found from the literature search is that aging workers can be having trouble in tempo-work, and therefore increase the average processing time. Elderly workers were observed to have less value-added than younger workers in a study done in South-Korea. This will decrease the average time spent on value-adding tasks when measuring it. Age increases the length of absenteeism, as elderly workers often get more severe illnesses. Some of these illnesses could also result in increased employee turnover rate as older workers in heavy manual jobs retired early. When it came to fatigue, age was correlated to increased fatigue resistance for the older workers, although they were weaker than young workers. To enable older workers to continue working, workstations can be designed to accommodate the strength reduction and the inability to work as fast as younger operators.

Gender as a human variation parameter was not researched nearly as much as age and skill. The differences found between male and female operators were only related to ergonomic factors. The female operators have different elbow angles than male operators when reaching, putting them at a higher risk of musculoskeletal disorders. This mean that a female operator might score differently in an ergonomic evaluation method, as most of them are focused on joint angles. Due to a lower strength average among females, when conducting the same task, females are operating at a muscular contraction level closer to their maximum. Combined with lower muscular rest results in higher fatigue accumulation among female workers. As a result of this, to accommodate for all operators, fewer heavy lifting tasks can be part of the work.

Anthropometry is about the physical measures of the human body, and within this human variation factor are the most prominent differences. The differences does not directly influence the production KPIs. The ergonomic evaluation methods are based on joint angles and body positions, so factors as height will influence scores from bending, arm length influences how far the operator can reach, and the size of the work envelope, and length of legs will impact sitting positions. This will result in variations in the score from ergonomic evaluation methods depending the operator using it. The time spent in the primary work envelope is dependent on the size of it. For operators with a high BMI the work envelope is smaller than those with a lower BMI, which will therefore reduce the time spent in it. There is a need for adjustable workstations for every worker to be able to perform their job within acceptable scores from the ergonomic evaluation methods.

The learning curve effect is a clear indication that more experienced workers will result in shorter processing time, and increase quality by making fewer errors. When conducting manual tasks, the operator can find ways to reduce non-value-adding tasks as turning the workpiece. It is also shown that skilled workers find better work postures than novice workers to reduce postural stress. A result will be a better score from ergonomic evaluation methods, less absenteeism, and less accumulation of fatigue.

From strength, it was found that as long as the work weight was within acceptable limits for the weaker operators, they were able to resist fatigue better than the stronger operators. This results in less fatigue and fewer breaks needed.

5.3. Which Industry 4.0 technologies can improve workstation performance, and how can it assist the human operator?

From what found in literature, the Industry 4.0 technologies presented in chapter 4.3 are the most promising for workstation performance-enhancing. They are either actively assisting the operators or being a helpful tool in design and testing.

Exoskeletons can be used to reduce the load of an operator significantly. By reducing the force exerted on the operator it can reduce absenteeism due to fewer cases of musculoskeletal disorders. The reduction in force required to do the manual tasks due to aid from the exoskeleton can reduce strain on older workers and make them stay in their position longer, keeping the knowledge and experience of the operators.

Augmented reality has the potential to reduce processing time and time spent on value-adding tasks. By highlighting what to pick when and having assembly instructions always visible, if using AR glasses, or projected on the working surface.

Virtual reality can be used in training workers to do complicated assembly tasks in a virtual environment before doing it physically. This can be useful if errors are costly and difficult to fix. By doing this, there is an increase in quality in production. Virtual reality is also useful in combination with a motion capture system to test workstation designs in an immersive environment. This way, flaws and errors can be removed through design before it is made physically.

Collaborative robots have the potential to improve the workstation performance in all KPIs used in this thesis, as it assists the operator. The processing time can be reduced by the cobot conducting picking tasks for the operator, or presenting the right storage box for picking. In combination with a cobot turning the workpiece for better assembly access is also increasing the time the operator spends on value-adding tasks. The score from ergonomic evaluation methods will be lower as heavy lifting and awkward positioning is reduced if a cobot lifts the workpiece, presenting the attachment spot at the correct working height and angle for the operator. This also results in more time spent in the primary work envelope. The ergonomic improvements of this can reduce absenteeism, enable operators to stay longer in positions that would usually cause musculoskeletal disorders due to stress and strain. The helping hand of cobots can also reduce fatigue otherwise caused by heavy lifting or repetitive tasks.

Motion capture systems have been proven to be useful for evaluating manual tasks and workstation performances. With the use of a motion capture system, it is easier and faster to pinpoint the exact part of the workstation that is not performing well enough. The ergonomic evaluation methods can be implemented in software being fed postural data from the motion capture system. This can then be used to find which point of the test there was a posture or movement that can be considered a health risk. It can be helpful to have a video recording of the test to see which movements were done at the time, other than the digital skeleton model in the software. It can also be useful to find harmful motions that would otherwise not be registered and calculated if the recording had been done manually. None of the presented evaluation methods are specially made for using a motion capture system to record movements, but it can be adapted for digital use.

Combining the use of a motion capture system with VR can be useful for design and training purposes. In Figure 1.1, the part needing more clarification from the specialization project of Vig (2019) this type of combination was intended for evaluating the design proposal. It removes the need for physical mock-ups in the design process, and changes can be done and tested digitally in much less time. This type of Industry 4.0 technology can help improve all the KPIs by design.

5.4. Weaknesses and Limitations

5.4.1. Psychosocial factors

Psychosocial factors have been found to impact operators in more ways than just their mood when working. There have been found connections between having a poor psychosocial environment at work and musculoskeletal disorders. Psychosocial factors are, therefore, likely to influence the ergonomic KPIs and, in extension the production KPIs too. It is important to be aware of this. However, the thesis would have been too comprehensive if the aspect of psychosocial factors were to be included.

5.4.2. Ergonomic Evaluation Methods

In Table 4.1, the number of papers each of the ergonomic evaluation methods appears does not necessarily mean these are the best suited methods for evaluating ergonomics. Most of them are quite old, and only one of them is made for dynamic evaluation. The reason for their number of appearances could be due to popularity in the research community. Some can maybe be adapted for dynamic evaluation in simulated environments or by using a motion capture system.

5.4.3. Not Including All Ways Human Varies

Not all human variation factors found from the literature search were included in the thesis. Only the most mentioned and most prominent factors were included. This removed ethnicity as one factor. There are differences in anthropometric measures between workers from different parts of the world. However, there can be extensive variations within the same ethnicity as well. E.g., a workstation designed for the northern European market is likely to be too big for most workers in the Asian workforce. So this should be kept in mind if the producer makes them for the international market.

5.4.4. Privacy

From the literature on INDUSTRY 4.0 technologies implemented for enhanced performance, there were other technologies suggested as well. One of which was a GPS tracker and a heart rate monitor combined. These tools were suggested to aid the operators to plan and pace their work based on their scores. Although there are potential benefits to both the operator and the company, it was considered as a too intrusive technology to be suggested for this thesis.

6. Conclusion and Recommended Future Research

6.1. Conclusion

In this thesis, key performance indicators to use for the evaluation of workstation performance in terms of production and ergonomic goals were found. By using these KPIs, designers can discover if their proposed design is satisfactory or if changes need to be made. Other potential users are managers wanting to assess if there is need for an upgrade of the workstation for the work they are doing.

Human variance influences all tasks conducted by humans and can lead to very different experiences from one individual to another. In the thesis, some of the most prominent factors of human variation were studied to find how it influences the performance of workstations. It resulted in expected and unexpected discoveries. The list of how human variation affects workstation performance is not close to complete, but some important aspects were discovered. As discoveries of human variation are researched, it can be added to the list.

Through Industry 4.0 technologies, the manual work processes can get a fresh breath of air and change for the better for operators. Since manual tasks are the most flexible way of production, but their performance is not stable due to their variations, assistive Industry 4.0 technologies are showing promise to reduce the variance and also provide better workplaces for the operators. These technologies should not be used as an excuse to cut corners in the design process of workstations, but be used in combination with a well-designed workstation to remove or reduce the issues that cannot be fixed through design.

The outcome of this thesis is a set of KPIs that can be used by facility managers to evaluate their current setup, or by workstation designers to test their design either through a physical mock-ups and prototypes, or virtual ones. How human variation influences different performances in the workplace can be useful for other types of work than assembly and packing tasks too. The digital tools presented can also apply to other types of work.

In this thesis, all information is based on the research of others and informed assumptions made by the author. Using empirical data would have been a better way to evaluate the influence of human variation, as well as testing if the KPIs are enough for workstation evaluation.

The objectives of this thesis were to find a way to be able to decide whether or not the workstation performance was satisfactory, to understand how human variation influenced this and study how Industry 4.0 technologies can be useful to increase the performance. This was answered in this thesis, without deciding what the satisfactory level is. The goal level, and which performance indicators to optimize, must be decided by the design team in collaboration with the stakeholders.

6.2. Recommended Future Research

In this thesis, the use of the KPIs for evaluation and the different performances operators have at a workstation has only been studied from a theoretical point of view, using published papers and books available online. Testing the actual differences due to human variation, and if the KPIs mentioned in the thesis are applicable for workstation evaluation, should be conducted in a case study. The practicality of the KPIs is easier to assess in a practical study through empirical data collection, and by having access to data from a company.

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