Quantifying production complexity in the assembly of industrial robots

Does everyday complexity affect the quality of your product?

Master's thesis in Master Program Production engineering

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ABSTRACT

With the advancements of Industry 4.0 being rapidly achieved, Industry 5.0 aims to create a sustainable and socially responsible industrial practice. The framework of Industry 5.0 centrally aims to integrate the human workforce with advanced digital technologies thereby striving for inclusive growth and societal acceptance.

Understanding the current state of a production system helps relevant stakeholders to focus on key areas to improve and achieve a smooth integration between humans and digital tools. Complexity affects daily production activities in numerous ways. Understanding the causes of complexity helps in tackling the perceived problems of the workforce and finding deviations in production activities.

This thesis project explores the ways to define and quantify complexity in a production line using an objective and subjective method. The results show that out of the 6 assigned assembly lines for the study, 4 lines were concluded to be complex for the operators and from a general overview. The possibilities to manage complexity have also been discussed for application in a similar research environment in the future.

Keywords: Complexity, Quantify, Management, Production, Assembly, Manual, Quality.

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Arun Maslekar & Dat Le Trong Thanh, Gothenburg, June 2023

List of Acronyms

Underneath is a list compiled of acronyms in alphabetical order that have been utilized throughout this thesis :

CA	Correlation analysis
CXB	Complexity Basic
CXC	CompleXity Calculator
CXI	CompleXity Index
DMAIC	Define Measure Analyze Improve Control
KTC	Knowledge and Technology complexity
L6S	Lean six sigma
MCI	Manufacturing Complexity Index
OC	Operational complexity
OCC	Operator choice complexity
PMTS	Predetermined motion time systems
RI	Robust Index
TQC	Total Quality Control
VR	Virtual Reality

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Introduction

The following chapter gives a brief introduction to the study being carried out and provides a background with an overall view. The necessity of the thesis work is established by providing a problem statement which is further narrowed down to an aim and research question(s). Lastly, the delimitation and the structure of the thesis report are presented so that the reader has a comprehensive view of the thesis report

1.1 Background

The Covid-19 pandemic has brought to light the need to re-approach how manufacturing companies plan and execute their operations[2]. This period has exposed some of the vulnerabilities in terms of the supply chain, economic situations, and most importantly the human workforce. Modern manufacturing companies must now diversify their focus apart from purely economic dominance to creating a socially sustainable organization that continuously addresses socio-environmental issues. Industry 5.0 is thus an emerging concept that aims to provide a pathway that enables companies to integrate digital technologies such as the Internet of Things (IoT), Artificial Intelligence, and Augmented Reality (AR) into their daily operations not only for purely economic value but to create a benefit and improve the convenience of each citizen of the society[3].

Companies involved in make-to-order manufacturing are required to fulfill production orders along with being flexible and adapting quickly to emerging opportunities and uncertainties which results in frequent changes in internal strategies [4]. As seen in recent years, shortened product life cycles have increased the need for innovation, complexity, and requirements within a manufacturing environment, thus existing approaches for value creation are not suited [5]. This paved the way for the concept of the fourth industrial revolution wherein a set of technologies, devices and processes were used to create a self-sufficient production model that operates with minimum to no human intervention [6].

After about 10 years since the introduction of the Industry 4.0 concept, Industry 5.0 began to appear as a vision that aims beyond creating efficiency and productivity. The concept centrally aimed at respecting human values by putting the workers' well-being at the center of the manufacturing/production processes [7]. This transition from Industry 4.0 to 5.0, therefore, aims to address social expectations by focusing on three areas of development: create a production system that emphasizes being human-centric, sustainable, and resilient by considering the key dimensions of social sustainability [7].

In the context of Industry 4.0 and its rapid digitalization of traditional manufacturing systems, the decision-making power still lies with the humans operating these digital technologies. A direct consequence of this has increased complexity in the work environment for production and logistics personnel [8]. Therefore, companies have among several challenges, the challenge of establishing and maintaining a flexible production system that synthesizes with a diverse workforce yet remaining resilient under extreme circumstances.

Among several challenges faced by manufacturers, increasing complexity has been seen to influence the development of production processes and performance indicators of a company [9]. The understanding of the concept of complexity and its sources and effects must therefore be a key consideration for relevant stakeholders to make better quality decisions.

Manufacturing companies are today looking to invest in technologies that increase productivity, improve product quality and adopt a more data-driven approach to everyday processes. As a consequence of this, investment into fixed, programmable and flexible automation solutions has seen a significant increase across all types of manufacturing and process-based industries since the last decade [10]. The company under study is one such key player in providing discrete automation solutions and is involved in the manufacturing and sales of several types of industrial robots and automation control systems that cater to a wide variety of industrial sectors ranging from automotive to food processing. The company forecasts a rise in demand for its products and plans on introducing new product variants to cater to a wider market in the near future.

[redacted]

Figure 1.1: Assembly line

In line with the growth in the industrial robotics sector, the company wishes to gain a clear insight into its internal production disturbances for future preparedness and build a resilient workforce. Therefore, the company first wishes to understand *Complexity* and its causes and "if" it can be quantified in any sense. The company also wishes to understand how this concept of *Production Complexity* affects assembly-related quality and if any reflections be drawn up to manage it in the future.

1.2 Problem description

The quality department of the robotics division of the company is interested in understanding what is *Production Complexity* and what are the underlying drivers, as a few previous academic thesis studies at the company have linked production complexity to several assembly quality issues. The company, therefore, wishes to investigate the possibility to quantify production complexity, identifying the factors that cause it, checking if they affect assembly quality and how this can be better managed in the future.

1.3 Aim of the study

- This thesis study aims to understand what production complexity means and how it affects the production processes.

- By understanding the concept and its underlying causal factors, the study shall aim to find the deviations in terms of assembly quality and if they are any direct relations.

- Methods to approach in managing production complexity shall also be investigated and draw conclusions that suit the present scenario.

1.4 Research Questions

The aim of the thesis study can be framed into the following research questions.:

- *RQ 1:- What are the possible methods that exist to quantify production complexity? How do they compare against each other?*

- *RQ 2:- Does production complexity affect the overall assembly quality of industrial robots? Are there any implications?*

1.5 Delimitations

The scope of this thesis has been restricted to solely investigating and quantifying the complexity of assembly processes of articulated industrial robots. There may be several factors that contribute to the complexity of the production system and consequently affect assembly quality such as product design, supplier material quality, quality inspection methods, and business decisions; these factors shall not be investigated since this thesis study is limited by the decision of the company in terms of the area of the thesis study.

1.6 Thesis report structure

The following section provides a brief overview of the thesis for readers see to what to expect see in figure1.2.

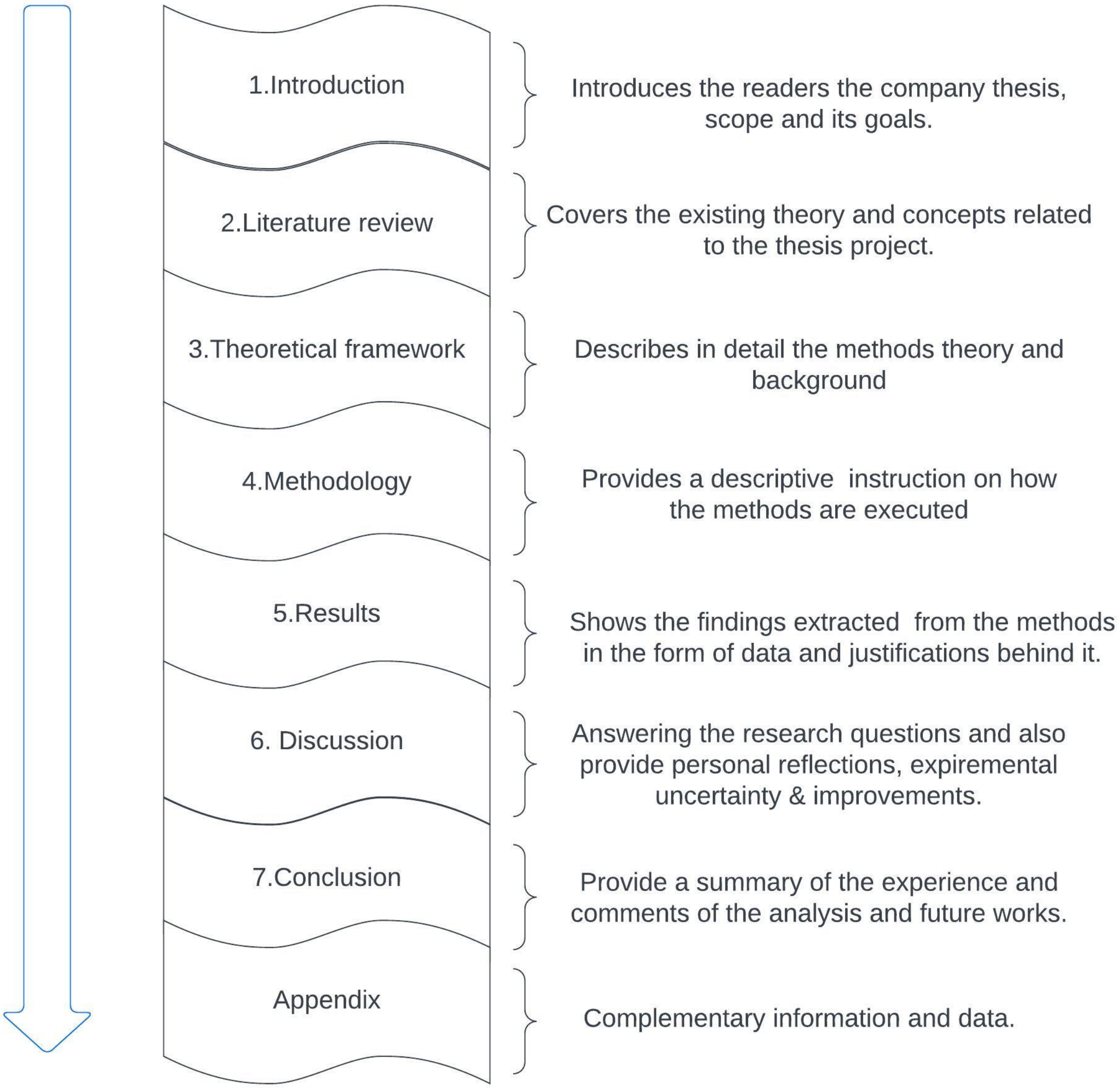


Figure 1.2: Thesis structure

2

Literature Review

2.1 An overview of previous studies

A complex system in a general view is a system that consists of arrangements of a large number of various elements which are related through intricate relationships and interconnections which makes it difficult to model or predict future states. The Oxford Dictionary defines ‘Complexity’ as “the state of being formed of many parts; the state of being difficult to understand”[11]. While the American Psychological Association defines it as “the state or quality of a thought process that involves numerous constructs, with many interrelationships among them”[12].

In everyday life, we often classify something as “complex” only when it is difficult to understand the system or predict some event in the future. Applying this concept within the engineering domain, Nam. P Suh [13] has defined complexity in engineering as “the measure of uncertainty in achieving the functional requirements of a system within their specified design range”.

A production system can be considered a complex system due to its intricate mixture of elements such as raw materials, machinery, human workforce, processes, facilities and the flows related to the information and documentation [14]. Therefore, for a company to prepare itself for competitive market conditions and prepare for uncertainty, a study of its internal complexity is necessary. A quantifiable measure of this complexity in production operations and ways of managing it shall help companies in the process of planning, which can help drive efficient use of resources from the material, and equipment to its human workforce and drive optimum productivity[15].

In this study, an attempt is made to first understand what is complexity and how it affects production-related operations. Further, an analysis is conducted to see how the factors that cause complexity affect the quality of sub-assemblies and final assembly of articulated industrial robots and look for correlations between them. Finally, a few reflections and conclusions are drawn up based on literature findings to manage complexity and how this study can be a useful tool for stakeholders for planning and executing future production operations.

Various researchers have established subjective and objective models that use a set of known variables present in a production scenario to predict the behaviors and identify key indicators that cause complexity within the system. These factors have been shown to affect the output of the production system in terms of the quality of products, productivity of its workforce and ultimately costs for the company.

This study focuses on identifying the complexity drivers using appropriate methods and analyzing their effects in a production environment. Thus it only becomes necessary to establish how “Complexity” is defined in a production environment and further study how can one measure and manage them. A formal definition is thus required which is presented in the subsequent section.

2.2 A review of previous research in Production Complexity

2.2.1 Towards a definition

According to [14] an early literature that dealt with the complexity of a system can be traced back to 1963 and ever since, every passing decade has seen a rise in the number of research articles conducted in the subject domain. Since complexity can be applied to different disciplines, the interest in the subject matter has grown steadily.

The earliest research [16] that has attempted to quantify complexity in a manufacturing environment has stressed the fact that a credible measure for complexity has two distinct components. One is used to measure the structure of the system and the other to measure the system’s uncertainty[16].

To be able to quantify complexity in a scenario, it becomes necessary to gain an understanding of what complexity means in the context of a production line where operators assemble parts of a final product. A formal definition of Production Complexity is thus needed before the methods used to measure it are investigated.
Within a manufacturing system, complexity is defined concerning several variables such as its origin, quantity and variety, time and system relationships according to [9].

- **Origin:** A causal factor for complexity can originate from within the company or from the outside or a mixture of both. Internal complexity can be related to flows of products and information while external can be associated with the flow in the supply chain[9].

- **Time and behavior:** In this variable, complexity can be either static or dynamic. **Static** complexity can be associated with a characteristic of the manufacturing system, it can be linked to the structure or design of the production plant. Whereas, **Dynamic** complexity is related to the changes of variables in the processes over a period of time[9].

Therefore, static complexity is one in which the variables do not change over time whereas dynamic complexity does.

Based on theoretical and empirical studies complexity has been defined in a few ways:

> *"Complexity is the degree of difficulty to predict the system properties, given the properties of the system's parts"* [17]

> *"A complex system is one, which has a large number of parts, whose relationships are not simple. Note that the parts themselves, may be simple, but that their relationships are not simple"* [18]

After gaining an understanding of the concept of complexity, it becomes necessary to focus on finding a definition of complexity within the domain of a production scenario. Several authors and researchers stress the fact that a good definition of production complexity should be generic to apply to different production systems and should also be time specific to guide the decision maker if a system is complex or not[19].

A few pieces of literature have proposed formal definitions of Production Complexity which shall be used as the basis for this study:

> *"Complexity is the sum of all aspects and elements that makes a task mentally difficult, error-prone, requiring thinking and vigilance and inducing stress"* [20]

> *"Production complexity can be defined as the interrelations between product variants, work content, layout, tools, and support tools, and work instructions"* [21]

Combining the above two definitions, a perspective of what production complexity means is presented:

"Production Complexity is the degree to which a system, process, or task consists of multiple interconnected and interdependent elements or aspects that can induce stress, require careful thought and be error-prone. It can be attributed to the interrelated factors that contribute to the manufacturing of various product variants, nature of work, layout, tools, support tools, and work instructions, which make the production processes particularly difficult to understand, predict, or control".

2.2.2 Methods of Measurement

The causes of complexity in a production line may be initiated by either external changes such as introducing a new product or equipment or internal such as rescheduling or routing changes [22]. The main parameters that were found to be common within all three were [22]:

- Number of product variants.
- The layout of the workstation.
- Material Supply.
- Ergonomics-Physical and Cognitive.

The approaches that exist today to measure complexity in a production scenario are grouped into two categories. The first is an "Objective production complexity" which is defined as inherent to the system that uses objective factors and which are independent of the personnel involved [23]. These methods use metric information based on the type of technology and other measurable factors present in a production system.

In the case of "Subjective production complexity", an existing production system or a situation may be perceived differently by individuals based on several factors such as skills, competence, and experience [22]. Therefore, it becomes necessary to also measure complexity from individuals who experience it daily. The studies done to measure subjective complexity looks to map how complexity is perceived by different functions in a production facility such as operations, re-balancing, internal logistics and man-hour planning[1].

After several literature studies, it became evident that there are both qualitative and quantitative methods to measure production complexity. In a manual assembly line, it was seen that the higher the degree of complexity, the higher the reactive action costs for the correction of these assembly-related quality issues[24]. Thus, measuring complexity and the methods presented by various researchers has been discussed thoroughly in the subsequent section.

In this study which focuses on measuring the complexity of the assembly line that produces industrial robotics, it was necessary to measure both subjective and objective complexity to compare and contrast the findings and also investigate its effects(if any) on the quality issues that were present historically.

The subjective method of measuring complexity can also be used to understand in depth previously identified bottleneck stations and also obtain indications of improvement potentials. This is done by visualizing the interrelating factors of complexity and identifying key areas that need to be considered for improvement projects[1].

2.2.3 Management of Complexity

Previous research in the context of production complexity management has dealt with the step sequence of identification, measurement, analysis and control of complexity. These steps can be summarized into three strategies that are commonly used: avoidance, reduction and dealing with complexity. The strategy of avoidance and reduction mainly applies to product development upstream of production[23].

A production line can be understood as a system with elements, and relationships that are embedded into the environment. Thus, the production system itself can be considered complex due to a high number of variability, diversity of components, the processes involved along with the uncertainty and predictability of the behavior of the system. Complexity is therefore not a problem that directly hinders the production system but is rather considered as the inability of humans to deal with this periodically leading to serious consequences[25].

In a production company, human decision-making is decisive in the areas of planning and execution[26]. With the increase in outside competition and rapid changes to product development[21]. The personnel responsible for production activities are overwhelmed in assessing existing problems and identifying solutions continuously. The objective is to streamline problem-solving in factory planning and operation by analyzing and organizing the current production systems in complex scenarios. This involves reducing the complexity of the situation and effectively managing it within the specific production area.

2.2.4 Comparing existing methods

Underneath, several existing methods related to quantifying complexity are briefly summarized.

1. Knowledge and technology complexity (KTC): This method utilizes two concepts: knowledge and technology complexity. Knowledge complexity is measured regarding the decision maker's knowledge, the initial data at hand, and the interpretation to make decisions. Technology complexity measurement is based on computer technology[27].

2. Manufacturing complexity index(MCI): Urbanic developed a model of the complexity of products, processes and operations based on three elements: information content, quantity and diversity. It aims to evaluate alternatives and risks in the design stage[28].

3. Robustness index (RI): Developed in-house at VCC, based on FMEA/Lean methodology, its purpose was to evaluate risks and problem areas, from a management perspective. Another purpose is to secure the robustness of a part. The method RI became a foundation for the development of CXI[29].

4. Entropic measurement (EM): This method was based on "entropy", which implies that it measures the unpredictability and randomness in a system. The Entropy is based on the probability of a specified state happening and is then multiplied by the probability of that state. The model could be applied to stations or lines/systems [30].

5. CompleXity Index (CXI): This method is a questionnaire, developed to provide an index for the subjectively perceived complexity at a manufacturing station by the operators. This results in a score that is color coded for visualization. The CXI method has been utilized to assess the current state of a production line in several studies[31].

6. CompleXity Calculator (CXC): Developed by the Belgian Complex Project, this method measured the complexity of manual assembly workstations in an objective and reproducible aspect. The data is collected from data logs/systems and is inserted in an algorithm that calculates the complexity, which classifies either HIGH or LOW complexity[20][31].

7. Complexity Measurement (CXB): Developed in Chalmers, this method is an index for measuring complexity in the automotive industry. The methods can classify a station's HIGH or LOW complexity depending on several criteria. Its primary purpose is supporting product preparation resulting in increased productivity and lowered costs[32].

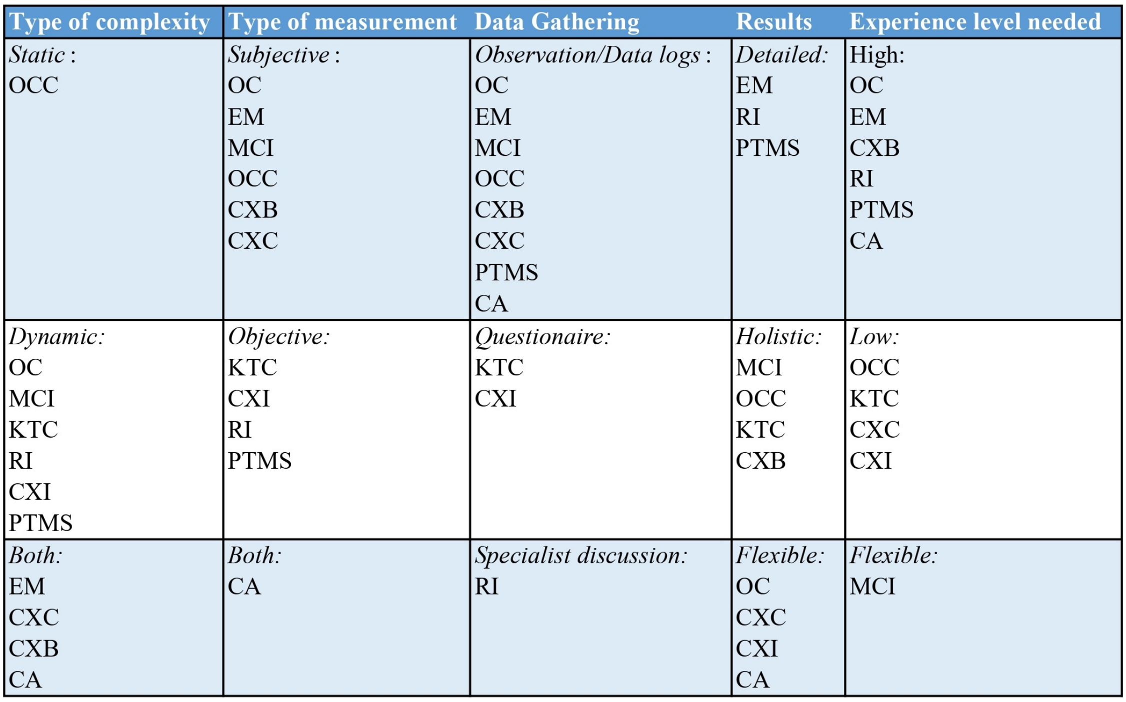
8. Operational complexity (OC): Sivadasan measured complexity by basing it on monitoring and mapping the information flow. The purpose was to manage information and material flows. The information/data is gathered through observation in several time intervals[33].

9. Operator choice complexity (OCC): Its main purpose is to find the cause, and plan assembly sequences for the assembly line. OCC measures human performance in making choices, based on an entropy function and is afterward defined as the average uncertainty or randomness[17].

10. Predetermined motion time systems (PMTS): PMTS is originally intended to calculate the labor rate for a manual assembly line. PMTS breaks down operations into basic human movements and classifies them, based on motion elements, mental functions, and the conditions it is set in[34].

11. Correlation analysis (CA): Its intended use is to see whether a relationship/-connection between the different variables could potentially drive complexity. It could also determine the gravity of the relations in terms of being direct or indirect affecting each other, or could potentially identify new drivers[23].

Subsequently, the criteria have to be established to systematically narrow down the best existing methods suited for quantifying complexity. There are five criteria that the different methods were examined and compared in the table below:



Type of complexity	Type of measurement	Data Gathering	Results	Experience level needed
Static : OCC	*Subjective* : OC EM MCI OCC CXB CXC	*Observation/Data logs* : OC EM MCI OCC CXB CXC PTMS CA	*Detailed:* EM RI PTMS	High: OC EM CXB RI PTMS CA
Dynamic: OC MCI KTC RI CXI PTMS	*Objective:* KTC CXI RI PTMS	*Questionaire:* KTC CXI	*Holistic:* MCI OCC KTC CXB	*Low:* OCC KTC CXC CXI
Both: EM CXC CXB CA	*Both:* CA	*Specialist discussion:* RI	*Flexible:* OC CXC CXI CA	*Flexible:* MCI

Figure 2.1: Comparisons of 11 existing methods

To find the best suitable method if it could cover every aspect. Unfortunately, having only one singular method is not sufficient since none can cover all criteria according to figure 2.1, and it eliminates cross-verification between methods.

CXI and CXC were initially selected. Both methods have been validated in numerous industries[1]. CXC can cover large amounts of stations by taking internal system-based data, in rapid succession that provides a broad perspective[20]. Whilst The CXI is in-depth operator-oriented, meaning it measures the perceived complexity from the operator's perspective that is involved at the workstation[31]. Both the CXI and CXC have similarities in terms of content but are different ways of measuring the parameter. For example, product variants, tools, and layout are used in both methods but are measured differently[31]. These methods are particularly important since it's the operators that experience firsthand the complexity. Having both methods complements each other, in terms of the type of complexity, viewpoint and results.

Another justification for the selection is also based on the comparison table. CXI and CXC cover both the dynamic and static complexity when combined. In terms of measurement, both had subjective and objective approaches. CXI and CXC have different data gathering such as the observational and questionnaire method. The results for both CXI and CXC were classified as flexible since they would both be holistic since captures numerous areas and detailed results[21]. The last criterion was especially critical for the thesis since other methods required a high level of experience or expertise to execute it. However, the CXC and CXI required minimal knowledge [31] beforehand that can initialize the process rapidly and minimal training is required, which can be beneficial for the thesis's realistic time frame and for the company's convenience.

One could argue that OCC and KTC could also be possible candidates for the thesis since the methods also cover combined all the criteria. The reason it was not selected due to KTC was developed in 1993 meaning it has become outdated, its purpose was to manage software development and today's current technology vastly differs from 20 years ago, making it difficult to apply[27]. Another drawback was that this method is only limited to technology and knowledge, and it is not targeted toward the thesis scope which is manual assembly[31].

OCC had relevant aims and intentions for the assembly stations, but its aim was focused on directly or continuously improving the assembly line. Unfortunately, this does not align with our scope, which is to quantify the complexity of what could potentially improve the stations[17].

This has resulted in having **CXI** as the qualitative approach and the **CXC** as the quantitative approach that will be utilized to quantify complexity.

2.3 Contextual Background

2.3.1 Industry 5.0

Industry 5.0 is the latest emerging industrial revolution that has primary concerns with human skills and innovation combined with developed automation. It aims to create a symbiotic relationship between humans and machines, complementing each other with their unique strengths to be more efficient [35]. For the relationship to flourish, the definition of the word "Robot" had to be redefined as not only a re-programmable machine that could perform the tedious task but can be a human companion, that can collaborate alongside operators with ease of mind[36].

From a more holistic perspective, it puts the well-being of humans at the center of the manufacturing process to achieve societal goals and sustainable development. In other terms, the fundamentals or characteristics of Industry 5.0 is based on sustainability, human-centricity, and resilience which can be seen in the figure [35][37] below:

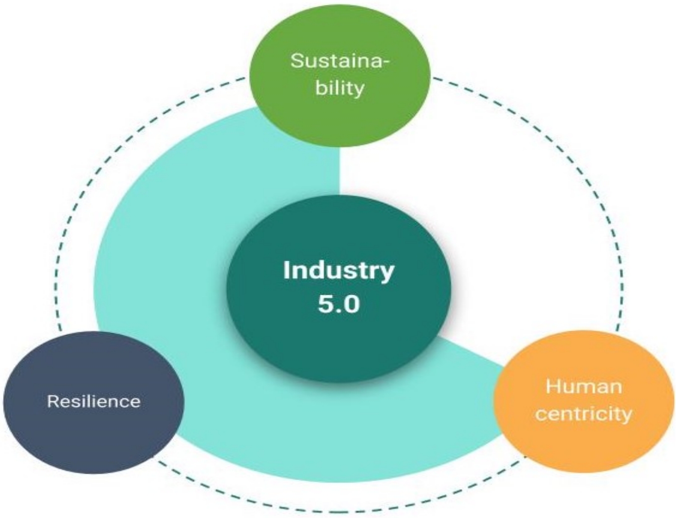


Figure 2.2: Industry 5.0

2.3.2 Difference between industry 4.0 and 5.0

Industry 4.0 focuses on automation, data exchange, and digital technologies that improve efficiency. In contrast, as previously mentioned, Industry 5.0 puts heavy emphasis on a human-centric approach, where robots and automation work alongside and complement each other. The approach focuses on the society and sustainability aspects to create more individualized products[38][37].

In essence, Industry 4.0 shows a shift from the previous revolution, with a focus on digitization, automation, IoT and big data analytics, and much more. Whilst Industry 5.0 builds upon the foundation of Industry 4.0 by adding a human-centric approach and a more holistic and sustainable perspective to manufacturing[37].

The reason Industry 5.0 is required is that Industry 4.0 ignores the human aspect, that humans in the future would be replaced for better optimization. Industry 5.0 shall mitigate the resistance to change. Unfortunately, Industry 4.0 does not focus as much on the social sustainability aspect. Industry 5.0 does have a strong focus, that not only gives a trending competitive edge for the company but also better for the environment[36].

2.3.3 Resiliency

Resilience in this matter refers to a production system to maintain or recover at rapid speed to an optimal state, during and after a disaster or natural emergency, such as the COVID-19 pandemic or trade wars[35][37]. Both of these major catastrophic events exposed how vulnerable the globalized supply chain is, making resilience a recognized vital core in Industry 5.0. Corporations should not only pay attention to the uncertainty of the customers, supply chain, and market but should also put attention to the holistic perspective such as the entire value chain and the industrial eco-system of the country[35].

Resiliency is not exclusive to manufacturing systems, but also to operators. The resilient operator 5.0 is a concept that describes a worker who is intelligent and adaptable to be able to operate in dynamic and complex production environments[39]. The reason the Resilient Operator 5.0 is included is that it will play a crucial role in the future of manufacturing since it will perform various amounts of tasks and utilize different technologies. This includes working with advanced automation systems and robotics and collaborating with other humans as well[39].

To be able to handle future manufacturing, key competencies are required, such as technical, social, and cognitive skills. Meaning that current workers need to be provided with additional skills which are also known as Upskilling. For technical skills, virtual training can be provided[36]. Meaning that operators can be trained in a simulated environment, and the virtual training can be flexible to be updated to provide continuous upskilling. Virtual training is essential to create a skilled workforce without hampering productivity or endangering trainee workers in hazardous environments. This is especially important in work tasks that consist of repetitive actions since it provides cost-effective training without exposing workers to potentially dangerous scenarios[36].

2.3.4 Human centricity and Automation

Industry 5.0 focuses on the human-centric approach to manufacturing, recognizing that humans are not completely replaceable by robots or machines due to mass individualization from the consumers. Humans centric manufacturing is necessary for flexible, agile, and robust factories that are resilient towards disruptions, which requires a synergetic relationship between humans and robots[37]. Collaborative robots (Cobots) work alongside humans by granting the operator creativity, critical thinking, and craftsmanship whilst the robot does cumbersome operations such as heavy lifting and technical precision[37][40]. Meaning that skilled operators and robots combined create individualized products for consumers[36].

2.3.5 Sustainability

Creating socially sustainable manufacturing is a key focus in Industry 5.0 since the world has experienced increasing challenges to society in terms of environmental pollution and social instability[41]. Having a sustainable profile gives competitive benefits as previously mentioned, but to achieve sustainable development goals, better policies for the social workforce and renewable energy sources have to be considered and implemented[41]. Due to high customization, the customers demand further transparency and traceability on the supply chain to make a sustainable purchase[35][37].

2.3.6 Challenges of Industry 5.0

Industry 5.0 faces numerous challenges to be solved to be successful for businesses. Below are potential identified challenges in different categories. The challenges are (1) Competence skills, (2) Investments, (3) Cyber security, (4) Adoption of new technology and (5) Energy management .

1. As previously mentioned, workers are required to develop competency skills to handle advanced automation and the integration of AI and robotics[36]. The technical skills required are high which can pose a challenge for the workers and managers since if it is unchecked, it could lead to a skills gap, making it imperative to have upskilling programs to train in different areas[37].

2. Initial investments in advanced technologies. For example, Collaborative robots and additional training bring higher costs. Companies can experience difficulties in their budget to allocate funds to upgrade production lines to improve efficiency and productivity, especially for small and medium enterprises[37].

3. IT security poses a major challenge for Industry 5.0. With the integration of AI, robotics, 5G, and IoT devices in the manufacturing processes [38] there becomes an increased risk for cyber attacks that could leak valuable data such as intellectual property or lose control that could endanger operators[37].

4. Adopting advanced technology in Industry 5.0 is a major challenge due to several factors. Acquiring and implementing these advanced technologies is a high financial barrier for small and medium-sized enterprises. Second, is the resistance to change, workers especially the senior operators [36]could be hesitant of learning new skills, making it more challenging, which could hamper the adoption process. Infrastructure is also a factor since advanced technology could require modifications to the current infrastructure[37]. Another major factor is that the adopted technology has

to comply with the regulations and laws that are adapted for the new era. This is for the technology to be fully integrated sanctioned and protected to itself and others, otherwise, it could be a risk of legal penalties or physical harm[40].

5. By having more Industry 5.0 applications and technology connected, not only does it poses a cyber security threat, but it also poses a challenge in energy management for the magnitude of technology that requires electricity to operate. In today's climate, it is more important than ever to conserve energy for the company's and consumer's benefit in terms of sustainable costs[40].

3

Theoretical framework

3.1 Qualitative study

The Complexity Index (CXI) was developed by Sandra Mattsson and her colleagues at Chalmers Technical University in Sweden. The index is based on the idea that perceived complexity is a subjective measurement that depends on how simple or difficult it is for operators to understand and use the assembly station[42]. The index is designed to capture the subjective experience of complexity, by asking participants to rate how difficult or simple it is at the particular assembly station[31].

The CXI consists of 23 statements that cover all the factors/aspects contributing to complexity which. These statements were developed based on previous research on perceived complexity, literature research, and interview with experts. The CXI was also validated through data triangulation, i.e. different participants were asked identical things. After the development, the statements were pilot tested in numerous companies with participants with different background and was continuously refined and identified which can be seen in the appendix A.2.[43].

The participants had to rate each statement on a 5-point Likert scale where 1 meant: completely disagree and 5 represented: completely agree. The participants based their ratings on their previous experience at the assembly station. An example will be presented below:

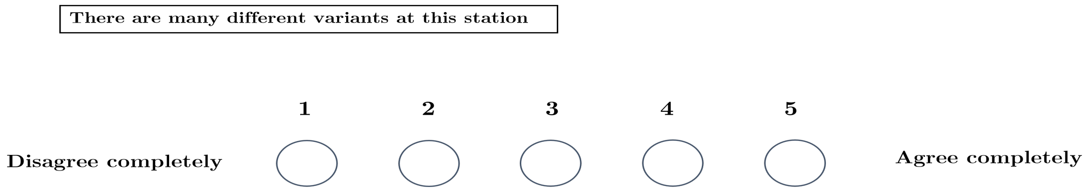


Figure 3.1: Example statement

Once the answers have been submitted by the participants, the responses undergo evaluation by using a specific formula. It begins by calculating each complexity area (first part of the formula (3.1)). Subsequently, the second part(3.2) of the formula, ensures that the high values of the complexity areas are obtained, meaning individual differences are captured in the station CXI. The highest median for all complexity areas (maximum median) is taken and divided by four[31].

$$CXI_e = \frac{\sum_{P=1}^{n} M_{ep}}{n} \tag{3.1}$$

$$CXI = \frac{\sum_{e=1}^{k} CXI_e}{k} + \frac{max_{e=1..k} CXI_e}{4} \tag{3.2}$$

Where:
CXI = total complexity index for the station
CXI_e = complexity index for complexity area e
M_{ep} = median of questionnaire answers for complexity area e for respondent p
k = Number of complexity areas
n = number of respondents [31]

After the score has been calculated and established, it becomes color-coded for further visualization. Meaning that the higher the score, the higher the severity of the complexity, and depending on the severity it yields different colors at the station which can be seen in the table below [31].

Numerical limits	**Complexity level**	**Color**	**Actions**
x<2	Low	Green	No action
2 ≤x>3.5	Medium	Yellow	Need change
x≥3.5	High	Red	Urgent change

Table 3.1: Criteria of CXI

From the visual color carpet, the causes of complexity are combined into three complexity areas: (CXIA) Station design, (CXIB) Work variance, and (CXIC) Disturbance handling. The complexity areas include these causes of complexity [43][31]:

- **CXIA**: Station design views how well designed the workstation is in terms of layout, work instructions and tools & support tools. The layout refers to the structure of the workstation. Station design also takes ergonomic causes such as physical load and reach ability into account. Tools and Support tools regard the number of choices the operator have to assemble or the risk of making mistakes by what tools the operators have in possession and if it is effective to help them. For example, The way information or data is presented for the operator can decrease the perceived complexity i.e. through paper, digital screen, etc. Finally, this area also handles the assessment of understanding work instructions, and how effective the documented guidelines for assembly.[43][44].

- **CXIB**: Work Variance refers to the variance in work content and product variance. Work Content refers to the number of work tasks for the operator and how much influence in terms of planning and change they have on their assembly work. All the tasks involve tools, procedures, and components which are related to Product variance. Product variance means to assess the number of product variants, the frequency of the rare variants, and if the variants have similar features or components in the assembly. Also, Work variance handles the competence of handling assembly systems, meaning if the operator is trained sufficiently to handle dynamic situations that could cause assembly complexity[43][44].

- **CXIC**: Disturbance Handling regards work content related to handling disturbance, meaning rare product variants that arrive in the assembly and how efficiently the operators handle it. The disturbance is an important aspect due to uncertainty and unpredictability can create complexity in the assembly system. This complexity area also takes into account if the operator influences planning the assembly tasks[44].

3.2 Quantitative study

The Complexity Calculator (CXC) is the objective approach for assessing the complexity of the assembly stations. Its origin and use can be traced to conducting workshops within the automotive industry and its personnel such as production engineers, and line managers that constantly tackle interconnected issues. Given the information, the workshops had been able to identify several complexity drivers seen below that will play a vital part in the CXC method[20][19].

The CXC method does not involve operators but rather has objective logged data from the stations, minimizing perceived information. The objective data that is obtained is divided into complexity-driving variables. The variables were developed through numerous workshops in collaboration with automotive manufacturers that amassed into identifying 11 drivers which can be seen below[19][20].

The Robot assembly line that is the focus of this study is very similar to the nature of an automotive production line. The product moves along an assembly line while workers at the stations operate on the product under a specific time (takt time). Thus, the variables used by the authors that proposed the CXC method will be used in this study as well.

Complexity drivers	*Type of value*	*Description*
Picking technology	(F)Fixed	(F): Components are always taken from the same location
	(S)Signal	(S): The component's locations is indicated by a signal i.e light or display
	(C)Compare	(C): Operators compare information (symbols, colors)
	(M)Manual	(M): Operators are required to read information from manual instruction
Bulk sequence kit	(B)Bulk	(B): The components of the same type are in their package.
	(S)Sequence	(S): The components are in a package in an assembly sequence
	(K)Kit	(K): The parts are delivered in a Kit, for one operation
Packaging types	Integer number	The number of different packaging types. A type has a certain layout, meaning 2 identical boxes with different content equal 2 different types.
Tools per workstation	Integer number	The number of tools the operator requires to perform all possible operations for every variant.
Machines per workstation	Integer number	The number of machines that is performed automatically without the assistance of the operator
Work methods	Integer number	Every unique set of work methods that the operator requires mastering. The work method consists of several steps.
Distance to parts	Meters	The furthest distance between the operator's ordinary location and the parts.
Variants same model	Integer number	The highest amount of variants that belong to one model. That also includes if multiple models were being assembled on the workstation.
Variants in this station	Integer number	The total amount of all the variant components, combining all the models.
Different parts in workstation	Integer number	The total amount of unique parts that are assembled in the workstation.
Assembly directions	Needing repositioning	The number of times the operator need to reposition to complete the operation, small repositioning of the hands are excluded.

Table 3.2: 11 Complexity drivers of CXC

To conduct a complexity measurement, the variables had to have some sort of value depending on the amount. The Likert scale for each variable was introduced, dividing the data range over 5 levels, meaning that the value could range between 0 to 4 which can be seen in the appendix A.1[20]. Once the scaling has been controlled, several approaches were explored to measure the complexity of assembly line stations. That resulted in three models:(1)Base model, (2) LOGIT model (3) 4-variable model.

The initial approach is based on the sum of the 11 variables. This measurement would determine whether a workstation would be classified as LOW or HIGH complexity according to equations 3.4 and 3.5 which would be the **base model**[31][20].

$$basic\ complexity(w) = \sum_{i=1}^{n} \frac{score(i) * weight(i)}{\sum_{i=1}^{n} *weight(i)} \tag{3.3}$$

$$complexity(w) = \frac{basic\ complexity(w) - \sum_{i=1}^{n} min\ i}{\sum_{i=1}^{n} max\ i - \sum_{i=1}^{n} min\ i} * 10 \tag{3.4}$$

Where:

- *Basic complexity(w)*: Complexity score of a workstation w.
- *Score(i)*: Value of the variable i according to the Likert scale.
- *Weight(i)*: Weight of the variable i.
- *Max i*: maximum possible score value for variable i
- *Min i*: minimum possible score value for variable i
- *Complexity(w)*: Complexity score normalized to a scale from 0 to 10

From previous studies, based on the initial approach, the calculated score can differentiate between the HIGH and LOW stations. Despite the outcome, it was reported that there were fluctuations in the complexity scores, meaning that variables could contradict each other or lack explanatory power. An adjustment of the weight or reduction of variables would be necessary[20].

A statistical model needed to be introduced to handle the fluctuations. Its objective was to predict the complexity of the workstation, based on the data and the weight of the variables. Since the complexity outcome is either HIGH or LOW, making it a binary variable, makes Logistic regression (LOGIT) viable since it can produce binary outcomes [45]. Logistic regression is a statistical model that is frequently used for classification and predictive analysis. This statistical model would be named instead of **LOGIT model**. By using Logistic regression it will calculate the probability that the workstation's complexity is high or low in the following formula below[20] [19]:

$$Odds = \frac{P}{1-P} = e^{A+BX} \tag{3.5}$$

$$Ln(Odds) = A + BX = a + b_1x_1 + b_2x_2 + ... \tag{3.6}$$

where:

P	Probability of having Low complexity
1-P	Probability of having High complexity
a	a constant
b_n	coefficient for variable n
x_n	value for variable n

Another approach was a reduced CXC calculation model called **4 variable (4var)**[19]. Instead of using every variable, it was reduced to only four variables was used, whilst still using the same two equations mentioned above. The results prove to be satisfactory and with less variability[19]. The four variables were:

1. Packaging types
2. Assembly directions
3. Different parts in workstation
4. Number of work methods

The output of the objective method is a graph that displays the complexity of the station and also a probability score on the Y-axis of the graph[20]. The results shall display the trend of complexity across a production line. A station's complexity score may differ either vastly or by a narrow margin from its predecessor. This can help visualize the production engineer's focus on the area of the production line where improvements can be carried out in the future. The results are attributed to the scales of the variables that are fixed, adjusting the scale values can affect the station's complexity score, thus having a pre-determined scale that accounts for the entire line shall help gain a more accurate score of complexity using the CXC method.

4

Methodology

The methodology chapter mentions the executions between the literature's qualitative and quantitative approaches.

4.1 Literature review study

To define production complexity, an extensive literature study is conducted with a combination of keywords on relevant scientific databases. Research articles that have attempted to measure and explore complexity in the field of manufacturing have attempted to define production complexity from their perspectives. Several definitions are then considered that are suitable to the scenario under which this study is conducted.

A comprehensive keyword list has been used to identify relevant research articles, publications and Ph.D. publications on the subject matter on credible scientific publication databases such as ScienceDirect, SpringerLink, ResearchGate, Google Scholar, Scopus, Web of Science, Statista, and the Chalmers University of Technology Library portal.

Keywords such as Complexity, production, manual assembly, manufacturing, and quality were used to search the databases. The boolean operator was AND used or for example, manual assembly AND complexity AND quality. This resulted in research papers about complexity in numerous areas of engineering such as engineering design, supply chain, and computer science. The title was reviewed and the abstract was read to gain an overview and relate it to the study being conducted

The research articles were classified according to the publish date, wherein the latest publications which are relevant to the research topic were given a higher preference. Research work that had a wider application across the industry and which was also used as references in other research work were classified as having a higher impact and were also prioritized for this study. Research that was conducted in an environment that was similar to the one presented for this study was also closely filtered through. From the literature review chapter, a comprehensive theoretical review has been conducted that has enabled a proposal of a formal definition of production complexity.

4.2 Qualitative Execution

To collect valuable data, areas of interest had to be identified. The quality team and the production managers recommended the robot lines A, B, C, and D and the cabinet assembly lines E and F since historically the team anticipated that these lines need to be focused on for future improvements.

To get the operator's perceived opinion, line managers had to be notified and typically the best optimal time was during scheduled production stop or clean up when the shift had ended, to ensure that production was disrupted as minimally as possible. The statements were imported into an online survey for digital traceability, and to log the data easily online. Afterward, a QR code was generated for the operators to scan and answer the survey on their own smart mobile devices.

Once the operator had answered the questions/statements, the data is transferred into a calculation tool that has been provided by the developer of CXI with the formulas pre-programmed. The overall process leading to the calculation can be seen below:

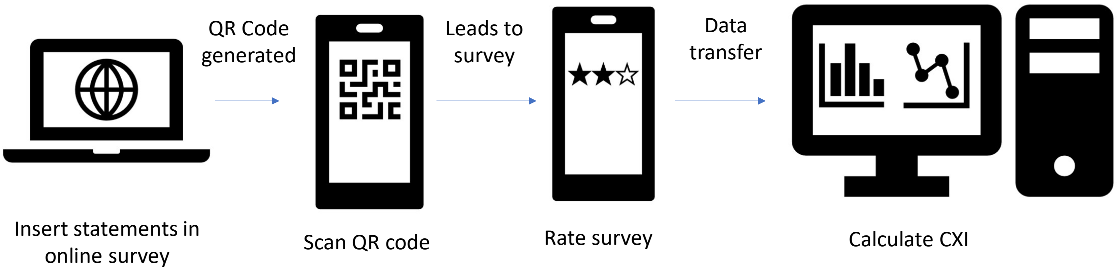


Figure 4.1: Process of acquiring data

When the data from the operators, have been transferred over to the CXI calculation tool, the following steps are:

- Raw data: The first step is to place the data into the empty designated rows.
- Calculation: The second step was to use the formulas [21] on the designated rows to calculate the CXI.
- CXI Matrix: After the calculation is complete, a color carpet would be generated that consisted of three complexity areas, in CXIA, CXIB, and CXIC, and would be used to become a final score in CXI. As seen in the table 4.1:
- Median matrix: Another color carpet is created, but this would be based on showing the medians of the online survey answers that contribute to the complexity areas(A-C), indicating if it is complex for every Line and each cause of complexity which can be seen on table 4.2.

		Line X
Station design	CXI A	Score
Work variance	CXI B	Score
Disturbance Handling	CXI C	Score
	CXI	Final Score

Table 4.1: CXI color carpet

Causes of complexity	**Line X**
Product variants	Median
Work content	Median
Layout	Median
Tools	Median
Work instructions	Median

Table 4.2: Median of the answers from the online survey

4.3 Quantitative Execution

The data collection for the objective study was done by a combination of physical observation and collecting system-stored data from relevant stakeholders. Due permission to gather and apply this data for this study has been sought. The stations selected for the collection of this data remain the same as the ones in the subjective method.

To execute the working formulas of the CXC method, the complexity variables had to be obtained first. Table 4.3 shows an overview of how the variables were obtained and from whom.

Complexity variables	*Method*	*People of interests*
Picking Technology Bulk sequence kit Packaging types Tools per workstation Machines per workstation Distance to parts	Observing, Classifying, Counting & Measuring by hand	From the actual physical workstation
Work methods Assembly directions	Reading Work instructions	Production engineers Quality engineers
Variants same model Variants in this stations	Asking higher Management	Production line manger & Team Leader

Table 4.3: Methods of acquiring the values

The majority of the variables were acquired by independent observation, classification, measurement, and calculation, with no operator involved.

- Picking technology: By observing the location of the component and the presence of assisting technology, it would be possible to determine the Picking technology.

- Bulk/Sequence/Kit: This could be acquired by also observing the location of the component to determine the character.

- Packaging types: This could be observed at the shelves and the workstation, to give an amount as seen in this figure 4.2.

Figure 4.2: An example packaging shelves

- Tools & Machines: By observing the workstation and workbenches, and having the knowledge of the difference, it would yield several tools and machines per station. This can be found in this figure for example:

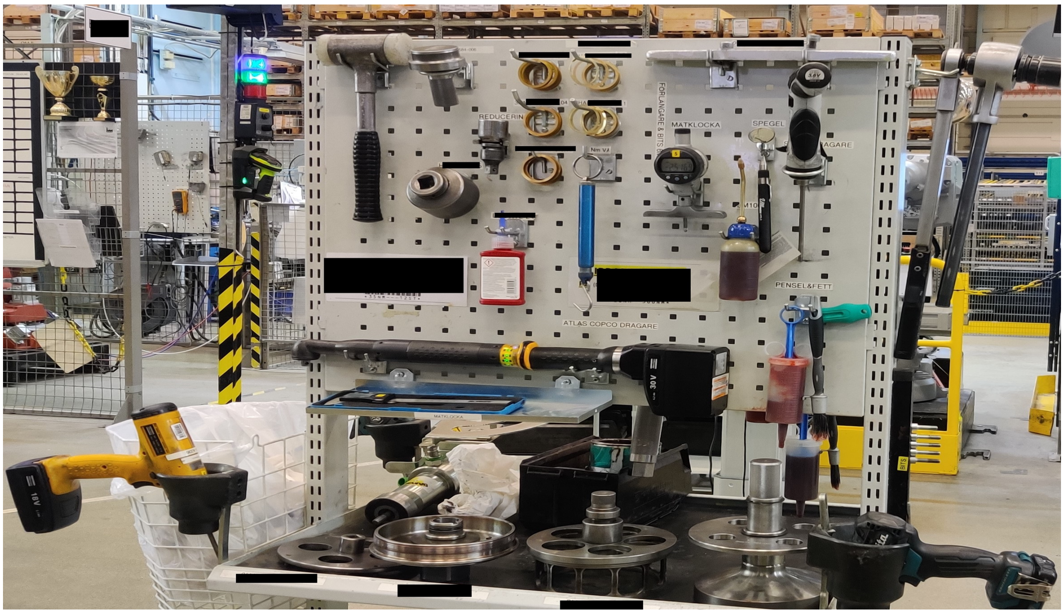


Figure 4.3: An example workstation

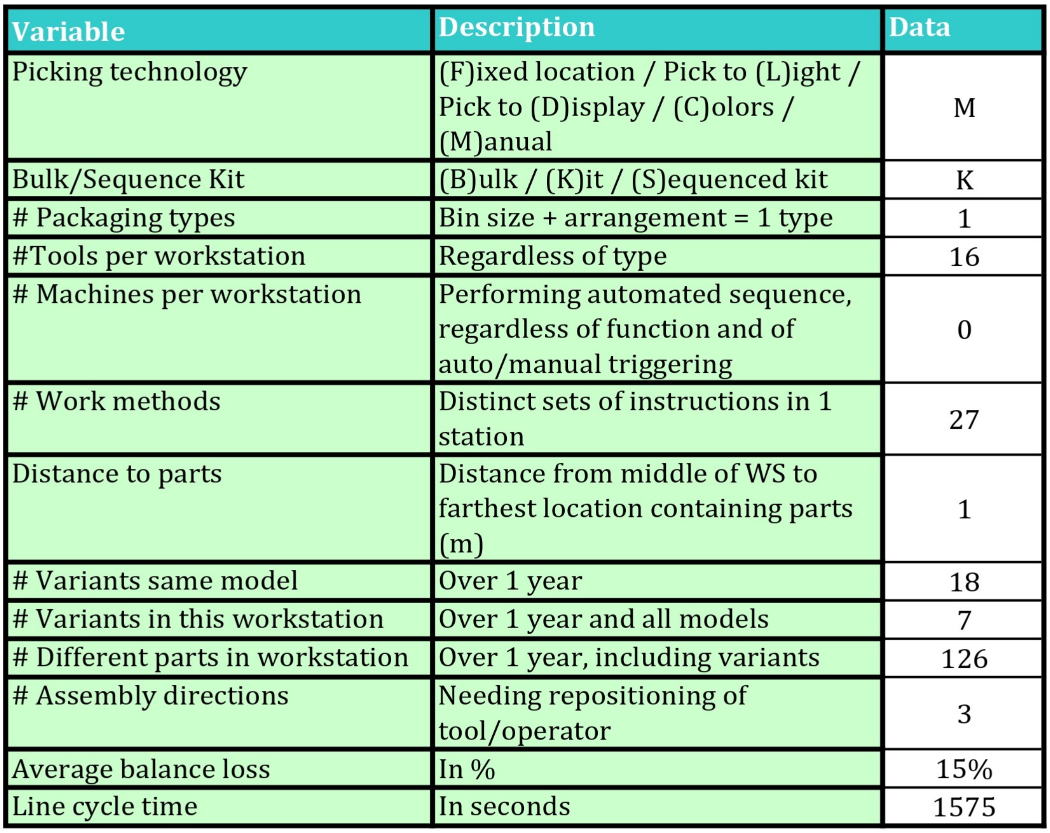
- Distance to parts: Locate where the operator's stationary location and measure the distance using measuring tape.

- Work methods & Assembly directions: The work methods are to be obtained by reading the standardized work instructions that are created by the production engineers. By inspecting the instructions and observing the assembly work for cross-verification, one can determine the number of positions the operators are in assembly.

- Variants same model in this station: This cannot be obtained by only observation, since variants can have minuscule differences which can be difficult to detect. The best way is to get the order list from the production line manager to read the number of variants to make an appropriate count.

Once the variables had been obtained from the respective stakeholders, the data were to be inserted into the calculation sheet with the formulas predefined. Following the insertion of the variables the calculation tool would yield data results based on the 3 models previously mentioned.

A typical column for any given station looks like the table below, with the columns being repeated in sequence according to the flow of the product.



Variable	Description	Data
Picking technology	(F)ixed location / Pick to (L)ight / Pick to (D)isplay / (C)olors / (M)anual	M
Bulk/Sequence Kit	(B)ulk / (K)it / (S)equenced kit	K
# Packaging types	Bin size + arrangement = 1 type	1
#Tools per workstation	Regardless of type	16
# Machines per workstation	Performing automated sequence, regardless of function and of auto/manual triggering	0
# Work methods	Distinct sets of instructions in 1 station	27
Distance to parts	Distance from middle of WS to farthest location containing parts (m)	1
# Variants same model	Over 1 year	18
# Variants in this workstation	Over 1 year and all models	7
# Different parts in workstation	Over 1 year, including variants	126
# Assembly directions	Needing repositioning of tool/operator	3
Average balance loss	In %	15%
Line cycle time	In seconds	1575

Figure 4.4: A typical data column for a station

Once the data for the relevant lines are collected, the objective then is to determine a particular station that can be used as the benchmark and set the scale to measure if the stations are complex or not.

The CXC method includes a process of setting up a range of values along with assigning a pre-determined weight for a majority of the variables and a fixed value for a few. The variables that have a fixed value are shown in the table below:

Variable	Sub-Variable	Score/Weight
Picking Technology	**(Fixed Location)**	**1**
	(Pick to Display)	**2**
	(Pick to Light)	**3**
	(Pick to Colour)	**4**
	(Manual)	**5**
Bulk/Sequence Kit	**Sequenced Kit**	**1**
	Prepared Kit	**2**
	Bulk	**3**

Table 4.4: Weights for two Variables of CXC

The scale of the remaining variables is adjusted based on the raw data collected and the weights are assigned accordingly based on the value for each variable based on the literature. The scales are adjusted to each of the stations as the variables differ largely based on the product being assembled while the weights remain the same.

The CXC calculator is then run and the output from the differing methods is studied to check which of the stations are considered complex by the LOGIT method[20]. The results are then plotted to study the trend across a given production line. The next step is to consider the CXC 4 Variable method, wherein the top 4 variables [20] that are deemed complex from a subjective perspective are chosen and plotted independently. The 4 variables in this robot production are:

- Picking Technology: This variable is considered one of the top variables that contribute to objective complexity as an operator needs to compare the Bill of Materials and select the proper parts either for the preparation of a kit or to start any sub-assembly.

- Packaging Types: From direct observations, it was seen that all the lines have several types of packaging for the raw materials and parts. Some of the parts are stored in color-coded bins. This is done to differentiate electro-static components from others. Several other critical components such as gears and drive units are also specially packaged and need extra caution while being picked from storage bins.

- Variants same model: The company offers its customers several configurations in its control cabinet system that invariably increase the variants significantly. Apart from this, the robots also have a few sub-variants that require careful attention during assembly.

- Different parts in Workstation: All stations along all the lines have several components that are used for a large number of variants. Thus, an operator is expected to know the exact storage location of the parts.

These top 4 variables are observed to influence the score of the complexity of a workstation. The graph plotted for the CXC calculator shows the trend for both the eleven variables and the four variables to compare and contrast how several variables contribute to the calculation of a station's complexity. Thus, the resulting values from the 11 -variable model and the 4-variable model are plotted together to visualize how the different methods quantify a station's complexity.

The resulting graphs of the individual product lines and sub-stations are presented in the following chapter followed by a discussion on the obtained results.

5

Results

The results from both studies are presented in this chapter with the relevant visualizations and graphs. This chapter only focuses on the obtained results from the studies conducted over the assigned lines and sub-stations by the company. Lines A, B, and C are for product line 1, while line D is dedicated to product line 2 and lines E and F are dedicated to an electrical control system that is used by all the product variants of the robot. With this background, the results of the subjective method CXI are first presented followed by the graphs of the Objective study (CXC)

5.1 CXI Results

Figure 5.1 illustrates the Complexity Index results of the perceived complexity of the operator's answers from the statements through a color carpet including the years in assembly and Line on average. The CXI has been used in six Lines A-F and these lines consist of several workstations. The areas of complexity mentioned in the color carpet carry the following meaning:

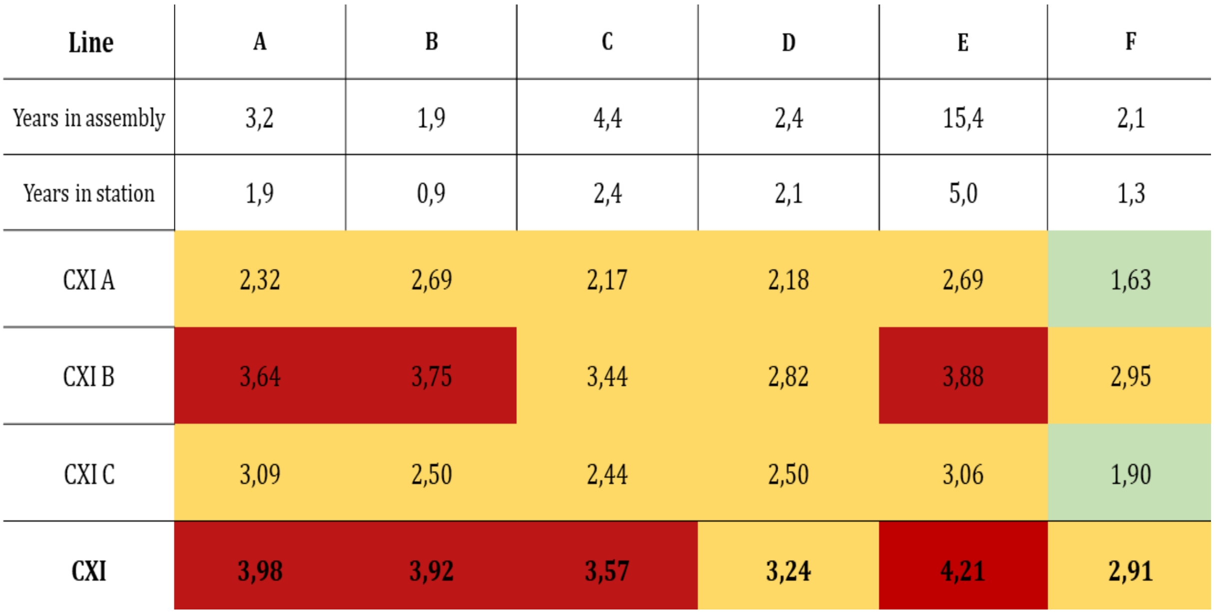
- CXI A: Complexity area A measures the complexity in terms of the station layout, work tools and instructions.

- CXI B: Complexity area B measures the complexity in terms of the work variance that refers to the work content and product variance. It also includes the competence of an operator.

- CXI C: Complexity area C measures the complexity in terms of handling unexpected events and satisfaction of information available required to work on the task.

CXI A, B and C are considered as different areas of complexity in a production line. While the actual underlying causes of complexity are listed as:

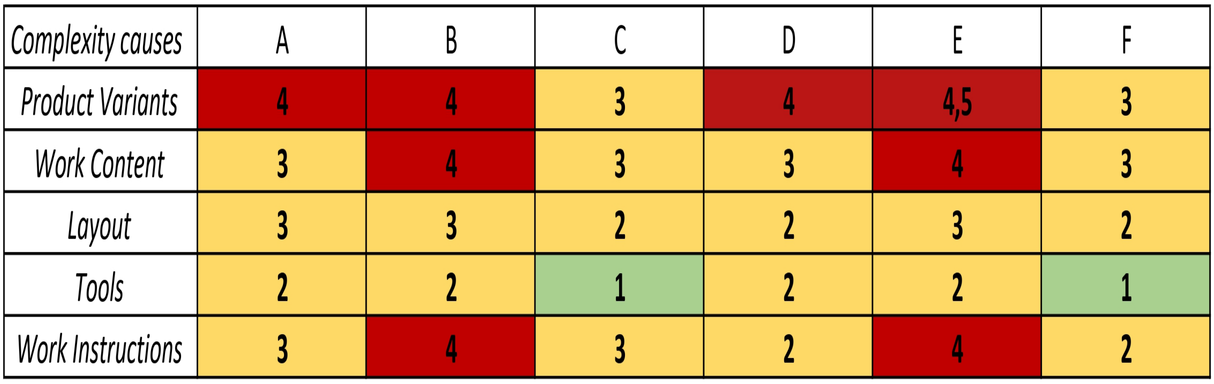
- Product Variants
- Work Content
- Station Layout
- Tools and Support tools
- Work Instructions



Line	**A**	**B**	**C**	**D**	**E**	**F**
Years in assembly	3,2	1,9	4,4	2,4	15,4	2,1
Years in station	1,9	0,9	2,4	2,1	5,0	1,3
CXI A	2,32	2,69	2,17	2,18	2,69	1,63
CXI B	3,64	3,75	3,44	2,82	3,88	2,95
CXI C	3,09	2,50	2,44	2,50	3,06	1,90
CXI	**3,98**	**3,92**	**3,57**	**3,24**	**4,21**	**2,91**

Figure 5.1: CXI color carpet results.

After the CXI color carpet, a summary carpet is presented showing the medians of the survey that contribute to the complexity areas (A-C), indicating complexity for every Line from A to F and each cause of complexity.



Complexity causes	A	B	C	D	E	F
Product Variants	**4**	**4**	**3**	**4**	**4,5**	**3**
Work Content	**3**	**4**	**3**	**3**	**4**	**3**
Layout	**3**	**3**	**2**	**2**	**3**	**2**
Tools	**2**	**2**	**1**	**2**	**2**	**1**
Work Instructions	**3**	**4**	**3**	**2**	**4**	**2**

Figure 5.2: CXI online survey answers in the median for Line A-F

5.2 Subjective results analysis

5.2.1 Line A

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line A score	2,32	3,64	3,09	**3,98**

Table 5.1: CXI results line A

From the findings of the CXI color carpet final score, which was above 3.5 the line was found to be complex according to the operator's perspective. This finding matched how the line managers and the quality team perceived the line. Upon inspection of the result in table 5.1, it was area CXI B that was the highest factor towards the complexity. This infers to the operator's work content and product variants were the most difficult aspect of this line. A typical operator at this line is involved in preparing the kit, working with an automated heavy press machine, and also assembly of critical drive components. Highly experienced operators usually take the work at the press machine, while the newer operators are involved in a mix of preparing the kits and assembly work.

Line A produces one of the most critical sub-assemblies of an industrial robot. The line managers and the quality team wanted the study of complexity to begin from Line A as it was considered one of the most difficult stations to work at and requires an above-average experienced operator.

It has been noticed that Line A requires a lot of tactile feel which, the work instructions have difficulty conveying. The tactile feeling is therefore gained from experience. The requirements to assemble differ depending on the variants and upon the operation. Meaning that if the operators were trained at the same time, some are assigned to one operation, whilst the most experience can handle all variants and operations. From the CXI survey for this line, it can be said that the operators feel the most challenged in handling a variety of work tasks at the station as well as dealing with the number of variants of models of robots.

It shall also be noted that the complexity area CXI C is very close to turning red, this area measures how an operator is equipped to handle unexpected events and the availability of information to conduct operations at their workstations. At the time of any unexpected event, every line in the production facility has a dedicated person who responds to the problem and resolves it. The operators might have given a higher score for CXI C since there is no ready information regarding the work instructions at the station and an operator must take time off to gather any information that is lacking or approach other experienced operators.

5.2.2 Line B

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line B score	2,69	3,75	2,50	**3,92**

Table 5.2: CXI results line B

From The CXI color carpet for this line, it is seen that area CXI B is the largest contributor to the station's complexity. Based on observations and casual interviews with the line managers, this line is one of the oldest in operations and has not undergone any major changes to its layout. The workstation also consists of newly installed support structures for the heavy sub-assembly of the robot, and a large number of cables for the tooling were mismanaged which could cause ergonomic issues.

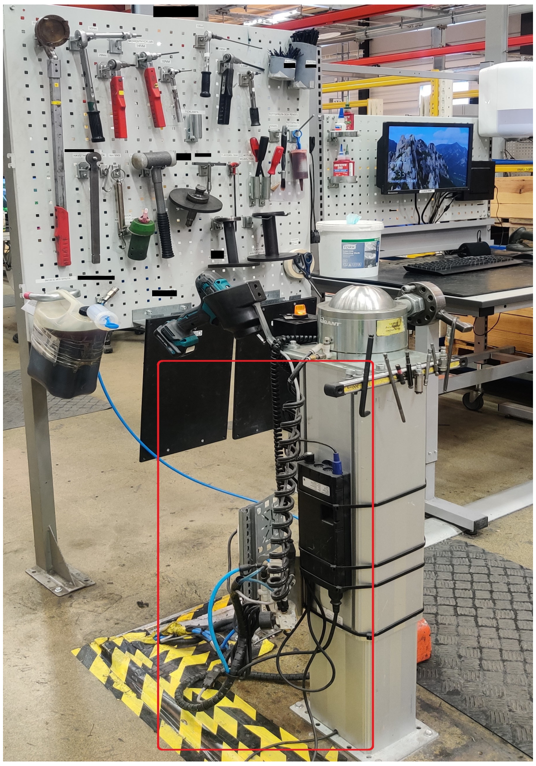


Figure 5.3: Line B workbench

Analogous to Line A, Line B also requires careful attention to the work content and handling of the product variants. Line B uses sub-assembled parts from line A and continues to build upon the robot. This line is slightly larger and consists of a pre-assembly station that prepares the parts for assembly. The workstations are dedicated to individual product variants since most of them require a special jig tool to hold the part in position while an operator works on it. The parts prepared at line A are delivered to line B through a buffer table and by a kit tray seen in figure

5.4 by an operator and the product assembly continues.

Figure 5.4: A tray kit consisting of a few parts for a sub-assembly

Line B has a bit of electrical wiring routing assembly and installation of motors and drives that are considered some of the most critical components for an industrial robot. From the observations of the authors, it was seen that several configurations/variants require attention to detail while completing the work within the takt time. This invariable increases the perceived complexity of an operator who is confined in a narrow station.

Apart from the work variance, some of the rare variants that occur in this station sometimes make the operators revisit the work instructions to ensure that every step in the assembly is correctly executed. This puts pressure on performing the task in the right manner under the specified takt time.

5.2.3 Line C

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line C score	2,17	3,44	2,44	**3,57**

Table 5.3: CXI results in line C

The results from the CXI carpet for line C show that no individual complexity area stands out but the overall complexity is red due to the fact the average score lies above the threshold and is concluded as complex. The complexity area CXI B is once again close to the red zone as the operators feel that the work variance and the variants are once again the top contributors to the perceived complexity. This follows our observation because the products assembled from Lines A to C are of one product family and thus it is easily seen that the complexity that is perceived at Line A is carried throughout the production area until it is finally assembled.

This line is where several sub-assemblies are brought together and joined to produce the final trim. Several stations at this line require specialized techniques to assemble both mechanical and electrical components. Precision alignment and positioning are crucial at this station and require complete attention to detail. From the observations, the number of work steps or methods at this line is not higher, but the nature of work requires skilled operators that can assemble several variants by completing multiple tasks in parallel.

5.2.4 Line D

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line D score	2,18	2,82	2,50	**3,24**

Table 5.4: CXI results in line D

Line D is one of the most recently built lines at the production facility that assembles a product range that requires less space but an above-average skill set to work on. The results from the CXI survey show that this station on an overall level is not complex. The only complexity area that stands out is area CXI B. But on average complexity is close to becoming a red on the color carpet. By conducting casual interviews with the line managers and some of the operators during the time of the questionnaire survey, the general opinion was that the line is very well designed in terms of space, tools provided and a digital interface to ensure traceability of the assembly work. An operator has sufficient time and cognitive support to carry out their work when compared to lines A, B and C.

Several operators claim that even though this line has the longest takt time among all the lines, the time required for the operations on some of the product variants is not enough. The work variance per operator is greater as the time allocated to an individual operation is high. When rare variants are to be assembled, operators face a slight cognitive pressure to complete the task effectively.

The Line has also standardized kit trays outfitted with pictures to avoid mistakes as seen in figure 5.5. This line demonstrates Poka-yoke (Fool proofing) and lean manufacturing [46] in terms of reducing unnecessary motion for the operator.


[redacted]
[redacted]

Figure 5.5: Standardized kit trays

5.2.5 Line E

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line E score	2,69	3,88	3,06	**4,21**

Table 5.5: CXI results in line E

This particular line gave the highest complexity score according to the CXI color carpet with a score of 4.21. The CXC results validate the CXI because it also classified the line complex. In the color carpet, CXIB was the highest contributor towards the complexity, indicating that it was work content and work variance that needed the most urgent change. This would also align with the results of the median of the survey answers. This station's operator's average experience is not a coincidence, but rather a necessity since it required a lot of experience based on personal observation and reflections.

The motivation behind the high complexity stems from numerous reasons. The first reason is based on observations, that there was a high range of variation between the products, from having assembled a minimal skeletal product to having numerous features and extra components that require extra time and experience to complete it.

Based on the personal observation of the authors, the line required precise assembly, due to a lot of components being of minuscule size concerning other lines and the components need small electrical wiring that requires further precision which can be seen in figure 5.6.

Figure 5.6: Line E

Line E is a special-purpose line that assembles the door of the control cabinet for an industrial robot. The cabinet door consists of a metal frame and provisions to assemble electrical components and a wiring harness. The control cabinet is the brain of the industrial robot consisting of computers, network adaptors, and the complete electronics and power control units that are required to program, control, provide feedback and distribute power to essential components of a robot.

The CXI results for line E follow the trend of the main robot lines with the CXI B area standing out. This line consists of a very large number of variants and work types. Every customer who purchases a robot has the option to configure their control system suited to different applications. Hence, the number of components is high and how these components are configured also varies from one order to another. A standard model is produced, but its occurrence is rare and hence the operator always works on a different configuration or variant during their work period.

The average experience and age of an operator at this line is the highest in the entire production facility. This shows that a high level of skill is required to assemble these delicate components, get the wiring harness connections right as the number of connections is high for a majority of the variants and ensure repeatability each time. The operators at this station stress the requirement of readily available work instructions for components that are unique and those that require careful attention to detail.
Based on the Color carpet the CXI C was the second largest contributor towards complexity that handled aspects of disturbance handling. This meant that operators would have difficulty handling rare variants due to not having readily available support information.

5.2.6 Line F

Complexity areas	*CXI A*	*CXI B*	*CXI C*	*CXI*
Line F score	1,63	2,95	1,90	**2,91**

Table 5.6: CXI results in line F

Line F produces the main control cabinet for the industrial robot. The line has 16 stations where 12 are dedicated to the assembly of the cabinet in a sequential flow while 4 stations are utilized for special variants. The line is one of the longest lines at the production facility and also has a short takt time at each station. The nature of the work involves the installation of electronic and electrical components into a control cabinet and install the wiring harness according to routing diagrams. Thus, the nature of assembly work requires knowledge and training in electrical equipment installation.

Based on 5.6, the CXI B is still the highest contributor towards complexity on the line but does not cross the threshold into the red zone. This indicates that the work content and product variants are still the driving force which is also observed in other lines. But the one area that line F stands apart from the other lines in terms of complexity area A and area C. The operators have responded positively in terms of the station layout and tools needed to execute their work. The operators also feel comfortable handling unknown events and have access to information needed to handle deviations.

As seen in line E, line F also faces large variations in configurations and since the operators are highly skilled, they can handle the work variance and product variants with ease. From personal casual interviews, operators have conveyed that new employees at this line F might face a longer learning time since it can be confusing at the beginning and emphasize the need to update and keep work instructions up to date at all times.

5.3 Objective results analysis

The figures below depict the Complexity calculator results starting with Line A-C first.

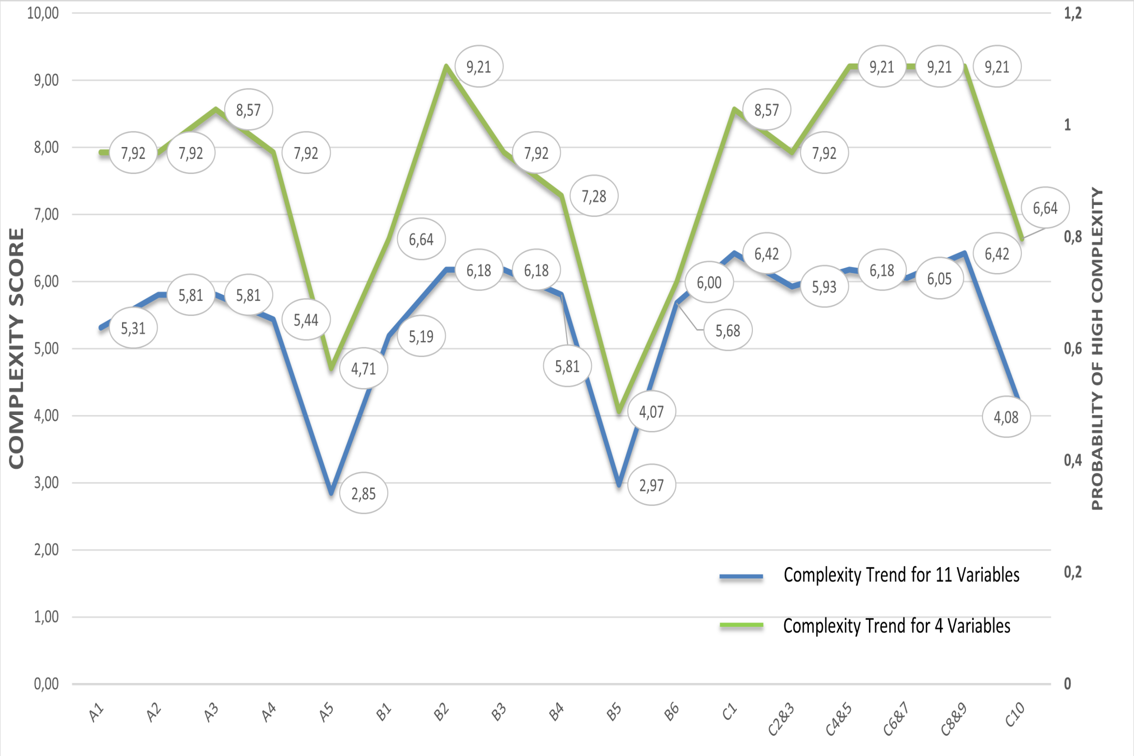


Figure 5.7: Complexity all variables Line A-C

5.3.1 CXC Results- Line A to C

The figure shows the trend for lines A to C, and the complexity score of the 4-variable model appears higher than the 11-variable model. This shows that the 4 variables are the driving force for the stations being complex. The right vertical axis shows the probability of a station being complex. Stations that lie above the probability 1 value will always be marked complex irrespective of the scale of the variables.

A production engineer would study the trend of the complexity scores along a line and determine the stations that are scored high to determine future improvement actions. In the case of line A to C, the variable product variants and picking technology remains the same across the entire line. Therefore, only the two other variables are the driving force for the complexity score. Several packaging types and the number of parts present in the station are observed to increase the score of the complexity.

From the observations of the authors, stations that require a larger number of parts are the stations that require more critical assembly work and the operators here are often highly experienced and skilled. Therefore, engineers at the company must see this as a station that can be simplified by designing the operations into simpler tasks or splitting the station into two. The stations that have extremely low complexity scores are the stations where no assembly work takes place but rather consist of equipment to test the sub-assembly for specifications. There are no parts or packaging types, but the only drivers are the variants and the tools.

5.3.2 CXC results- Line D

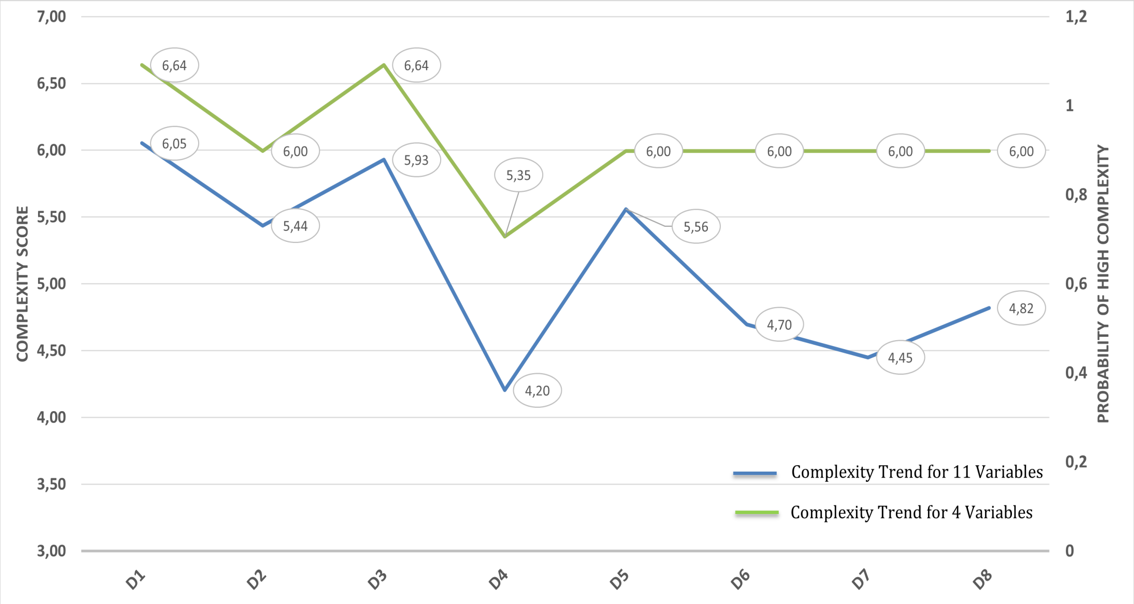


Figure 5.8: Graph complexity Line D

The results of the objective study at line D showed that stations D1 and D3 are highly complex and lie above the probability line 1. This matched the observations as stations 1 and 3 required pre-assembly of components and highly skilled operators were present who had a high experience working at this line. The stations also consist of a large number of tools, parts and fixtures compared to the rest of the stations in the line. This invariable increases the complexity of the entire line. But, the results contradict the results from the subjective study. The general opinion of the operators is that the lines are not complex but require some improvement in improving the approach to product variants and work content in the future.

5.3.3 CXC results from line E to F

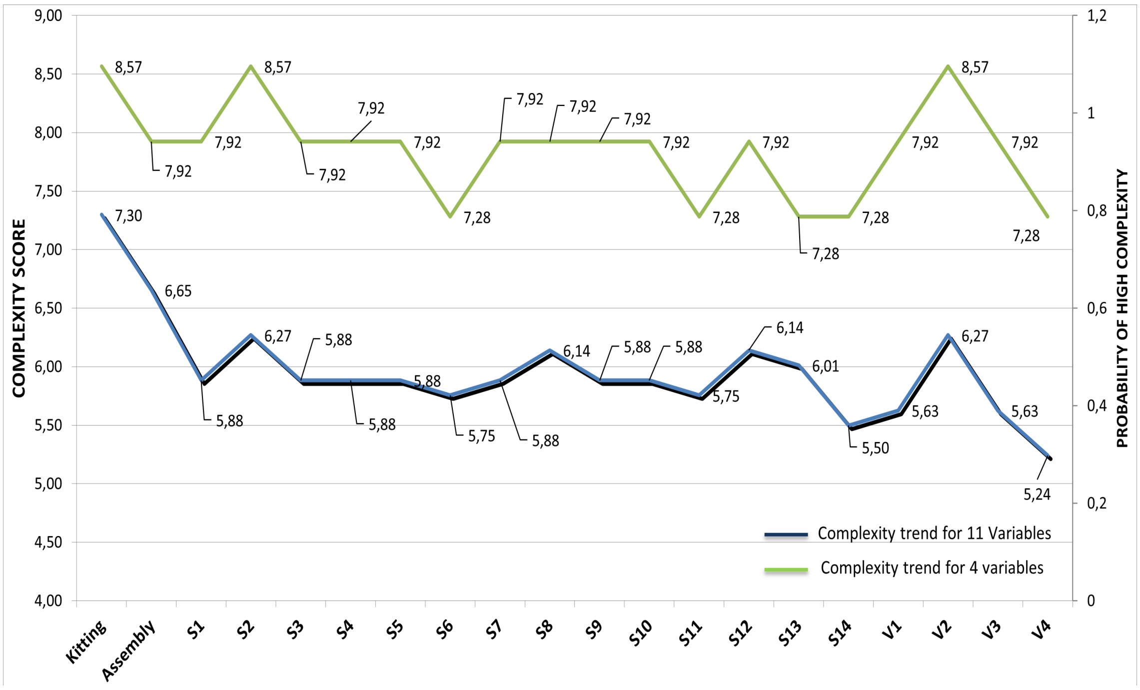


Figure 5.9: Graph complexity Station E-F

From both the subjective and objective analysis, line E resulted in having the highest score for complexity for the entire production facility. Numerous reasons and observations have been presented in the discussion from the subjective method. The kitting and assembly line shown in figure 5.9 comprises a kitting line and the 4 identical assembly lines for this station. Line F begins from S1 to V4 which (in figure 5.9 comprises 16 stations. Fourteen out of the sixteen stations have a similar station design in terms of layout, tools and work instructions. Stations V1 to V4 are stations that handle variants.

Lines E and F as mentioned in the previous discussion have a very large number of product variants to assemble and thus require extensive requirements of storing parts in their stations. Whereas, for line E, an operator prepares the kit according to the variant but the operators build upon additional components along the line. Since the nature of work done at lines E and F is very difficult to automate, the suggestion from the authors is to manage the complexity at these stations by investing in training and creating digital work instructions as a high priority.

6

Discussion

6.1 A brief summary

This chapter focuses on answering the research questions proposed by analyzing the steps that were taken during this entire study. Subsequent sections shall discuss how the resulting complexity can be managed using literature as a reference and also from the author's reflections and opinions.

6.2 Implications of this study

Once the definition of Production Complexity was established and the underlying factors were identified, the following objective was to find suitable methods that can relate to the type of production system under study. The methods proposed by Sandra Mattsson [21] and Luiza Zeltzer et. al [20] are tailored towards a production system where a product flow line exists and operators work on the product within a specified fixed cycle time. The robot production line under this study has a very similar system and is close to the operations of an automotive production line. Thus, another motivation for selecting the methods by the above-mentioned authors can be justified.

From the literature review, it was found that measuring the complexity of a system has two distinct approaches. From an engineering standpoint, complexity is the study of the interrelations of a great number of elements in a system. This kind of study is conducted during the design and operations of large aircraft, and the design of power-grid systems which are notable examples. Another approach is to measure complexity from those who directly endure it daily. The term complexity can also be associated with psychological well-being which measures how happy or stressed an operator is during their daily work activities.

Applying this field of measuring complexity in a production scenario requires an understanding of the daily operations on a production line, the nature of work an operator is supposed to execute, and the factors that play a key role in determining the targets of a production facility. The subjective method CXI and the objective method CXC fits into this scenario and were applied by the authors.

The objective data required for the study has been collected by direct observation and contacting relevant personnel for the required data 4.3 and was directly used in the calculation tool. The subjective data were collected by requesting the operators to answer the CXI method questionnaire during non-operative times. This ensured that the operators were under no pressure and hurry to answer the survey questions and had ample time to think about their responses.

From these steps, the authors were able to answer the first research question RQ1 :

- *RQ 1:- What are the possible methods that exist to quantify production complexity? How do they compare against each other?*

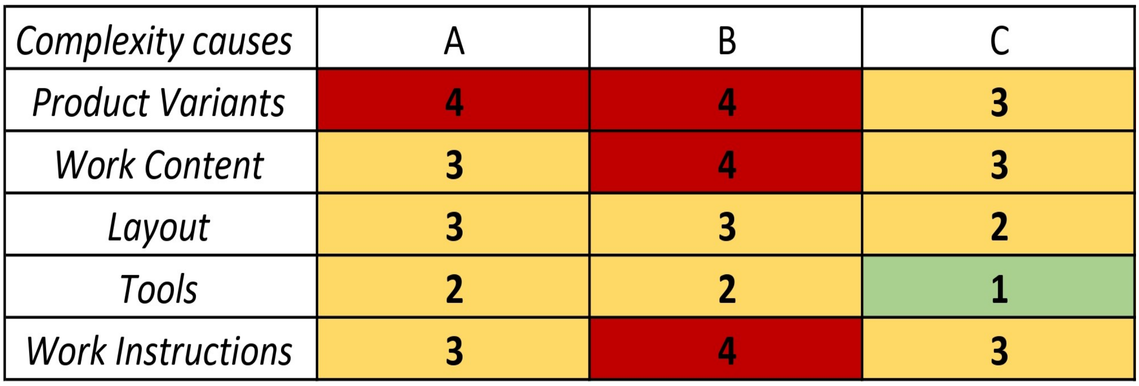
It is, therefore from the comparison of various methods, possible to quantify the level of complexity in a production assembly process by considering the operations that take place at each assembly line and summarizing it whole. It is quantifiable both from the subjective and objective perspective and the underlying factors that contribute to complexity can be weighed in by the survey answers by the operators (CXI) and also by adjusting the scales in the objective method (CXC). Thus, using the two literature references as benchmarks, the authors conclude that the possibility to measure production complexity exists and a value for this can be assigned based on the two methods involved in this study.

6.2.1 The Assembly Quality Analysis

The objective of this thesis study was to measure complexity to investigate if and how it affects the assembly quality of the products being assembled. Once the possibility of measuring complexity and its execution was completed, the analysis of the various factors that drive a station's complexity was established.

To obtain quality reports and findings, the authors had to approach line managers who were responsible to resolve and attend to major quality deviations. Upon a casual dialogue with the managers, it was learned that every quality issue is supposed to be notified and documented for future preventative measures but this does not occur in every instance. An operator might resolve the issue by themselves if it doesn't require extra attention. Therefore, any quality report that was presented to us will have a bias and only the most significant issues are documented.

6.2.1.1 Quality Report-Line A,B & C



Complexity causes	A	B	C
Product Variants	**4**	**4**	**3**
Work Content	**3**	**4**	**3**
Layout	**3**	**3**	**2**
Tools	**2**	**2**	**1**
Work Instructions	**3**	**4**	**3**

Figure 6.1: Causes of Complexity from CXI results

The figure above breaks down the survey results into individual complexity factors to gain a clear understanding of how the factors stand against each other in contributing to the overall complexity of the line. From the Objective study, lines A, B and C have a total of 11 stations out of 17 resulting in being complex.

Comparing and contrasting the results of both methods, we find that product variants, work content, layout (in lines A and B), and work instructions are the largest factors that contribute to complexity.

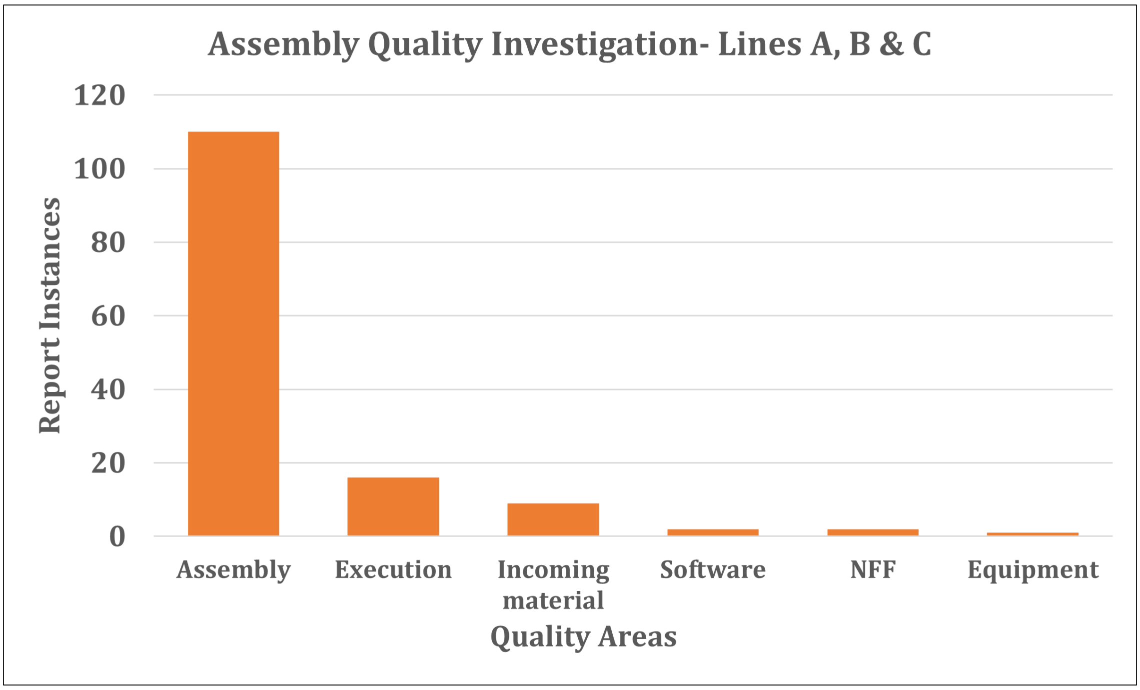


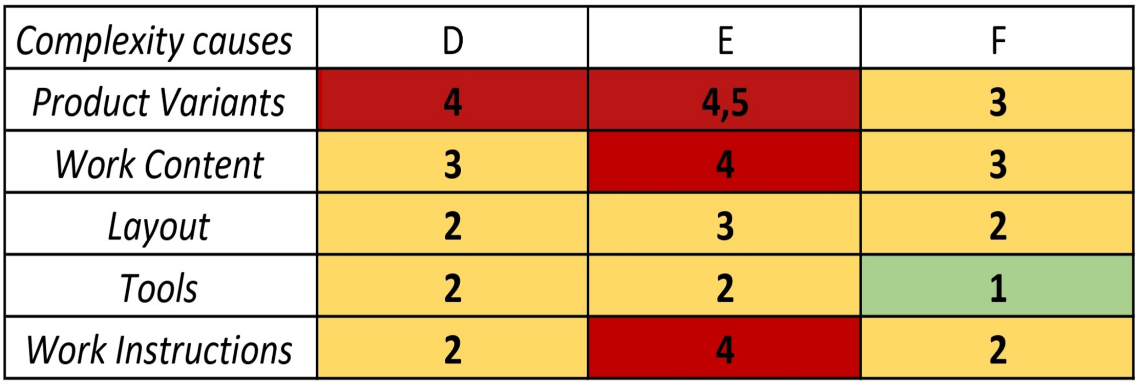
Figure 6.2: Quality Investigation Report for Lines A, B & C

The inference from the above figure 6.2, it is evident that the majority of quality issues reported from these lines point to assembly errors and/or execution of work methods. The quality problems are either found by other stations or at the very end during the quality control testing and are reported to the line managers who then input the reports into a digital database.

From the observations of the causes of complexity and the quality issues, it can be concluded that the operator faces issues in handling a variety of work tasks and product variants and this can be one of the root causes of quality issues to occur. Assembly and execution errors can be considered in the same area. Execution errors can be the methods and tools used to execute an operation that results in a faulty assembly.

Incoming material can also affect the overall assembly quality. The operators in their work tasks do not have to check for any quality conformity of the parts, thus any faulty part can also significantly affect the assembly quality of the products produced in these lines.

6.2.1.2 Quality Report- Line D, E & F



Complexity causes	D	E	F
Product Variants	**4**	**4,5**	**3**
Work Content	**3**	**4**	**3**
Layout	**2**	**3**	**2**
Tools	**2**	**2**	**1**
Work Instructions	**2**	**4**	**2**

Figure 6.3: Causes of Complexity from CXI results

From the figure above 6.3, product variants, work content and work instructions are the biggest drivers of complexity at lines D, E and F. In line E, the value is very close to 5 (possible maximum) which showcases the need to address this issue urgently. From the objective study, line D has 3 stations considered complex out of 8, line E has all stations marked complex and line F has 4 stations complex.

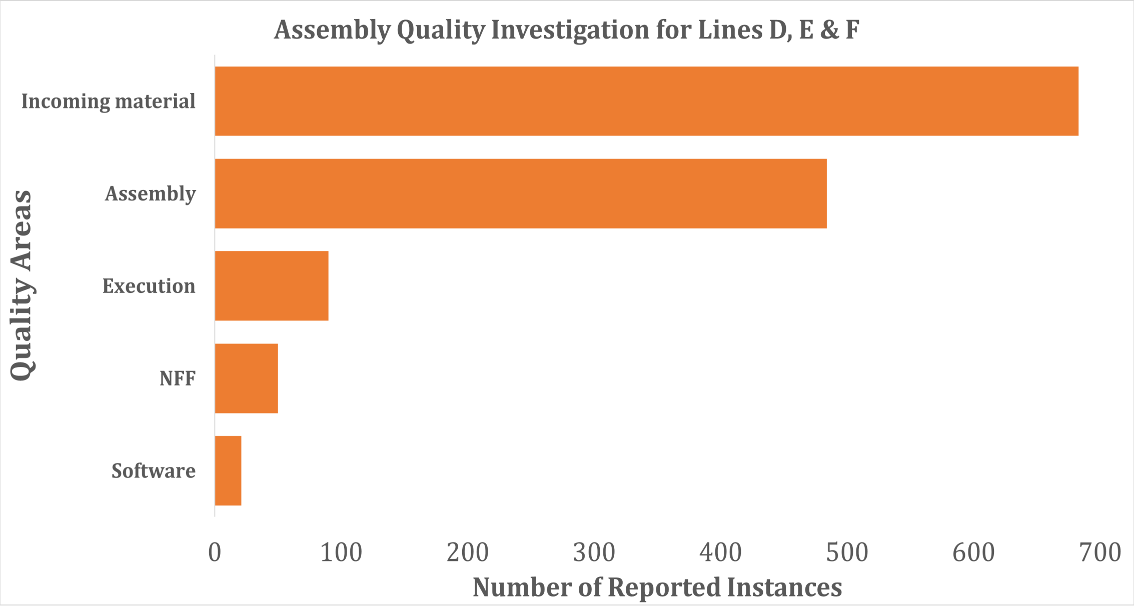


Figure 6.4: Quality Investigation Report for Lines D, E & F

The largest driving factors for quality issues at these lines are the quality of parts and sub-assemblies that are purchased from vendors. The quality issue is not known at the time of purchase and shipment or storage but is rather known during the assembly stage or at the end of the production line. A majority of the quality issues are detected during assembly by operators when the parts do not conform to the required specifications and are required to draft a fault report explaining the reason.

This can be one of the driving reasons why the operators perceive that the work content is high at these stations. Station D produces a variant of industrial robots while E and F produce the entire control cabinet system. Most electrical and electronic components are purchased through vendors and suppliers from all over the world, thus a large portion of the complexity lies outside of the production facility. The steps needed to address this issue are out of the scope of the current study.

Assembly and execution errors are a combination of human-made errors and errors that occur due to faulty parts. A highly complex work environment increases the probability of an operator committing errors during assembly that may go unnoticed until the final product is tested. From these observations, the cause for complexity can also be traced to the high volume of components an operator has to work with combined with the different work tasks and relying on work instructions for rare variants. This combination of factors increases the perceived complexity and can be one of the root causes of assembly quality errors.

From the quality analysis of all the lines A-F, it is found that the most recurring quality issues lie in the assembly of components or the nature of execution of the work method. A possible root cause for the occurrence of these issues can be traced to how an operator perceives their daily work and what causes an operator to either lose attention, look for lacking information, or rely on the training they have received to execute the task.

The result of the subjective complexity study showcases that the majority of operators perceive increased problems in the areas of handling a wide variety of product variants, handling different work tasks apart, and lack of updated work instructions to execute their duties. When these factors are combined, the probability of human-induced quality errors increases which was understood by going through the quality reports.

This analysis now helps answer the second research question:

RQ 2:- Do these factors of complexity affect assembly quality? Are there any implications?

The factors causing complexity from the subjective study have been shown to affect production complexity from the previous discussion. From all the lines under study (lines A-F), the major factors that are highlighted from the subjective study are

- Product variants

- Work content

- Work Instructions

The factors above are also the ones mentioned by [22] to be shown the underlying causes for complexity in a production environment. Apart from the mentioned, factors such as station layout, tools and support tools also are highlighted in the survey that also requires attention.

The company introduces new product variants as the requirements of the markets changes and grow, but requires a thorough analysis of the existing production system. For this study, a current state analysis needs to be done wherein the subjective method of assessing complexity can be applied.

Companies that look to automate tasks and provide assistive technologies to manual assembly work, can use the complexity study how satisfied their workforce is with the work content. Work tasks that involve a degree of repetitive actions can be automated to improve operator attention and reduce errors.

In the era of industrial digitalization, paper-based instructions need an upgrade with work instructions to be presented in the form of a digital interface. An operator can be encouraged to train in a digital setting that works on the setup similar to a computer game. Digital work instructions can also be presented to the worker at each product variant and can simplify the work task.

Therefore it can be concluded that complexity does affect the quality of assembly. Several factors can affect either individually or collectively causing an operator to lose focus by trying to remember details of a large variety of variants, get stressed due to increased work content and assume tasks by a lack of readily available work instructions.

6.2.2 Management of complexity

The framework for complexity management in a complex problem situation is based on the idea of socio-technical systems where humans, technology and the organization work together to achieve pre-defined goals. [25]. In a complex environment, the human role is increasingly important as humans are the ones that face complexity daily. Production complexity can be managed by preventing or avoiding, reducing, or simplifying complexity. This is done instead of completely removing complexity which is not possible due to how manufacturing operates[15].

In order to empower the operators, the company management needs the following features: (adapted from [15])

- *Sharing information on the organization's performance.* The company already has a monthly meeting with all the operators and does this to provide the short and long-term goals of the management.

- *Provide performance rewards.* The company also provides rewards for operators that come up with unique solutions to solve everyday problems.

- *Provide knowledge that helps operators to achieve greater work performance..* The company should invest in adapting digital technologies that help operators learn about their daily work with ease and create an environment where they can share ideas and opinions.

- *Give employees the power* that may influence the performance of the production system directly. While the controlling decision still lies with the management, a view of the employees and operators can also significantly add to the decision-making process.

From the results of the complexity measurement at the production facility, the dominant factors that caused complexity were Product variants, Work content, and work instructions. The factors are more human-centric when compared to factors such as station layout and tools that are dependent on the design of the production system. Therefore, managing complexity in this scenario begins with understanding how to empower the human workforce.

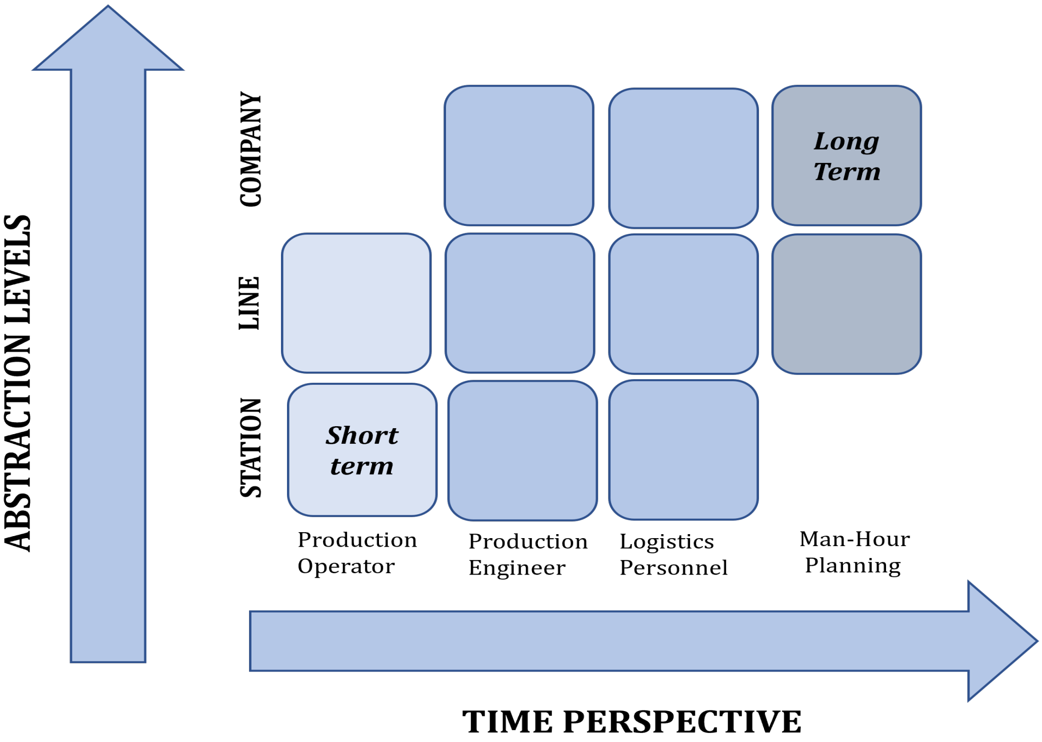


Figure 6.5: Subjective complexity dimensions- Adapted from [1]

The subjective study can be used by the management to make immediate improvements in the short term while the objective study can be used to map the stations that require an in-depth rework or upgrades. Therefore, the methods used in this study can be used as a visual decision tool to map key areas for development or continuous improvement projects.

To manage the factors that are at present causing the most complexity can be addressed in the following ways:

- Product Variants: While this area cannot be changed since it is needed for the company to stay competitive, the management can make a current-state analysis of the production lines to handle the introduction of new product variants. Operators that have experience and new recruits need to be trained and up-skilled to handle the new variants along with working with the existing models. This training shall ensure no loss of productivity and achieve higher working conditions.

- Work Content: This an area where line managers and the management can help create an operator empowerment and engagement platform. The questions that addressed the work content area in the subjective method covered areas in terms of takt time, unplanned events, and involvement of the operators in the decision-making that affects their work. Efforts that make the operators empowered shall help overcome this area of complexity.

- Work Instructions: From casual interviews and physical observations, it is learned that the work instructions are not continuously updated when the company introduces a new product variant. An operator is forced to rely on their previous work knowledge and apply them. A new operator with less experience might face a large learning period without the correct support information. Thus, the authors suggest that the company invest in digital work instructions and provide them along with each product that the operator has to work on. In this way, any confusion can be avoided and the probability of operator-induced error can be reduced[47].

  A recommendation would be to involve current and new operators in virtual reality (VR) training. This training would not affect real production. The VR can also help the operators to get accustomed to uncomfortable situations that stem from rare variants, making the operator commit fewer mistakes in reality if the VR has difficulty settings[48].

6.2.3 Reflections on utilizing CXI & CXC

CXI would however give a well-represented color carpet for visualization, for better understanding. The carpet makes it simple for anyone to understand the issues of the station, preventing silo knowledge. This allows anyone, especially the operators to communicate with the managers to give a suggestion for improvement and better collaboration based on the color carpet.

From personal observation, the CXI would have difficulty in finding precise root causes since it is limited based on the operators' experience. For example, the line could have several stations, and not all operators could handle them, meaning that operators would risk giving incomplete answers due to a lack of experience in the other operations. Also if it was only one person that answered for the specific station would yield only one person's perspective, and anonymity could be compromised[49].

CXI is a self-administered online survey for the operator to answer. Since the method is personnel-based, the risks of experiment bias are imminent. Meaning that the participants would answer in a manner that would give the researcher an expected outcome consciously or subconsciously[50], due be fear of backlash from management or resistance to change. Another risk is other operators' interference with the answers. An example was that operators would discuss the statements, which could compromise their judgment of the Line and could give an inaccurate result, which would lead to more homogeneous results rather than a diverse one.

Since CXI is personnel-based, availability becomes an issue. It can prove to be difficult to find an opportunity to ask them to fill out the online survey. This risks taking unnecessary time and leads to postponing the results.

Obtaining the data from the correct stakeholder and comprehending what type of data to obtain can prove to be difficult. For example, finding work instructions for the station, the correct stakeholder has to have the right workstation for the variants. After obtaining another hinder what pages of the work instructions are considered a step.

From the execution of the CXC, the initial impression of the calculator was that its weight was tailored toward the automotive industry[20], which causes inaccurate or different results. The weights were also seen as subjective and that alone can risk being inaccurate due to being subject to bias or disagreement.

Since CXC does not require operators to answer, the CXC can be routinely used to detect anomalies and trends at a larger scale i.e. the whole manufacturing plant[31].

The CXI and CXC have the potential to be viable tool to integrate into the DMAIC methodology from Lean six sigma that the company extensively uses. It has a lot of similar characteristics in terms of finding and identifying the issue (Root cause-analysis)[46], focuses on the operator's voice and indirectly reduces waste[51].

6.3 Contributions

This study contributes to realizing the goals of Industry 5.0 by assessing the current state of the workforce in a rapidly changing industrial setup. Not only do companies face complexity, but also the operator's cognitive workload needs to be quantified in some manner.

From an academic standpoint, this study has demonstrated that the methods, ordinarily used for the automotive industry with high-volume manufacturing, can be used in other industries that have manual assembly and in industries that manufacture special-purpose machines in a serial production line. This study validates the methods that have been proposed by the researchers to study complexity and compare the results that were expected at the beginning. This study can be used for further research into the era of socio-technical sustainability.

The industrial contribution of this study shows that the human workforce requires additional attention as companies grow their businesses. While critical decisions are required to stay competitive, a tool to assess the current state of human perception of daily work is certainly required which is the goal of the subjective method (CXI). As the design of production systems advance, a decision tool such as the objective complexity calculator (CXC) shall help engineers to decide if their designed station layout is highly complex or not compared to the other stations. The results of the complexity study can be used to communicate how the work tasks differ from each station through workshops and training sessions and gain feedback.

6.4 Future scope

The authors feel that measuring complexity should be expanded further to production companies that are increasing the adaption of automation and helping create a sustainable socio-technical workplace. With the increase in digital technologies, the future operator's perception of the areas of complexity is bound to change from what it is today. Therefore, complexity measurement should be expanded to production areas where adaptive automation is on the rise.

7

Conclusion

The measurement of assembly complexity has been demonstrated through methods that exist in the literature, and where the results of the majority of the lines matched and confirmed the company's expectations of being highly complex. It is evident that humans remain an important factor in measuring assembly complexity. Despite the drawback, it still harbors valuable information for the study. This analysis revealed that both the objective and subjective methods can complement and validate in several lines, but additional sources such as quality reports, observations, and reflections are required in order to fully gain a comprehensive understanding of the causes.

This study highlights the operator's significance in a highly complex environment and emphasizes the need for training-related technologies and empowerment. Further, the study underscores the potential of the method to be further developed and adjusted accordingly to encompass the entire manufacturing plant. This enables further root cause analysis for trends and deviations for future production planning and continuous improvement activities.

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A

Appendix 1

A.1 Likert scale for CXC

Table A.1: Drivers scale

Complexity drivers	**Likert Scale**			
Picking techology	F	S	C	M
	1	2	3	4
Bulk Sequence Kit	S	K	B	
	1	2	3	
Packaging types	1	2-4	5-8	>8
	1	2	3	4
Tools per workstation	1	2-4	5-8	>8
	1	2	3	4
Machines per workstation	0	1	2	>2
	0	1	2	3
Work methods	0-2	3-5	6-8	>8
	1	2	3	4
Distance to parts	0-1	1,1-2	2,1,4	>4
	1	2	3	4
Variants same model	1	2-3	4-5	>5
	1	2	3	4
Variants in this workstation	1	2-4	5-10	>10
	1	2	3	4
Different parts in workstation	1-4	5-10	11-20	>20
	1	2	3	4
Assembly directions	1	2-3	4-5	>5
	1	2	3	4

A.2 Statements

Causes of complexity	*Statements*
Product variants	1. There are a lot of different variants at this workstation
	2. A lot of variants are similar in characteristic and/or appearance
	3. There are variants that reoccur rarely at this station
	4.The variants at this station require different assembly methods
Work content	5. I have a lot of other work tasks beyond my assembly work at this station
	6. Takt time is generally enough for the assembly work
	7. My work is often affected by unscheduled changes/uncertainties
	8. During unscheduled changes/uncertainties, I have enough time to finish work
	9. During unscheduled changes/uncertainties, it is easy to find the information to execute the work
	10. I am a part of the planning for the changes of this station
	11. Work at this station is often stressful and/or frustrating
Layout	12. This station is well designed in terms of reachbility
	13. This station is well designed regarding heavy lifting
	14. This station is well designed regarding the ergonomics
	15. This station is well designed regarding the material facade
	16. Placement of the tools and fixtures are generally good for the station
Tools & Tool support	17. Tools/fixtures that are used at the station are well adapted for the assembly work.
	18. What support systems are at the station: - Pick by light -Bar codes and scanners -RFID -Feedback on-screen -Feedback from tool -Checkpoints
	19. The tools mentioned above help me perform my assembly work
Work instruction	20. The work instructions are easy to understand
	21. The work instructions help simplify the work
Miscellaneous	22. It takes a long time to learn the work tasks at the station
	23. In overall, I think the station is well designed

Table A.2: Statements used in the subjective approach CXI

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