TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

HUMZA WALI

HUMAN ROBOT COLLABORATION IN ASSEMBLY PROCESSES

Master of Science Thesis

Examiners: Prof. Minna Lanz
Asst. Prof. Roel Pieters
Examiner and topic approved on August 08, 2018

ABSTRACT

HUMZA WALI: Human Robot Collaboration in Assembly Processes
Tampere University of technology
Master of Science Thesis, 61 pages, 11 Appendix pages
November 2018.
Degree Programme in Automation Engineering, M.Sc. (Tech)
Major: Fluid Power (Automation and Hydraulic Engineering).
Minor: Life-Cycle Management and Engineering (Mechanical Engineering and Industrial Systems).
Examiners: Prof. Minna Lanz, Ph.D.
Asst. Prof. Roel Pieters, Ph.D.

Keywords: Human Robot Collaboration (HRC), KONE Corporation, KUKA LBR iiwa, Design for Assembly (DFA) methodology, Switch Module Assembly, DIN rail assembly

Human robot collaboration (HRC) in assembly processes, is a concept which aims to integrate the human workforce with the robots in a shared workspace. This is carried out to complement the human workforce to achieve key manufacturing metrics e.g. efficiency, ergonomics, etc. Assembly of the switch module (DIN rail components' assembly) was taken to be the product under investigation. Design of human robot collaborative assembly process was explored while considering the following objectives and knowledge areas: Design for Assembly (DFA) methodology, rules for task assignment between the human worker and the robot, Identification and mitigation of process hazards, and trainable collaborative setups. A total of five DFA axioms were found to be relevant for the design of human robot collaborative assembly process. Task Assignments between the human and the robot was explored while considering the following objectives: Optimal assembly cycle times and workspace ergonomics. Three out of four phases of assembly process offered room for collaborative endeavors. The task assignments during these assembly phases ensured optimal cycle times and work space ergonomics. Risk assessment along with risk mitigation strategies were evaluated on the basis of ISO 12100. Hand guided frame teaching methodology was used to train the collaborative setup. This enabled an operator friendly/oriented approach towards the design and implementation of collaborative assembly tasks. The obtained results ensured a reliable and industry scalable implementation of human robot collaborative assembly process.

PREFACE

First of all, I would like to thank God for giving me strength and determination for undertaking this thesis. I would also like to thank my thesis supervisors, Prof. Minna Lanz and Asst. Prof. Roel Pieters, for their insight, input and guidance; throughout the research and development process.

Being part of the Laboratory of Mechanical Engineering and Industrial Systems at Tampere University of Technology, I learned and gained valuable knowledge regarding the subject of Human Robot Collaboration in Assembly Processes. It was an honor and a great learning experience to work with the UNITY project team. My utmost gratitude towards the management of the case company, KONE Corporation, for providing support and assistance during this thesis.

Lastly, I would like to thank my family for their unrelenting support during this defining phase of my academic career.

Tampere, 02.11.2018

Humza Wali

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

OS	Operating System.
CEN	Comité Européen de Normalisation, European Committee for Standardization.
CENELEC	Comité Européen de Normalisation Électrotechnique, European Committee for Electrotechnical Standardization.
ETSI	European Telecommunications Standards Institute.
SME	Small and medium-sized enterprises
R&D	Research and Development.
ISO	International Organization for Standardization.
ISO/TS	International Organization for Standardization / Technical Specification.
TM	Total operation time.
CM	Total operation cost.
NM	Total of theoretical minimum part count.
ICT	Information and Communication Technology Systems.
IIoT	Industrial Internet of Things Products.
DFA	Design for Assembly.
SCARA	Selective Compliance Assembly Robot Arm or Selective Compliance Articulated Robot Arm.
HRC	Human Robot Collaboration.
EU	European Union.
CE-marking	Conformité Européenne, European Conformity: CE - marking signifies that the product meets safety, health and environmental protection requirements laid out for European economic area by the European commission.
S/No.	Serial Number
N/A	Not Applicable.
TCP	Tool center point.
COBOT	A robot designed for direct interaction with a human within a defined collaborative workspace. [1]
AMF	Atomic Monitoring Function. [2]
min	Minutes.
s	Seconds.
mm	Millimeters.
N	Newton - Unit of force.
DIN	Deutsches Institut für Normung

1. INTRODUCTION

1.1 Background

Human Robot Collaboration, a concept not alien to the industry of our time but developing at a dynamic rate; owing to the paradigms of the production processes. The idea nurtures as the physical entities like robots, machines etc. become sophisticated due to the fusion of sensors, actuators, ICT systems etc. The goal being to integrate these intelligent entities with the human workforce so that they complement each other in the production processes; yet keeping it ergonomic. This is just a glimpse of the future of automation which aims to integrate the technology with the humans and their society. It is termed as the 4th Industrial revolution or Industry 4.0 [3].

1.2 The Problem Statement and Objectives

The purpose of this thesis is to analyze the human robot collaboration in assembly processes alongside the key technologies used in it.

1.2.1 Research questions and objectives

The research questions and objectives are listed below:

1. What DFA methodology axioms are relevant for designing applications involving human robot collaboration?
2. What are the rules for task allocation between humans and the robot?
3. What are the risks in human robot collaborative assembly process?
4. Is the human robot collaborative process reliable?

1.2.2 Limitations

To aid industrial deployment, open source and typical R&D software such as Robot operating system, and MATLAB etc. weren’t utilized. These softwares require intensive trainings regarding the knowledge areas of software engineering e.g. MATLAB script programming language, and Ubuntu OS etc. Industrial stakeholders are potentially exposed to heavy incurred costs as a result of these training activities. Apart from this, the open source software also need extensive testing for stability and security issues. The SMEs which serve as the backbone of the European economy [4] are reluctant to the use of such softwares. Therefore, commercial software which are commonly used in the local industry were utilized only. These are given as followed:

1. Use of *Visual Components* Software for layout planning and simulation.
2. Use of *KUKA Sunrise.OS*.

During the development of this thesis, external sensor systems (machine vision-based safety and quality checking systems) were not utilized. Alternatively, the following IIoT products were used:

1. Inherent input/output devices of the collaborative robot and its mobile base.
2. Industrial electric screwdriver with programmable controller.

This enabled the laboratory setup at Tampere University of Technology to correspond with the presented scenario of the case study.

1.2.3 Research and Development Process

The research process, given in Figure 1, was used during the development of this thesis. It is divided into 4 steps. It starts with process overview. Switch module's assembly simulations and technical documents were utilized to prepare the case study. Then different DIN rail assemblies were analyzed using *Visual Components - 3D simulation software*.

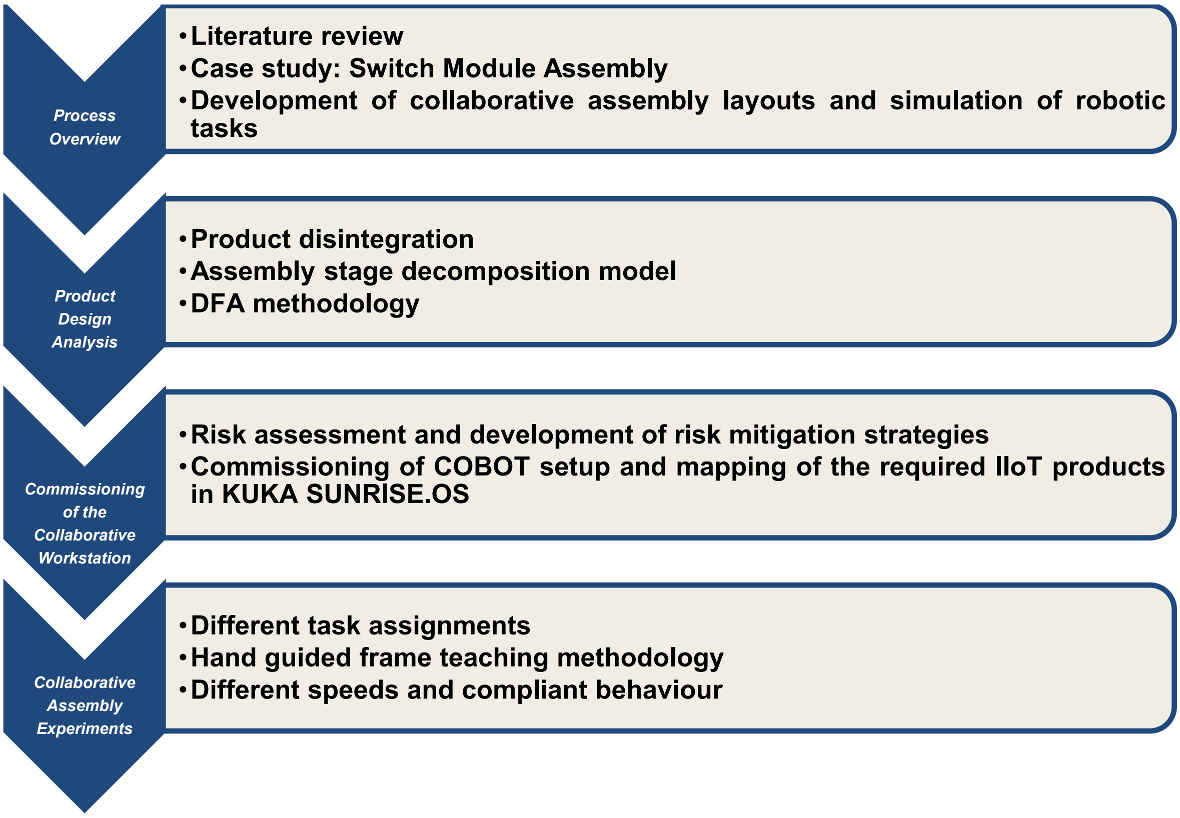


Figure 1. *Sequential steps of research and development process*

The product design analysis stage involves disintegration of the product. Assembly stage decomposition model was prepared for the product under investigation. It was also analyzed using Design for Assembly (DFA) methodology tools and axioms.

During the third stage, risk assessment was carried out. At the latter parts of this stage, KUKA Sunrise project was readied and tested by installing it on the robot controller. The last stage involves testing of the collaborative assembly process for its reliability and productivity.

1.3 The Structure of the Thesis

This thesis is divided into 7 chapters. These are explained in the following text.

1. The first chapter introduces the reader to the problem statement of the thesis and its objectives.
2. The second chapter deals with the literature review. Industrial revolutions, human robot collaboration, safety requirements and product analysis methodologies are discussed in this chapter.
3. The third chapter presents the case study. This outlines the assembly requirements of the switch module i.e. the product under investigation.
4. The fourth chapter discusses the design and planning of the human robot collaborative setup along with the necessary process details. This chapter includes: layout design, high level system architecture and risk/hazard assessment.
5. The fifth chapter discusses the design and implementation of the human robot collaborative assembly.
6. The sixth chapter gives the conclusions and results of this thesis.
7. The seventh chapter, which is the last one, discusses the future recommendations and developments.

2. LITERATURE REVIEW

The literature review presented here focuses on the related concepts and technologies which lead to the realization of human robot collaboration for the assembly of product under investigation.

2.1 Historical Context – Industrial Revolutions

The concept of human robot collaboration is evolving due to emergence of various latest technologies and knowledge areas like Internet of Things, Compliant robots etc. To delve deeper into the topic, industrial revolutions and their technological impacts were, hence, explored first.

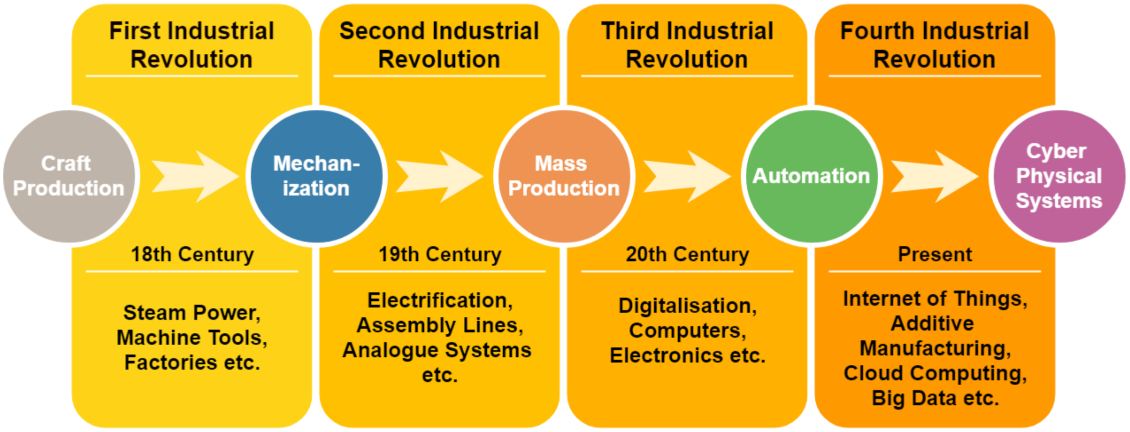


Figure 2. *The timeline of Industrial revolutions. Adapted from [5].*

Figure 2 represents the key technologies that enabled the development of the industry alongside their outcomes in a chronological order. The First Industrial Revolution transformed the agrarian and handicraft producing societies into mechanized societies. Inventions such as steam engine along with other mechanical tools were essential in the development of the iron and textile industry. During the 19th century, the industries expanded and grew due to innovation and advancement in technologies like electricity, internal combustion engine etc. Assembly lines led to mass production; thus, revolutionizing the industry and the environment.

The 20th century is considered the age of computers due to the development of digital systems. Innovations in solid state electronics/physics enabled the production of intricate control systems. Thus, paving way for novel industrial solutions which varied from partial to fully automated processes; depending on production, societal, environmental etc. paradigms.

The 21st century has seen the development of a lot of innovative technologies. These technologies have emerged as market leaders and have also contributed towards a shifting trend in R&D. These include additive manufacturing, cloud computing, trainable systems, and complaint robots etc. to name a few. Such technologies have already started to usher environmental changes globally. However, the impact on the industry worldwide is more or less related to the empowerment of its workforce.

2.2 Human Robot Collaboration

Robots and IIoT devices are dominating the current world market. In the foreseeable future their influence is more likely to alter life at work and home. Practices related to work, health, environment, and safety etc. will transform with time to keep up with the increasing human robot interaction. Human robot interaction has paved new horizons in the market. Improvements have been seen in the delivered services alongside creation of new jobs and diversification of current value chains. For instance, since HRC is a novel area in the present market; therefore, technology transfer from R&D sector to the industry offers a lot of room and potential for value adding activities. Furthermore, manufacturing is a key value adding activity where usually the robots are deployed for large scale volume production. However, Europe, being the global leader in production and supply of industrial robotics, plans to deploy robots for small scale volume production. This is done to maintain and nurture Europe’s production base, which is vital for its wealth generation cycle. Usually, to keep the labor costs low, varied to full automation is carried out throughout the production processes. These solutions are productive if the setup and the running costs are low. But for the small-scale volume production, the automated solution must offer high flexibility alongside low incurred costs. To achieve this, many novel solutions have emerged in the market e.g. collaborative robots, trainable systems, and customized interactive user interfaces etc. These solutions enable the placement of robot alongside the human worker, during the manufacturing processes, without the need of having typical safety fences. This concept is termed as Human Robot Collaboration and it is explained in the following text. [6]

In human robot collaboration, the human and the robot work in partnership to complement each other for achieving a common production/manufacturing goal. It is achieved by providing specific set of capabilities. Usually, the robot assists the human worker in carrying out non-ergonomic tasks e.g. repetitive tasks, lifting heavy objects etc. On the other hand, the human performs non-arduous tasks requiring human specific skills which are otherwise not feasible to be carried out by the robot e.g. human supervision, planning etc. However, human robot collaborative assembly lies midway, in comparison to manual and automatic assembly processes (Shown in Figure 3), when it comes to some key production metrics e.g. productivity, product variants, flexibility, and lot size etc. Automatic assembly is preferred when there is very less or almost no variation in products, high productivity is required, and the commissioned setup remains unchanged unless it is required for non-value-added tasks like maintenance etc. Manual Assembly process, on the contrary, is preferred when the lot sizes are low, productivity requirements are comparatively low, product variants are high, and the assembly process requires it to be highly flexible. [7]

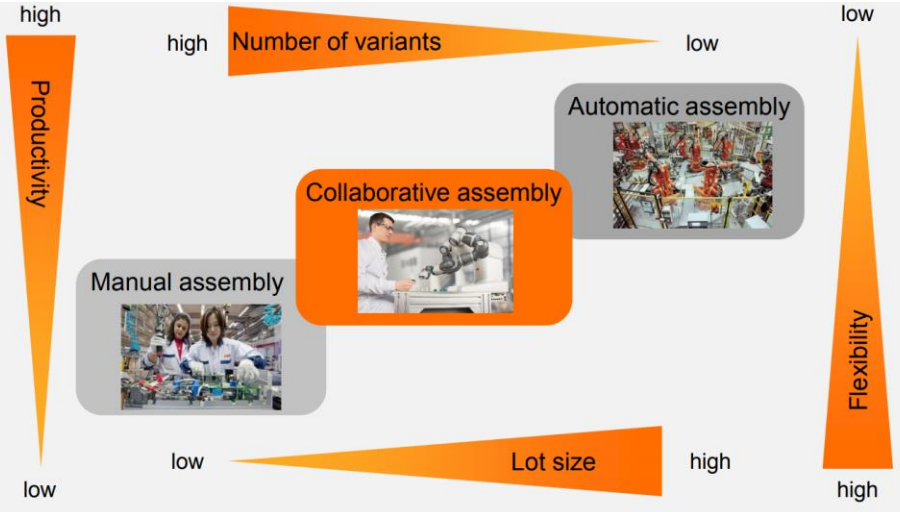


Figure 3. *The comparison between manual, collaborative and automatic assembly. [7]*

Figure 4 provides the idea of evolution of industrial robots and their respective workspaces. In the first scenario the robot is confined to a fenced workspace and the human is absent from the workspace while the robot is carrying out the required task.

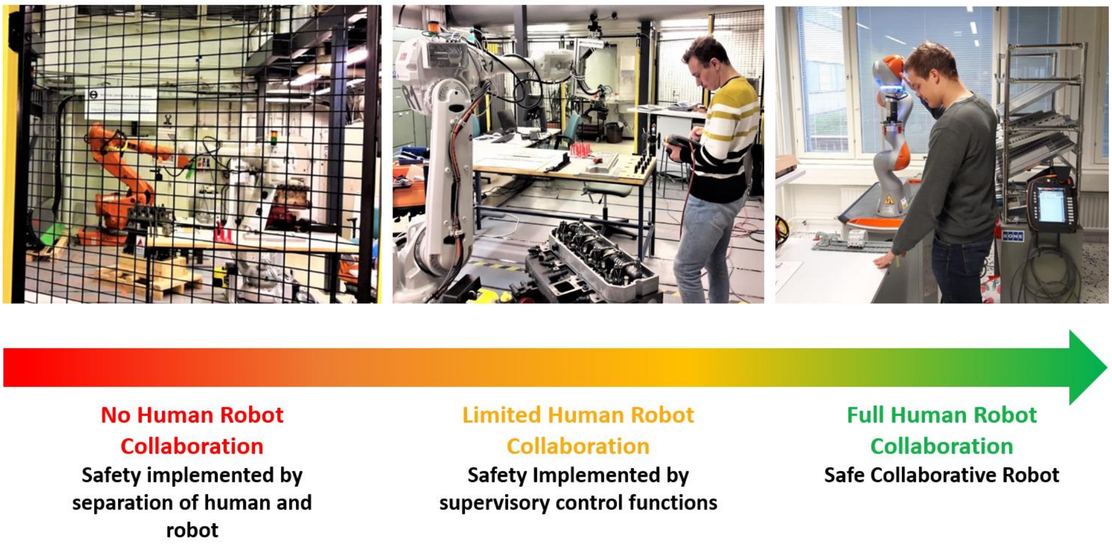


Figure 4. *The concept of Human Robot Collaboration.*

In the second scenario the robot is not fenced. However, the human is collaborating with the robot while holding on to the dead man’s switch on the teach pendant to ensure safe operation. In this case the robot’s senses are not well established to ensure safety for humans and its surrounding work environment. Moreover, a dead man's switch ensures safe robot operations and is activated if the operator is debilitated. In the third scenario, the robot utilizes its inherent sensors to ensure safety for the humans and its work environment. Therefore, the human collaborates with the robot confidently without having the need to hold on to the dead man's switch.

The research material presented here in the thesis focuses on full human robot collaboration and the key concepts involved in it are presented in Figure 5. A collaborative robot (COBOT) interacts directly with the human worker within the boundaries of a collaborative workspace to carry out manufacturing/production tasks simultaneously. A collaborative workspace is characterized by the autonomous operation of a robot. Safety for human workers is achieved in various ways e.g. varying speed on detection of human presence within the workspace [8], limiting the force delivered by a robot so that the separation between the robot and the human can be minimized etc. [9] [1]

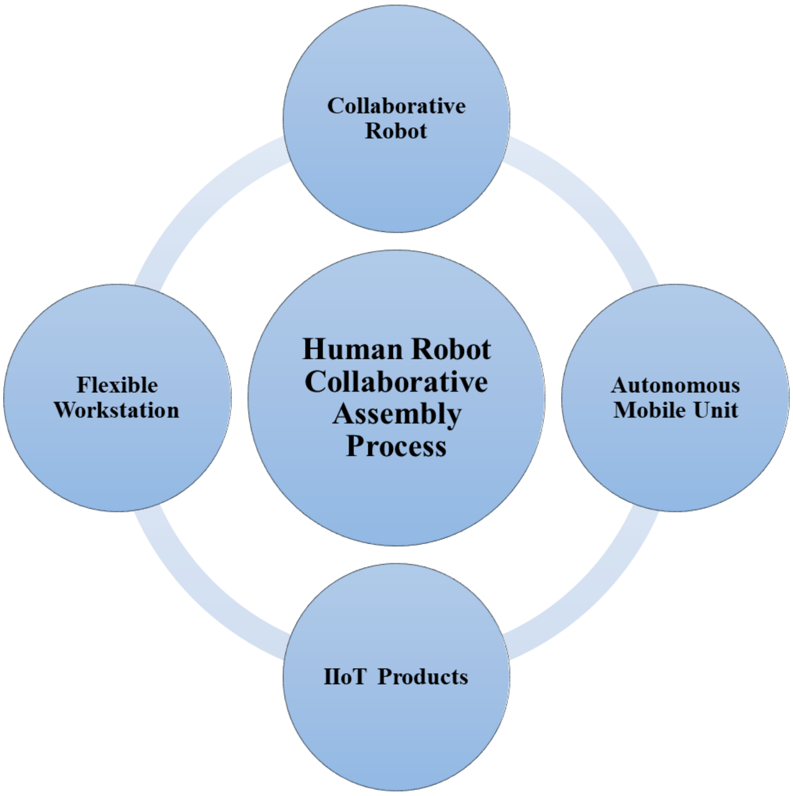


Figure 5. *The concepts/technologies used for the human robot collaboration in assembly processes.*

The robot is mounted on an autonomous mobile unit which provides flexibility in the form of mobility and quick deployment. It houses all the important modules belonging to the robot and the Industrial Internet of Things (IIoT) devices. [10]

Flexible workstation provides ergonomic adjustments to the human robot collaborative process. Adjustable pick up shelves/feeders and assembly table height boost the assembly activities and ensure ergonomic conditions. IIoT Products such as robot operating system (software), gripper system, external sensors, and actuators etc. exchange data via dedicated field buses. [5]

When the human and the robot are collaborating in a shared collaborative workspace, then the human can have two types of contacts with a robot. It can deliver static and dynamic forces to the human body. According to [11], these are of two types and given next:

1. Transient Contact
2. Quasi-Static Contact

Transient Contact is a type of contact between the human and the robot where the human body is not clamped in-between the robot's structure and the workstation. It can retract and recoil after the contact. However, in case of Quasi-Static contact, the human worker's body part is clamped in between the moving/stationary part of the robot or its work cell. The human is unable to retract and recoil. These contacts pose significant risks to the robot and its environment. To mitigate these hazards different strategies could be adopted e.g. use of vision-based safety systems [8], and active compliance of the robot etc. However, if the risk mitigation strategies are not applied carefully then it could result in an increase in the overall entropy of the process [12]. The same applies to the case of robot motion planning.

2.3 Safety and risk assessment requirements for Human Robot Collaboration

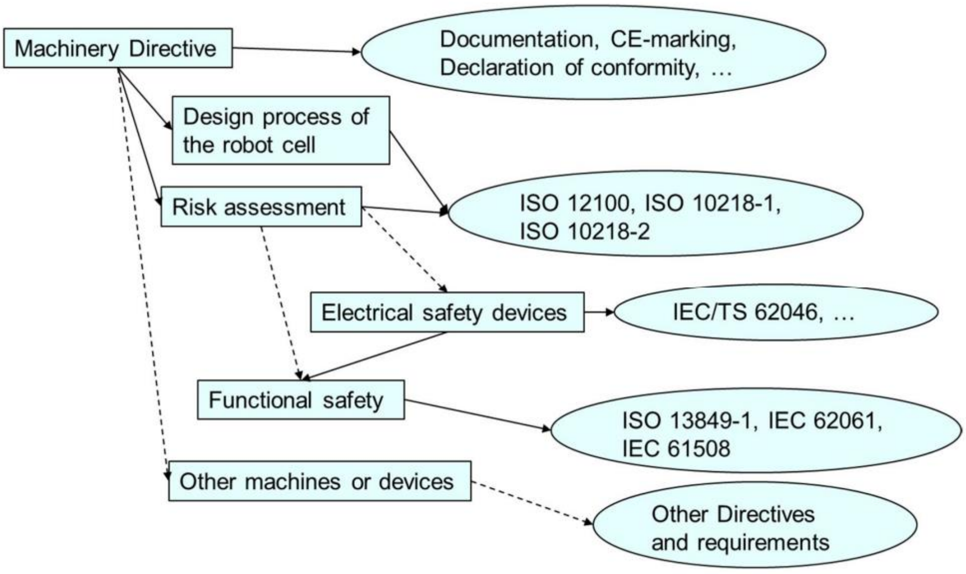


Figure 6. *The overview of safety measures and requirements for Human Robot Collaboration (HRC). [13]*

A technical report presented by [13] gives an overview of the related standards and directives for safe robot operations and these are schematically presented in Figure 6. Further explanation to the subject is given in the following text.

2.3.1 Machinery Directive

According to [14] a directive is defined as, *"a legislative act that sets out a goal that all EU countries must achieve."* Therefore, it can be stated that the European Machinery Directive 2006/42/EC gives the necessary regulations regarding the health and safety requirements for a new machinery to be placed in the EU market. It ensures free movement of the machinery in the EU market. It also aims at providing maximum protection to EU residents and its industrial workforce. Key activities relating to the use of machinery directive are: risk assessment, preparation of technical manuals and instructions, CE-markings at the machines, declaration of conformity documents (a declaration specifying the responsibility of design) etc. National laws (e.g. Finnish laws) regarding machinery, which are obligatory to follow, are defined according to the machinery directive.

This directive is further explained by the *Harmonized Standards.* These are developed on request of European commission by recognized European standards organizations such as: CEN, CENELEC, ETSI etc. The use of a harmonized standard is intentional, and it aims to give valid solutions within its scope.

Alongside harmonized standards, the machinery directive also refers to other standards and technical specifications such as ISO 12100, ISO/TS 15066 etc. to make machines and their operations safe.

2.3.2 Standards Type A-B-C

As per the definition of [15], Type-A standards are the basic safety standards which give basic concepts, principles for design and general aspects that are applicable to a machinery. Examples for this type are: ISO 12100 – Risk Assessment, IEC 61508 – Functional Safety, etc.

As per the definition of [15], Type-B standards give generic safety guidelines and these deal with one safety aspect or one type of safeguard which can be used across a wide range of machinery. Examples for this type are: ISO 13849 – Safety of machinery part 1 and 2, ISO 11161 – Integrated manufacturing systems etc.

As per the definition of [15], Type-C standards provide detailed safety guidelines for a particular machine or group of machines. These are also termed as individual safety standards. Examples for this type are: ISO 10218-1 – Robot, ISO 10218-2 – Robot system/cell, ISO/TS 15066 – Collaborative Robots.

2.4 Assembly Stage Decomposition Model

To conduct thorough examination of the product and its assembly requirements different modeling techniques are used mostly. The product is disassembled before the creation of the model. This enables the identification of the various components and their assembly features. One such modelling technique was presented in [16] and its resulting schematic model is called Assembly Stage Decomposition Model (Shown in Figure 7).

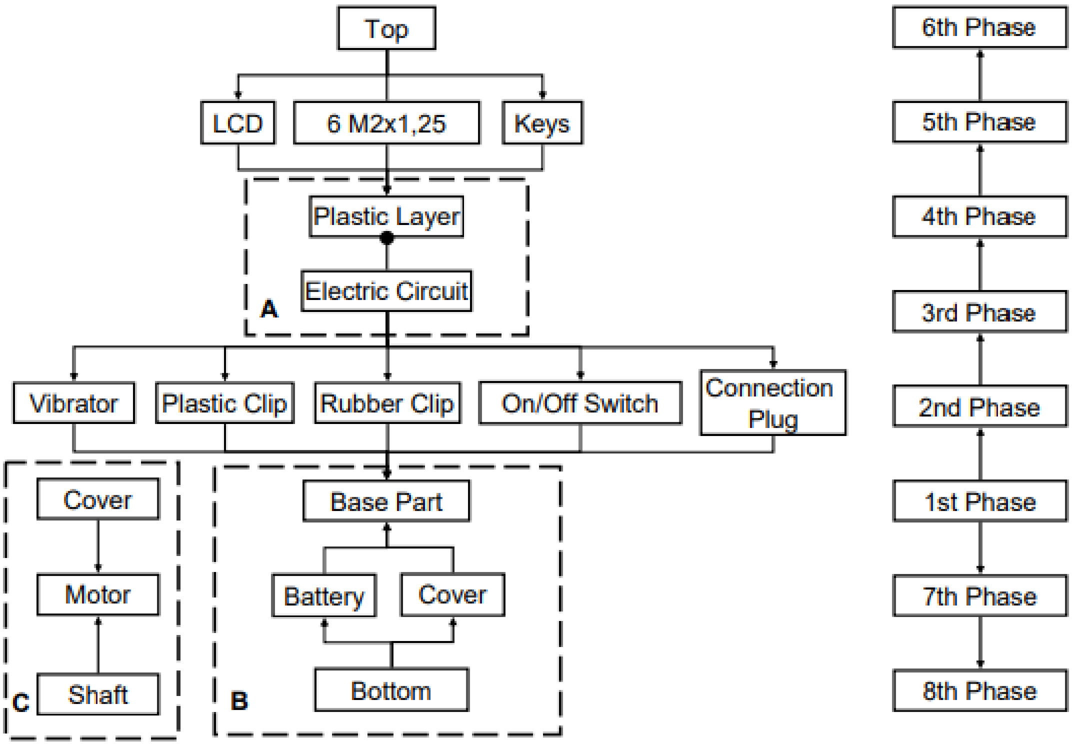


***Figure 7.** Assembly stage decomposition model. [16]*

It outlines the phases of the assembly alongside the added features/components of the product simultaneously. The case shown in Figure 7 represents the model for a mobile phone assembly, where the assembly process starts with the first phase. This involves securing the base part first to ensure a bottom up directional approach for assembly. A direct connection between the two components is shown by arrows and it represents functional and geometrical mating. However, an indirect connection between the two components is represented by a dot (between plastic layer and electric circuit during 3rd and 4th phase of assembly). Indirect connection's definition is based on precedence constraint scheduling logic. According to this logic several events/tasks are dependent on each other. And some tasks cannot be completed unless the other tasks on which it depends are carried out first. Moreover, the enclosed areas represented by A, B and C outline the subassemblies of the product.

2.5 Design for Assembly (DFA) Methodology

Design for assembly is a concept which aims to facilitate the industrial workforce in designing/planning the assembly processes with maximum achievable production/manufacturing metrics such as: efficiency, economy, ergonomics etc. However, in practice, usually a compromise is made among these key metrics. [17] [18] [19]

2.5.1 Guidelines for DFA

DFA, simply put, aims to reduce the number of parts; thereby, simplifying the assembly process and reducing the timings involved in it. Moreover, DFA methodology could be better understood by the axioms identified from [17] and [18]. And these are given below:

1. Simplification of the joining methods.
2. Reduction of parts.
3. Minimizing the assembly directions.
4. Availability of options for modification/customization at the final assembly level.
5. Testable entities.

Decreasing the number of mechanical fasteners such as bolts, screws etc. in a product can ease the assembly process significantly by bringing down the part variability. Less number of parts and reduced variation leads to simplification; thus, reducing potential mistakes and unnecessary confusions. With this approach the assembly process design becomes lean as the number of tool changes are reduced. Space issues which arise due to the use of tools in the assembly process, as they themselves consume a considerable amount of space on the assembly table/station and around the product, can be eliminated by simplifying the joining techniques. However, the joining methods should be designed in a way so that the product can be easily analyzed using qualitative and quantitative techniques. These analyses help the development of product and its life cycle.

Reduction of parts is a good strategy to simplify the assembly process. This approach saves the time in almost all the phases of production processes; such as: planning, execution and monitoring/quality checks. The process of material handling and replenishment of the feeders becomes more simplified. As the individual parts have various costs associated with them, therefore, reduction of parts leads to an overall cost reduction of the final assembled product. A good design strategy is to combine the individual parts together into chunks at every stage before the final assembly stage. Unless the reasons stated next are to be satisfied, a good practice would be to eliminate the part altogether or it should be integrated together with other similar parts. The reasons for part retention are:

1. The part moves with respect to other parts and these respective movements cannot be generated through the material properties or any other known methods.
2. Objectives related to the order of assembly and maintainability/service of the product require the part to remain as an independent entity.

3. If the intended design feature/function of the part is likely to be compromised because of integration; then it must be retained as an independent entity.
4. If the integration of part results in poor manufacturability (could be due to a lot reasons such as: production costs, complex molds etc.) then it should be retained as an independent entity.

Minimizing the direction types/changes for the assembly tasks is a general rule to keep the assembly process simple and lean. For industrial manipulators and SCARA robots, usually, a top-down approach is feasible. Moreover, the assembly process should be designed in a way so that the positioning of the part is well aided by the worker's senses e.g. visual perception, hearing, touch etc. Same goes for the automated assembly as well i.e. it should be well aided by the integrated sensors/IIoT products. For the manual assembly process, two hands should be enough for any assembly task. However, if a task involves assembly by one hand then replacing the human workforce with an automated process (Preferably with an industrial manipulator/SCARA Robot) should be given a consideration.

Final assembly level customization capabilities provide the product life cycle professionals with an opportunity to leverage their key process related resources: assembly automation, quality testing, design economy, ergonomics etc. This strategy helps to eliminate the bottlenecks involved in an assembly process and aims to minimize the idle time associated with work cells/stations.

The assembly process must be designed in a way so that the objective of providing leverage for quality testing/troubleshooting endeavors can be achieved. For instance, in manual assembly tasks, the human worker should be able to assemble the product with quality; and at the same time, he should be able to inspect it. Such an approach should be taken which allows the inspection of sub assembled parts at every stage of the assembly; thus, making the process as lean as possible. Modular design of the product and elimination of loosely fit parts help in the realization of this methodology.

2.5.2 DFA - Analysis

The purpose of DFA methodology and analysis (qualitative and quantitative) is to optimize the assembly process. The following methods have been used and mentioned in [17] and [18] for DFA analysis:

1. Qualitative and quantitative analysis of the assembly process steps.
2. Qualitative and quantitative analysis to identify part relevance.
3. Estimation of the cost of assembly

DFA analysis involves examination of parts, sub-assemblies and final assembly model/drawing/proposed sequences. Handling of parts, assembly orientations and non-value-added process steps are evaluated next. Then the parts are examined for similarities and relevance. The aim here is to determine the theoretical minimum number of parts to reduce the actual part count and minimize the stages of assembly. These tasks are carried out in the future redesign processes. Evaluation and estimation of costs involved in the assembly processes are critical in the decision-making process of assembly task design.

DFA analysis (work sheet sample shown in Table 1) involves some terminologies which are described next in this chapter:

1. Angle of symmetry (α+β) (Presented in Figure 8)
2. Operation time
3. Operation cost
4. Estimate of theoretical minimum part count
5. Design efficiency or DFA Index

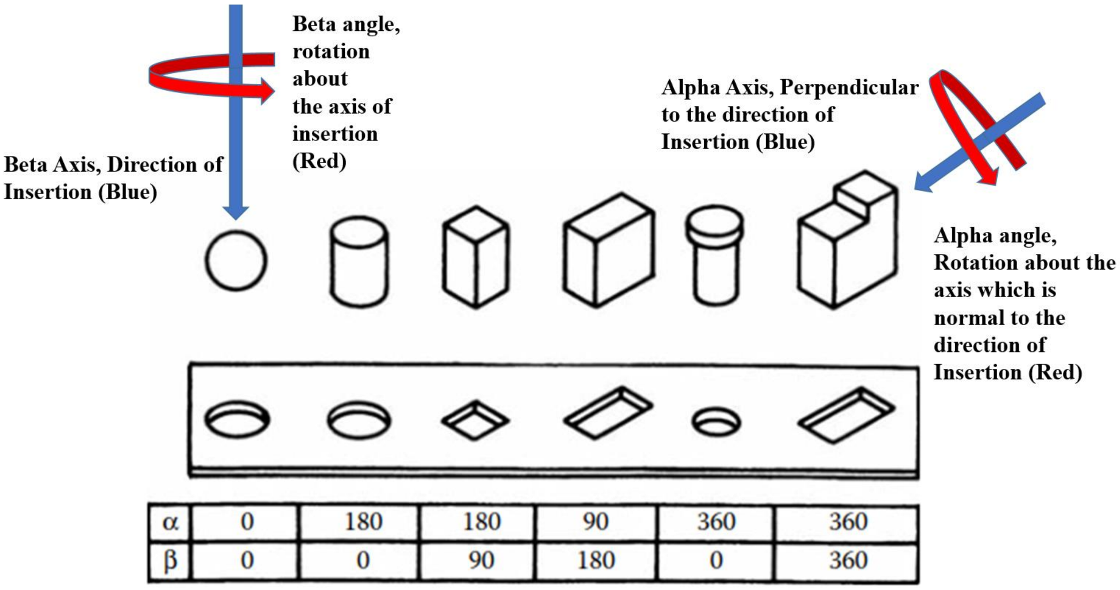


Figure 8. *The concept of total angle of part symmetry (α+β). [17]*

The total angle of part symmetry (α+β) is evaluated in degrees and it ranges from 0 to 720 degrees. Alpha or α axis is the axis perpendicular to the direction of insertion. Alpha symmetry is the concept which depends on the angle (alpha angle) through which a part must be rotated about alpha axis. Whereas Beta or β axis is the axis in the direction of insertion. Beta symmetry is the concept which depends on the angle (Beta angle) through which a part must be rotated about the Beta axis. The design improvements related to this concept aim at reduction of the total angle of symmetry. [17]

Table 1. *The worksheet template for DFA analysis. [18] [17]*

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	**NAME OF THE PRODUCT:**
PART ID:	**Total Angle of Symmetry (α+β), Degrees**	**No. of times the operation is carried out consecutively**	**Two-digit Manual Handling code**	**Manual Handling Time per part**	**Two-digit manual insertion code**	**Manual insertion time per part**	**Operation time, Seconds (t_m)**	**Operation cost, Euros (c_m)**	**Estimate of theoretical minimum part count**	
Total										DFA Index = $t_{m,min} \times \frac{NM}{TM}$ =
							TM	CM	NM	

The operation time (t_m) combines all the timings related to an individual part. These usually involve the handling and insertion timings. Summation of the individual part operation times gives the total time of operation referred to as TM in Table 1.

Similarly, operation cost (c_m) combines all the costs associated with the individual part. The costs are usually evaluated depending on the material handling technique and the method of insertion utilized in the assembly task. Summation of the individual part operation costs gives the total cost of operation referred to as CM in Table 1.

Theoretical minimum part count is the classification-based value evaluated from the analysis of individual parts (of the final assembly). This analysis is based on the correspondence/symmetry in physical, functional etc. properties of the sub-assembly parts. It could also be based on the similarity of an operation e.g. similar fastening method, similar feeding method etc.

Design efficiency or DFA index is a percentage measure of how convenient it is to assemble a product and it is given by:

$$DFA_{Index} = t_{m,min} \times \frac{NM}{TM} \times 100\% \rightarrow (1)$$

Whereas, the variables used in this formula are described in Table 2.

Table 2. *Description of variables used in computation of DFA index. [17]*

Variable	**Explanation**
$t_{m,min}$	The basic assembly time (handling and insertion) of the part having minimum value. It is taken as 3 s on average.
TM	Total operation time for the assembly in s.
NM	Total of theoretical minimum part count.
DFA_{Index}	Also known as the design efficiency. Rule of thumb suggests this value to be < 60%

3. CASE STUDY: SWITCH MODULE ASSEMBLY

KONE Corporation, a world leader in the production of elevators and escalators, like all other industrial giants is exploring the field of full human robot collaboration. The human robot collaborative process was showcased as a 3D simulation in a seminar held in Espoo, Finland on March 07, 2018.

KONE elevator’s controller box (shown in Figure 9) assembly line was presented as a simulated scenario. Assembly of the switch module, which is an internal component of the controller box, was to be carried out by utilizing full human robot collaboration. [20]

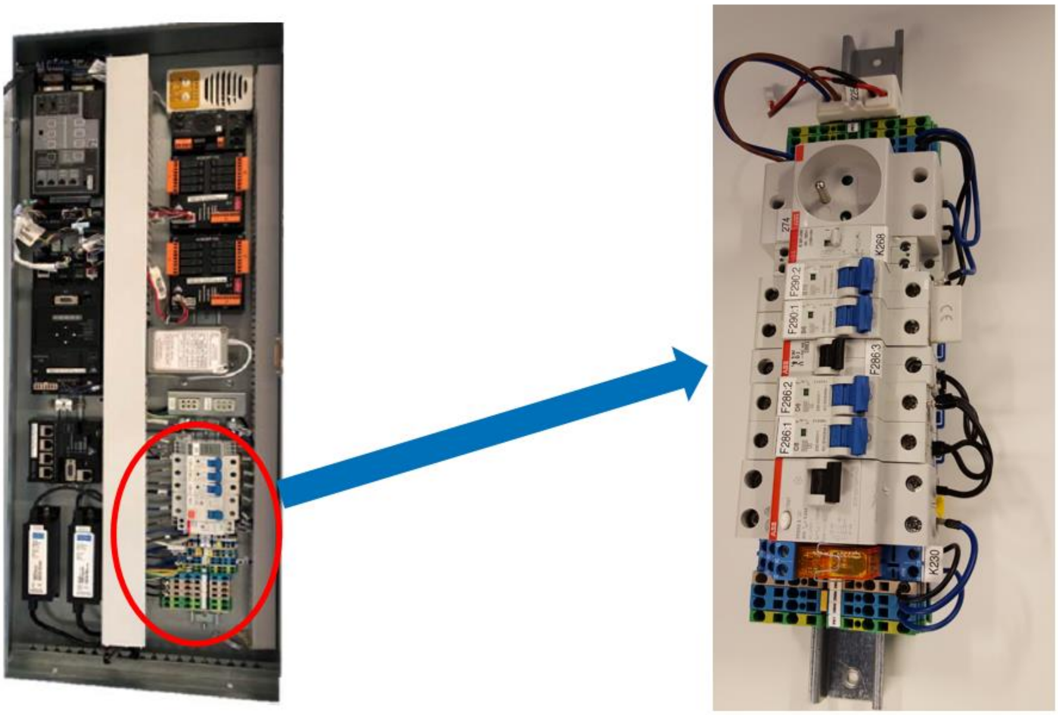


Figure 9. *The inside of controller box (left) alongside the magnified view of switch module (right). [20]*

3.1 Factory Floor Layout

The current factory floor is shown in Figure 10. It only has human workers in the assembly, quality testing and packaging sections of the factory floor. Eight human workers are deployed on the assembly line to produce controller box for the elevators. Here they assemble and inspect the product using naked eye while following the standard measures. Then the assembled product is forwarded to the quality testing area of the assembly floor.

Here 2 factory workers check the product for quality e.g. using multimeters etc. to ensure the circuits and the related modules are complete.

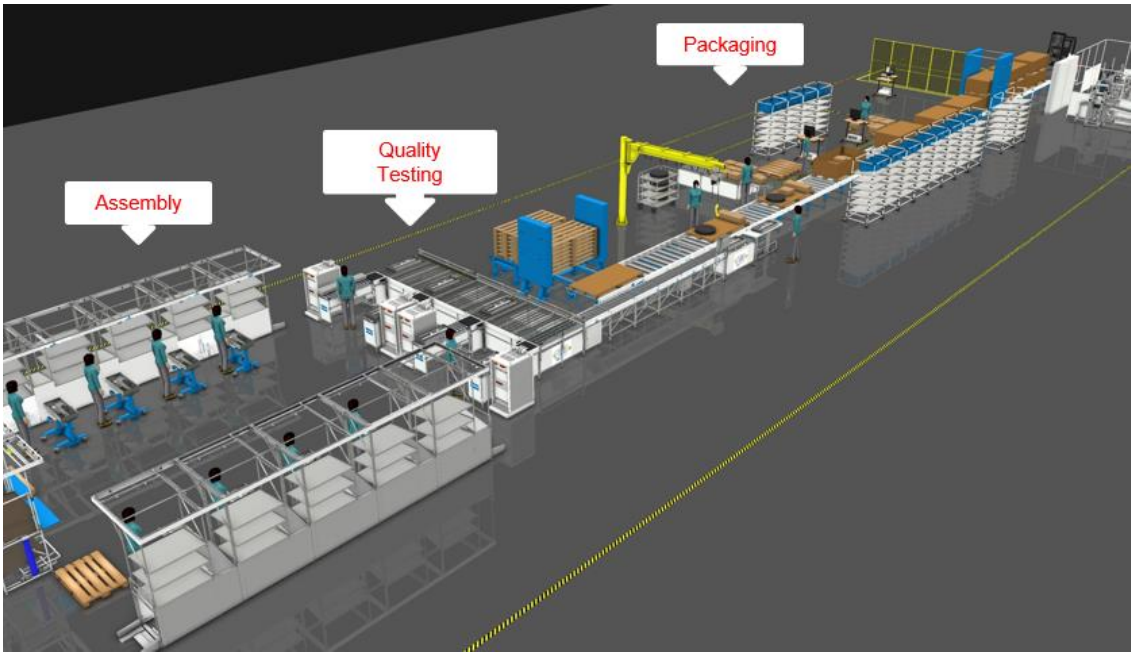


Figure 10. *The factory floor layout for controller box assembly. [20]*

After the quality requirements are met, the controller box is forwarded to the packaging line via conveyer belts. A total of 5 human workers are deployed here for handling and packaging of the finished product. To see the potential of full human robot collaboration, the assembly of switch module was chosen to be the test product and it is discussed in the following text.

3.2 Product Description

The switch module consists of terminal blocks, circuit breakers, sockets and switches mounted on a DIN rail (Shown in Figure 11). It has electrical connections to two other modules of the controller box which are: control power module and lighting module [20]. The components along with their labels and quantity, according to their respective electrical drawings, are listed next in the Table 3.

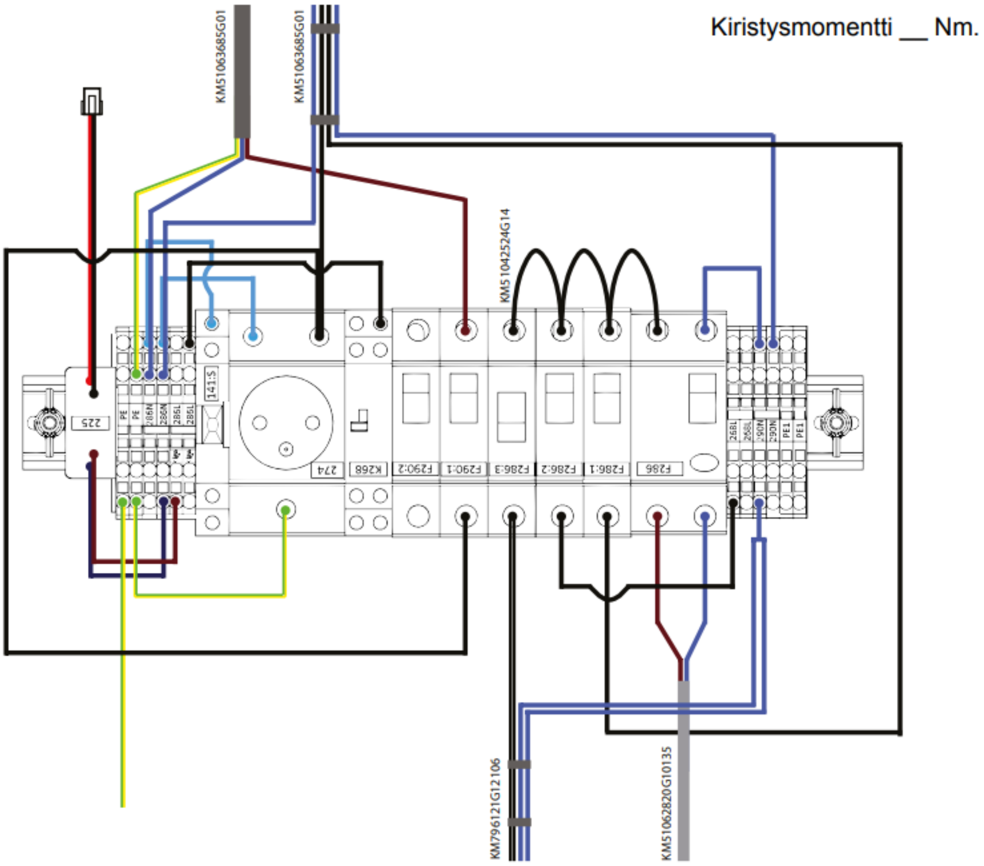


Figure 11. The top view of switch module assembly. [21]

Later in the thesis, assembly cycle times shall be evaluated and discussed for the items given in Table 3. However, it should be noted that the components vary from one elevator model to another. The model shown in Figure 11 represents a particular case out of various models from different KONE factories around the globe.

Table 3. *The bill of materials for switch module assembly. [21]*

S/No.	Name of the item	Labels	Quantity
1	ABB E216	141: S	1
2	ABB Socket	274	1
3	ABB E251-230	K268	1
4	CHINT B10	F290:2	1
5	CHINT B6	F290:1	1
6	ABB D2	F286:3	1
7	CHINT D6	F286:2	1
8	CHINT C6	F286:1	1
9	ABB FH202 A	F286	1
10	ZDU 2.5/4AN (GREY)	268L (CONTROL POWER MODULE), 286L (LIGHTING MODULE)	4
11	ZDU 2.5/4AN BL	290N (CONTROL POWER MODULE), 286N (LIGHTING MODULE)	4

12	ZPE 2.5/4AN (GREEN)	PE1 (CONTROL POWER MODULE), PE (LIGHTING MODULE)	4
13	DIN rail	N/A	1
14	Wire Set	KM796121G12106, KM51042524G14, KM51062820G10135	3
15	Labels	N/A	21

3.3 Manual Assembly Process

Currently, according to [21], the assembly tasks are being carried out by the human workers. The quality control at this stage (assembly line) is carried out by visual inspection i.e. using naked eye. Moreover, there is one human worker per workstation for assembly task. The assembly steps are given below:

1. Clamping the DIN rail onto the assembly table.
2. One by one placing the components onto the DIN rail in the order given in Figure 9. The order of assembly could be either way from left to right and vice versa.
3. Making electrical connections by utilizing the provided set of wires and jumpers. At this stage, designated screw drivers are used for securing the wires into the terminals.
4. Placing the respective labels on the DIN rail assembled components.
5. The switch module assembly is now complete.

This module can now be forwarded to the next work station or retained at the same work station for integration with other modules such as control power module, lighting module etc. The assembly cycle time for the switch module, shown in Figure 11, is around 11.5min. However, it only takes 3.5 - 4 min to complete the assembly of other individual modules (control power module, lighting module, etc.) of the controller box. Thus, it can be said that the sub assembly of the switch module is the bottleneck in the assembly process of controller box and has the highest cycle time of 11.5mins. [20]

Next the Takt time is evaluated according to different customer demands. Takt time determines the required speed with which an assembly task must be carried out to keep up with the customer demand. It is the ratio of total available production time to the average customer demand. [20]

Takt Time is given by:

$$Takt\ Time = \frac{Total\ Available\ Production\ Time}{Average\ Customer\ Demand} \rightarrow (2)$$

The available production time per day and three different customer demands, as presented in [20], are given next in Table 4:

Table 4. *Input values for the calculation of Takt times.*

S/No.	Variable	Value	Explanation
1	Total Available Production Time	7.5 Hours/Day	Day Shift
2	Demand$_{\text{Customer1}}$	30 Units/Day	Current Demand
3	Demand$_{\text{Customer2}}$	113 Units/Day	Future Demand
4	Demand$_{\text{Customer3}}$	210 Units/Day	Unusual Spike in Demand

Therefore, the calculated Takt times are given next in Table 5:

Table 5. *Calculated Takt times for different customer demands.*

S/No.	Variable	Value
1	Takt Time$_{\text{Customer1}}$	15 min
2	Takt Time$_{\text{Customer2}}$	3.98 or 4 min
3	Takt Time$_{\text{Customer3}}$	2.14 min

The current setup with the available no. of resources is capable of coping with the current Takt time; since the highest cycle time is 11.5 min. However, to keep up with the future and unusual spikes in customer demands, more human workers are needed. The future demand for the human workers is discussed next.

For the future demand, having a calculated Takt time of 4mins, the highest cycle time is taken to be 3mins. To achieve this timing, 4 more assembly workers must be added to the existing assembly section and it is calculated next.

$$1\ assembly\ worker = 11.5\ min$$
$$No.\ of\ assemlby\ workers = \frac{11.5min}{3min} = 3.83\ or\ 4$$
$$\therefore 4\ assembly\ workers \approx a\ cycle\ time\ of\ 3\ min\ for\ switch\ module$$

Similarly, for the case of unexpected spike in demand, having a Takt time of 2.14 min, the cycle time was taken to be 1.83 min. This can be achieved by adding 7 workers to the existing assembly section of the factory floor. The calculations are given next:

$$1\ assembly\ worker = 11.5\ min$$
$$No.\ of\ assembly\ workers = \frac{11.5min}{1.83min} = 6.28\ or\ 7$$
$$\therefore 7\ assembly\ workers \approx a\ cycle\ time\ of\ 1.83\ min\ for\ switch\ module$$

Finally, it can be stated that 7 human workers are needed to cope with the highest mentioned demand of 210 Units/Day. Moreover, a low Takt, and hence, a low cycle time suggests the assembly process to be non-ergonomic. The reason here is that the assembly task has become repetitive and spans over a very short time period; in comparison to the assembly process where the demand was merely 30 Units/Day. [20]

3.4 Human Robot Collaborative Assembly Process

For the customer demand of 113 Units/Day, the Takt time was calculated to be 4 min. And to achieve this, 4 more assembly workers need to be added to the assembly floor. Alternatively, the same result can be achieved by the addition of 2 human workers alongside 2 collaborative robots. Moreover, if there is an unusual spike in the customer demand i.e. 210 Units/Day then it could be managed by doubling the resources required to meet the demand of 113 Units/Day. This is calculated next:

$$113\,\frac{Units}{Day} \times 2 = 226\,\frac{Units}{Day}$$

Therefore, as per the initial analysis, the collaborative setup has the potential of reaching 226 Units/Day. However, the main idea here is to shift the non-ergonomic tasks from the human worker to the COBOT. Additionally, the COBOT setup also offers flexibility in terms of operational deployment. For instance, the COBOT, when needed, can easily be shifted from the sheet cutting area of the factory to the assembly area of the factory; in order to assist the human worker in meeting the customer demand. In case of a temporary demand, it is considered rather convenient and quick to deploy a COBOT than to hire a new assembly worker for a short period of time. [20]

Figure 12. *Simulated human robot collaborative assembly process. [20]*

Figure 12 shows the simulated scenario where the human worker performs the assembly task in collaboration with the collaborative robot. The task distribution among the human worker and the robot is given next in Table 6. During the execution of task no.1, the robot picks the DIN rail from the feeder and places it on the assembly table. The human worker secures the DIN rail with the help of a toggle clamp. After this, during the execution of task no.2, the robot picks the electrical components from the feeders. During the execution of task no.3, the robot assembles the components, picked up during the previous stage, on to the DIN rail. However, some components, which are inherently difficult to be grasped by the COBOT, are assembled by the human worker (These are numbered 10-12 in Table 3). Task no.4 is carried out by the human worker as it requires cognitive and precise grasping capabilities; which are inherently difficult to be provided by the current COBOT setup. To secure the electrical connections, the human worker houses the wire set into their respective terminals with one hand. Additionally, the human worker also guides the manipulator (COBOT), which holds the designated screwdriver, to the respective screws on the components. Hence, it can be stated that task no.5 is done collaboratively by human and the robot. The task no.6 (like task no. 4) requires precise grasping capabilities which cannot be provided by the current COBOT setup, therefore, the labels are placed by the human worker. [20]

Table 6. *Gives the assignment of assembly process tasks (for the simulated scenario) among the human worker and the robot. [20]*
Table Key: 'X' sets the task assignment.

S/No.	Task	Human	Robot
1	Securing the DIN rail on to the assembly table.	X	X
2	Picking up of DIN rail assembly components from the feeders.		X
3	Assembly of the components onto the DIN rail.	X	X
4	Guide and insert the wires into the respective components at correct positions	X	
5	Fastening the assembled components' screws to secure the electrical connections in the respective terminals.	X	X
6	Place labels on the assembled components	X	

The task assignments are based on some key factors which are: ability to grasp, repeatability, reliability and cognitive capability of the asset. However, some task assignments are done based on the feedback from the assembly workers. For instance, during the execution of task no. 5 (Presented in Table 6), manipulator's gripper system holds the designated screwdriver (Usually industrial electric screwdriver). This is done to avoid the wrist injuries/sprains reported by the assembly workers. Such cases arise due to the repetitive exposure of human wrist to the mechanical vibrations produced by the screwdriver during the assembly process. The robot during this stage is set in complaint mode (discussed in detail in the later chapters of the thesis). This helps the operator in guiding and positioning of the screwdriver. The positioning is done in line with the specific screw (to be fastened) of the respective electrical component. Moreover, once the fastening operation starts, the unwanted vibrational energy generated by the screwdriver is effectively dissipated via virtual damper implemented as part of the complaint behavior of the manipulator. [20]

Table 7. *Comparison of collaborative robot setups. [20]*

S/No.	**Organization**	**COBOT**	**Reach**	**Payload**	**Autonomous Mobile Unit**	**Gripper**
1	KONE Corp.	KUKA LBR iiwa 14 R820	820mm	14kg	KUKA flex-FELLOW H750 extended	Robotiq's Adaptive 2 finger gripper
2	TTY Foundation.	KUKA LBR iiwa 7 R800	800mm	7kg	KUKA flex-FELLOW H750 extended	SCHUNK EGP 50 Gripper (2 finger gripper for small parts)

Table 7 gives the comparison between the COBOT setups. KONE Corporation's setup has more reach and can take more load. This enables it to be deployed elsewhere in the factory where it is needed. And it can effectively have more than one tool attached at the end of the robotic arm. Since both the setups are similar, and to promote Industry-Academia collaboration, the simulated scenario along with the items given in Table 3 were provided to the 'Mechanical Engineering and Industrial Systems Laboratory' of Tampere University of Technology (also referred to as TTY Foundation.). It was done to explore the simulated results in a practical environment. Additionally, it was encouraged to design the assembly process with the idea of human worker having gone through the operator's training and having no skills in programming related knowledge areas. Therefore, the upcoming chapters discuss the design and commissioning of collaborative setup along with the productivity of the human robot collaborative assembly process.

4. SYSTEM DESIGN - COLLABORATIVE OPERATION

4.1 Layout Design

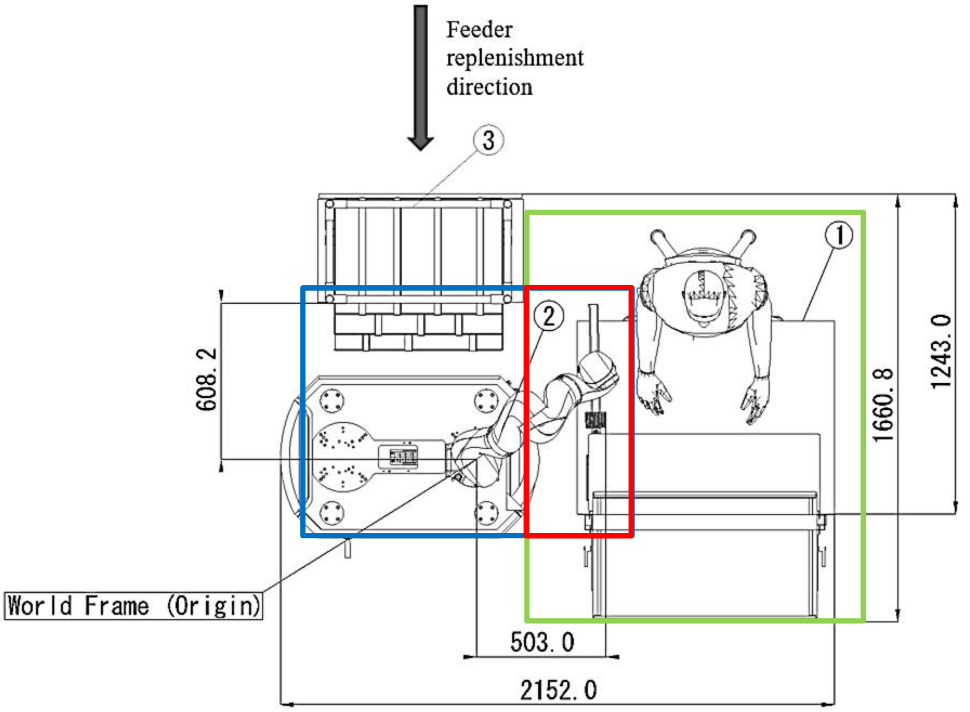
The system design starts with the layout planning of the collaborative workstation. During the layout planning phase, a 3D simulation software is used (Visual Components for the case under study). The whole assembly process is simulated to analyze the robot's reach, poses and movements (while picking the components up from the rack and followed by assembly on the DIN rail). Components' feeders are mounted on the rack (Labelled as 3 in Figure 13). There are two types of feeders in this collaborative setup and these are: gravity feeders and magazine type feeders.

The simulated scenario is shown in Figure 13. And the idea here is to have minimum possible idle time for the human worker and the robot. For instance, when the robot is picking and assembling the components from the feeders; the human prepares and then inserts the wires into the already fitted DIN rail components.

Figure 13. *Shows the simulated collaborative workstation.*

Figure 13 shows the collaborative workstation and this setup can be functionally divided into 3 parts. These are given next (as labelled in Figure 13 respectively):

1. Assembly table fitted with a toggle clamp to secure the DIN rail in a fixed position.
2. The COBOT setup – *'KUKA LBR IIWA 7 R800'* mounted on '*KUKA flexFELLOW H750 extended'*.
3. Component inventory rack with feeders.



Legend:
1.) Assembly table fitted with a toggle clamp to secure the din rail in a fixed position.
2.) COBOT setup.
3.) Rack with feeders.

Figure 14. *The top view of the collaborative workstation layout. Area enclosed in red boundary indicates the overlap region of human worker and COBOT's workspace (also known as collaborative workspace).
Area enclosed in green marks the human worker's workspace.
Area enclosed by blue is robot's workspace.
NOTE: All the dimensions are in millimeters.*

Figure 14 is used to identify robot's operational space and collaborative workspace. Collaborative workspace, as defined in [11], is the shared region between the human worker and the robot. During the assembly process, the human and the COBOT work simultaneously in cooperation within this workspace. To detect the presence of human in the collaborative workspace, COBOT's inherent position and joint torque sensors were considered in this design. No external sensors (e.g. laser scanners, cameras etc.) were considered while designing the layout plan.

4.2 High Level Architecture – IIoT Products

KUKA Sunrise Cabinet (Robot Controller) runs *KUKA Sunrise.OS 1.11*. Offline Robot Programme is built on *Sunrise.Workbench 1.11* which utilizes the *Java* programming language. The *Sunrise.Workbench 1.11* on the Windows PC and the *KUKA Sunrise.OS 1.11* synchronize the projects via Ethernet interface. A *Java* software project can also be installed (usually the workbench and controller projects are synchronized) on the controller by clearing the previous projects or by overwriting them.

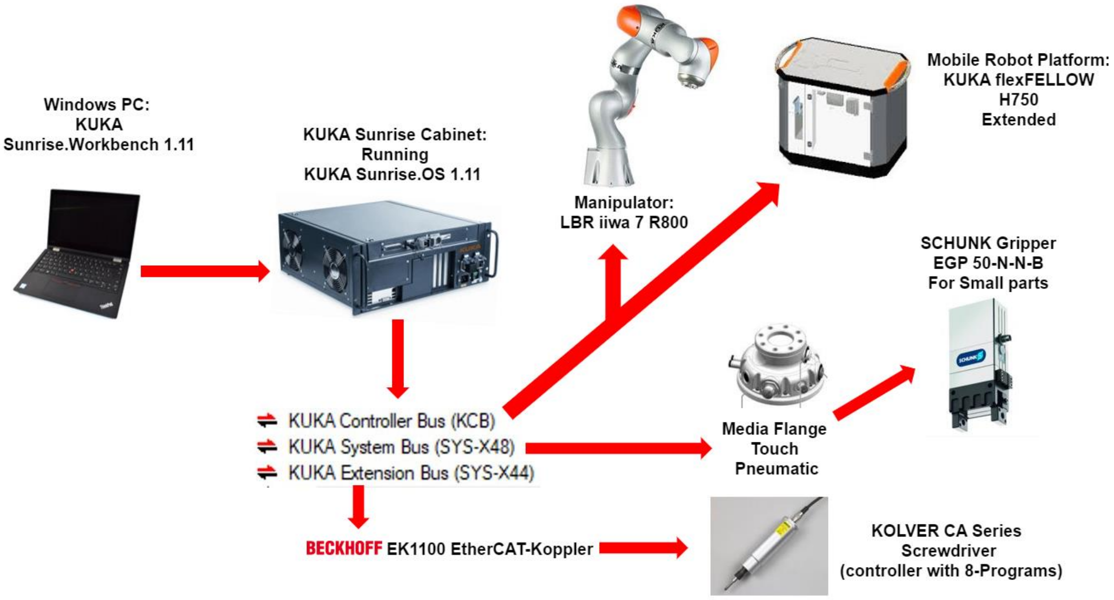


Figure 15. *Shows the High-level architecture of the system.*

The *KUKA Sunrise Cabinet* (Shown in Figure 15) has 3 field buses to ensure communication between the robot controller and the IIoT products. Each of them is explained next:

1. *KUKA Controller Bus* (KCB) connects the *Control PC* (KPC) to the power drive system of the manipulator and *KUKA flexFELLOW*. *Control PC* (KPC) runs the *KUKA Sunrise.OS 1.11.*
2. *KUKA System BUS* (SYS-X48) is used for communication with the gripper system via *Media Flange touch pneumatic.*
3. *KUKA Extension Bus* (SYS-X44) is used to select the programs from the controller of the screwdriver via *EK1100 EtherCAT-Koppler*. *EK1100* connects the EtherCAT with the EtherCAT Terminals (ELXXXX) e.g. EL2624 relay module is used to send input signals to the screwdriver's controller.

4.3 COBOT Setup

The COBOT Setup comprises of *KUKA LBR iiwa 7 R800* (Collaborative manipulator) mounted on *KUKA flexFELLOW H750 Extended* (Autonomous mobile unit). The mobile unit acts as a base for the manipulator and houses the control/accessory units of the attached IIoT products. The manipulator is a 7 degrees of freedom robot (Shown in Figure 16).

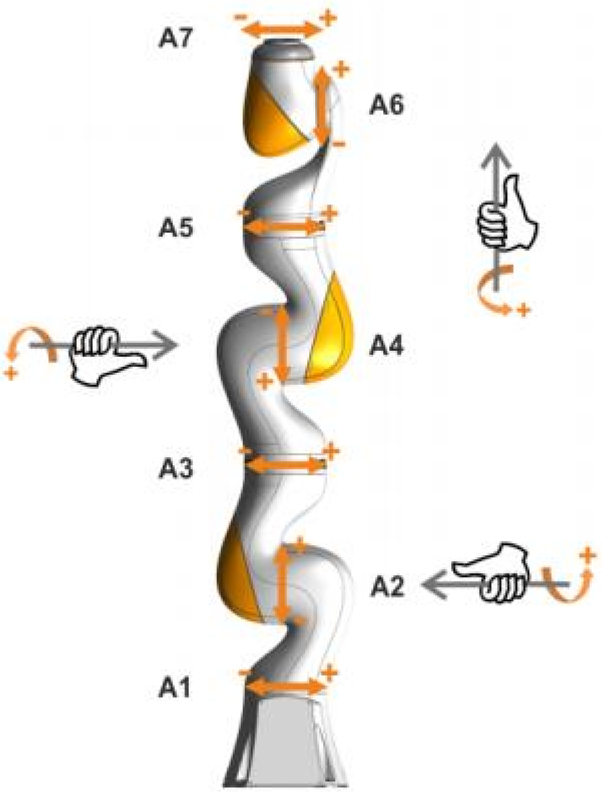


Figure 16. *Manipulator joints and their axis specific jogging. [2]*

The Offline Robot Programme, for the case under study, utilizes point to point (PTP) movements and linear (LIN) movements for the execution of assembly tasks. PTP movements are used for general orientation/positioning of the manipulator. However, linear movements are utilized where repeatability is required.

A point in space is presented by a frame in Offline Robot Programme. Frames are usually characterized by Task Space Coordinates (m) and redundancy information (presented in Table 8). Redundancy information, used for null space movements, is characterized by redundant coordinate angle *'r'* (Value: 0 - 1 Radians) and joint configuration values; these are based on logical assignments which are presented in [22].

Table 8. *Configuration and task space coordinates. [2]*

Coordinate System	**Value for KUKA LBR iiwa**
Task Space Coordinates *(m)*	*m=6*; 3D Cartesian Coordinates (x, y, z) and Euler Angles (a, b, c)
Joint Space coordinates *(n)*	*n=7*; seven joints – A1, A2, A3, A4, A5, A6, A7.
Redundant coordinates *(r=n-m)*	r=1; Used for *null space motions.* [22]

During the execution of null space movements, the end effector's position and orientation is constant in space (m is constant in space). The idea behind null space movements is based on the fact that a point in the Cartesian space can be reached with multiple joint configurations (different set of joint values). Thus, the redundancy information is used to avoid unambiguous joint configurations during the planning and execution of different robot motions. During null space movements, the value of 'r' depends on the freedom of the 3rd joint. [22]

4.3.1 Sensors and available control modes

The *KUKA iiwa LBR* series manipulators, inherently, have two types of joint sensors and these are:

1. Joint position sensors
2. Joint torque sensors

In an ordinary industrial robot, joint position sensors are, generally, available only. However, the controller implementations, are made possible due to the mentioned joint sensors. There are two types of controller implementations and these are:

1. Position controller
2. Cartesian impedance controller

Position controller makes sure that the current position always matches the set point on the commanded trajectory with minimal possible difference. Position controllers treat the external stimuli as disturbances and make sure that the set point is reached with minimum possible difference. Therefore, if there is any obstruction in the planned path then the robot tries to counter it by reacting towards it as a rigid structure. Apart from the damage to the robot's surrounding, excessive buildup of forces around or on the manipulator could ultimately damage it. Class *PositionControlMode* represents the position controller in *Java* Robot Offline Programme. If no control mode is specified in the Robot Offline Programme then this controller is utilized by default.

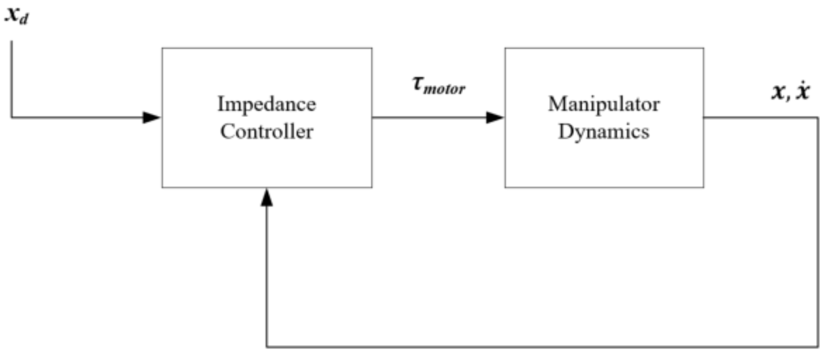


Figure 17. *Generic model of an impedance controller. Adapted from [23]*

Cartesian impedance controller enables active compliance (complaint model discussed next in detail) for the robot. It is realized by acting on the information delivered by inherent sensors of the robot. The robot becomes sensitive to external stimuli like obstacles and forces. The whole kinematic chain becomes less rigid and more sensitive. External forces in the robot's path can cause it to deviate from its planned path. Cartesian impedance controller can be utilized through the class *CartesianImpedanceControlMode* in Robot Offline Programme. Figure 17 gives the concept of impedance controller. Whereas, the description of variables used in Figure 17 are given next:

$\boldsymbol{x_d}$: $Point\ along\ the\ commanded\ trajectory\ in\ space.$
$\boldsymbol{x}$: $Current\ position\ (TCP\ for\ our\ case)$
$\boldsymbol{\tau_{motor}}$: $Motor\ torque\ as\ output$

According to [24], a compliant mechanism is defined as, *"Mechanical systems which use their structural elastic deflection as a function."* In manipulators, active compliance is achieved by introducing a virtual spring-mass-damper system (Shown in Figure 18) in-between the end effector (TCP) of the manipulator and the commanded trajectory. The equation for the second order damped harmonic oscillator (spring-mass-damper system), as mentioned in [23], is given next:

$$\boldsymbol{M_s} \cdot (\ddot{\boldsymbol{x}}_{\boldsymbol{d}} - \ddot{\boldsymbol{x}}) + \boldsymbol{B_s} \cdot (\dot{\boldsymbol{x}}_{\boldsymbol{d}} - \dot{\boldsymbol{x}}) + \boldsymbol{K_s} \cdot (\boldsymbol{x_d} - \boldsymbol{x}) = \boldsymbol{F_{external}} \rightarrow (3)$$

Where,

$\boldsymbol{M_s}$: $Mass\ matrix\ of\ the\ system.$
$\boldsymbol{B_s}$: $Damping\ Matrix\ of\ the\ system.$
$\boldsymbol{K_s}$: $Stiffness\ Matrix\ of\ the\ system.$
$\boldsymbol{F_{external}}$: $Net\ external\ force\ matrix$

The values of $\boldsymbol{K_s}$ and $\boldsymbol{B_s}$ can be assigned in the Robot Offline Programme. Whereas, the mass matrix is determined, inherently, by the *KUKA Sunrise.OS 1.11's* robotic applications package - *'com.kuka.roboticsAPI'.* It is based on end effector's load information and manipulator's inertial parameters.

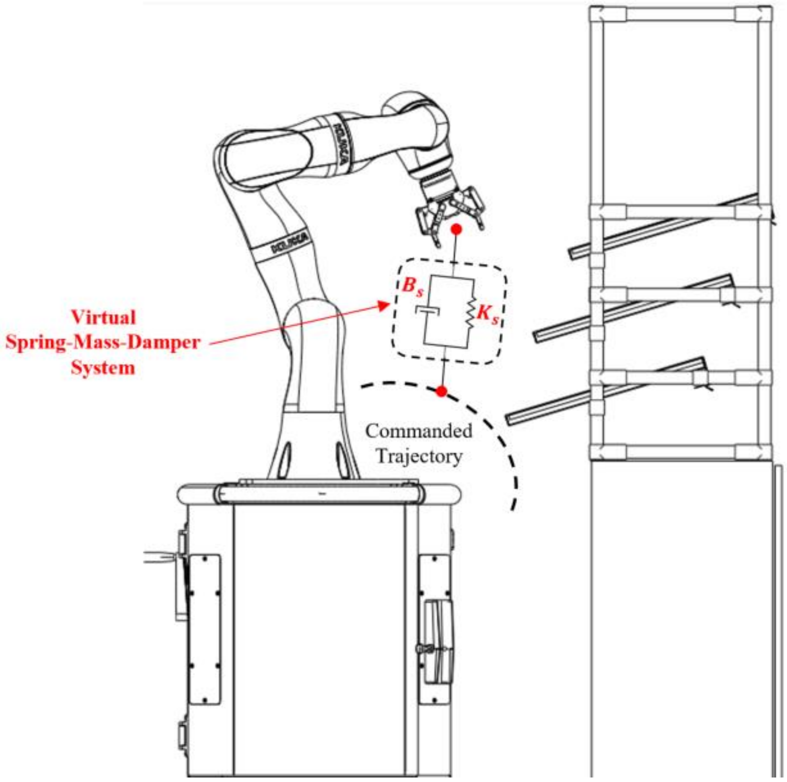


Figure 18. *Implementation of compliant behavior with Cartesian Impedance Control Mode.*

4.4 Risk Assessment

In order to commission the collaborative workstation, risk assessment was performed to identify and mitigate hazards. For collaborative operations, the clauses 5.10.5, 5.11.5.5 and 5.5.5 of [9] (ISO 10218-1), [1] (ISO 10218-2) and [11] (ISO/TS 15066) respectively were considered. Moreover, the current system design was limited to the use of inherent sensors of the COBOT setup. Therefore, the identified risks could be mitigated by limiting the static and dynamic forces delivered by the manipulator to its surrounding (human worker and the rest of the workstation). The inherent output devices of the COBOT setup could also be used to alert the assembly worker. Risk assessment was carried out, according to [25] (ISO12100), in the order given next:

1. Identification of the use cases.
2. Hazard identification.
3. Risk level estimation.
4. Risk mitigation.

Moreover, for detailed study the risk assessment worksheets, for the case under study, are given in 'APPENDIX A'.

4.4.1 Identification of the use cases

The first step involves identification of the use cases, their respective actors and frequency. A total of 7 use cases were identified and these are given next:

1. Commissioning and robot offline programming
2. Assembly Operation – Automatic mode
3. Human Intervention in Robot only operating zone
4. Foreseeable malpractices in the assembly process
5. Maintenance/Service of collaborative workstation
6. Cleaning/Housekeeping
7. Decommissioning

The first use case involves commissioning of the robot and its offline programming. It is carried out by a certified robot commissioning engineer. This is done during the planning phase of the assembly process and the activity is carried out quite rarely; unless, a major change in the assembly process has to carried out. For instance, mapping of additional IIoT products (additional sensors or grippers) in the Robot Offline Programme.

The second use case involves the assembly operation. The robot's operation mode is set to Automatic mode (AUT) in this case. As this is a value adding activity, therefore, it is frequent and time consuming as compared to the other mentioned cases. Moreover, the human assembly worker and the robot have a constant and frequent interaction as well; since, they share the collaborative workspace (Area marked by red outline in Figure 14) during this phase.

The third use case involves human intervention in the robot only workspace (Area marked by blue outline in Figure 14). This case includes the human assembly worker; who has, typically, gone through the operator's training. However, the risky situation arises, if a feeding problem is detected. And the detected problem needs immediate correction in order to resume the normal assembly operation.

The fourth use case involves assembly process malpractices. This particular case focuses on the presence of a non-authorized personal within the premises of collaborative workstation. It could be anyone e.g. a visitor to the assembly area or a co-worker. The frequency of occurrence for this event is unknown prior to the commissioning of the collaborative workstation. Since, the risk assessment is done, beforehand, during the planning stage.

The fifth use case involves the maintenance/service of the collaborative workstation. It is usually carried out by a trained technician/engineer. Maintenance/service activities are considered rare as these are usually carried out once a year.

The sixth use case involves housekeeping of the Collaborative workstation. It is carried out, on a daily basis by the human assembly worker, at the end of the work shift.

The last use case is about decommissioning of the collaborative workstation. It is carried out to ship the workstation. Or it could be done in order to dispose the workstation. It is considered to be a rare event as compared to the other mentioned use case activities.

4.4.2 Hazard identification

The second stage involves identification of hazards related to the previously mentioned use cases. 4 types of hazards were identified for the use cases and these are given next:

1. Entering Robot's Workspace
2. Transient Contact
3. Quasi-Static Contact
4. Damage to the workstation (All 3 functional zones)

4.4.3 Risk level estimation

For the evaluation of risks involved in the already mentioned use cases, hazard rating number system was utilized. Table 9 gives the estimated risk levels.

It is observed that use case no. 2 and 4 have a higher risk level as compared to the rest of the use cases. During collaborative assembly the human assembly worker and the robot share the workspace all the time. They interact constantly during the whole assembly process. Therefore, the risk is considerable.

Moreover, for use case no.4, the risk is also considerable. The reason for this is based on the assumption that the non-authorized person (or persons) entering the collaborative workstation has not received any training or orientation for the collaborative work cell. Therefore, such an act could expose the work cell and its surrounding to unforeseeable hazards.

Table 9. *Risk level estimation results*

S/No.	Use Case	Risk Level
1	Commissioning and robot offline programming	Very Low Risk
2	Assembly Operation – Automatic mode	Considerable Risk
3	Human Intervention in Robot only operating zone	Very Low Risk
4	Foreseeable malpractices in assembly process	Considerable Risk
5	Maintenance/Service of collaborative workstation	Meaningless risk
6	Cleaning/Housekeeping	Meaningless risk
7	Decommissioning	Meaningless risk

For the use cases no. 1 and 3 the risk is determined to be very low. The reason for it is based on the assumption that the use case actors i.e. commissioning engineer and the assembly worker will have gone through necessary work cell trainings and orientation sessions.

For the use case no.1 the frequency of occurrence is low. However, in case of a collision between the manipulator and its surroundings, the damage could be considerable. The reason for this is that the safety features of the robot might not be well established during the different stages of robot commissioning process.

For the use case no. 3, the human assembly worker enters the robot workspace if there is an issue with the feeders. And it is assumed to be rare. However, in case of a contact with the robot, the injury is assumed to be minor at maximum.

For the use cases no. 5 to 7, the risk is estimated to be meaningless. The reason behind it is that the robot during these cases is assumed to not be in the automatic operation mode. For maintenance tasks, it is assumed to be operating in KRF mode (recovery mode). This is the case when the robot has encountered an unwanted situation and needs to be retracted for service/maintenance. For the case of house keeping it is assumed that no robot application is running, and the joint brakes are active. Similarly, for decommissioning the robot it is assumed to be set in Transport position while utilizing T1 or T2 operating mode (operation modes with controlled speeds). Dead man's switch is available during these operating modes.

4.4.4 Risk mitigation

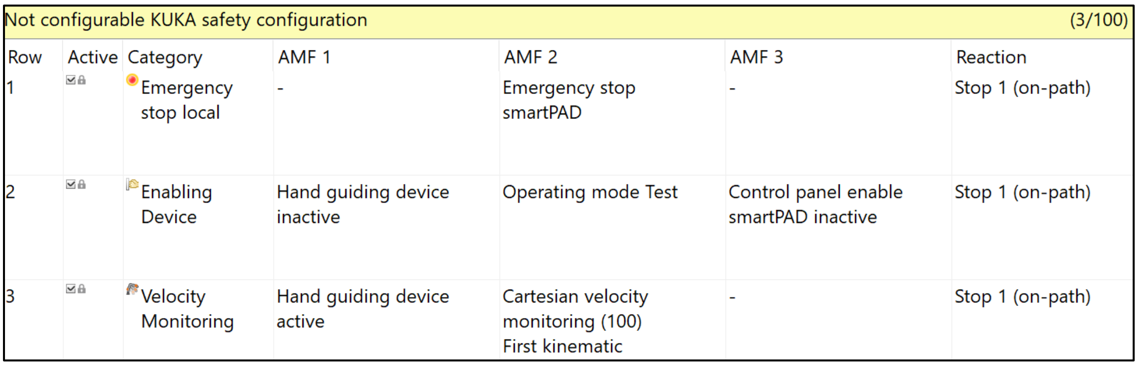
This phase marks the end of the risk assessment process. All the use cases are evaluated to mitigate the identified risks. Table 10 gives the risk mitigation strategies. To sum up the results presented in Table 10, it can be stated that the risks can be effectively mitigated by controlling the speed of the manipulator and using active compliance. Thus, limiting the dynamic and static forces delivered by it in case of a contact with its environment.

Table 10. *Risk mitigation strategies*

S/No.	Use Case	Risk Level	Risk Mitigation Strategy
1	Commissioning and robot offline programming	Very Low Risk	By always using modes with controlled speeds (e.g. T1 mode during Robot Offline Programming and frame teaching operations)
2	Assembly Operation – Automatic mode	Considerable Risk	By limiting Power and Force (using active compliance). By having controlled speed of the manipulator. Alerting the operator when the robot is in collaborative workspace e.g. Use of flex Fellow's Buzzer System to alert the operator.

3	Human Intervention in Robot only operating zone	Very Low Risk	By having controlled speed of the manipulator. By limiting power and force (using active compliance etc.). Switching from automatic operation mode to T1 or T2 operating modes in order to correct the problem. The dead man's switch is active during these operating modes.
4	Foreseeable malpractices in assembly process	Considerable Risk	By limiting power and force (using active compliance). By having controlled speed of the manipulator. By having markings and signs to alert the people around the work cell.
5	Maintenance/Service of collaborative workstation	Meaningless risk	Taking standard measures as presented in [2]
6	Cleaning/Housekeeping	Meaningless risk	Taking standard measures as presented in [2]
7	Decommissioning	Meaningless risk	Taking standard measures as presented in [2]

The COBOT setup offers different ways to implement safety measures and these are given in the following text.

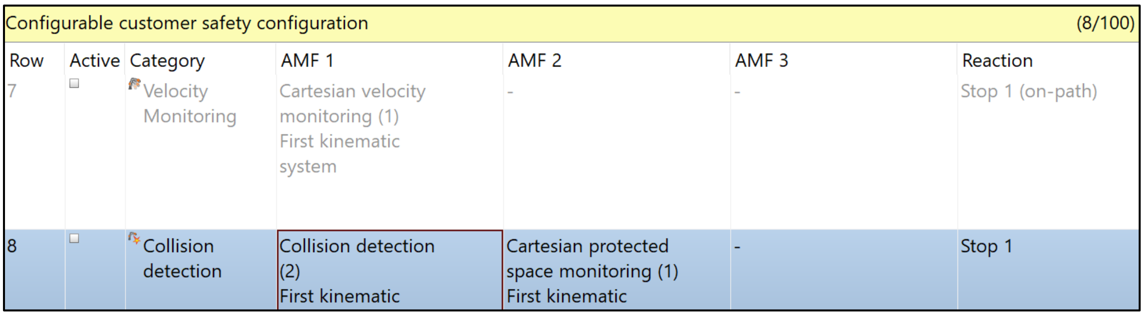


Not configurable KUKA safety configuration (3/100)

Row	Active	Category	AMF 1	AMF 2	AMF 3	Reaction
1	☑🔒	Emergency stop local	-	Emergency stop smartPAD	-	Stop 1 (on-path)
2	☑🔒	Enabling Device	Hand guiding device inactive	Operating mode Test	Control panel enable smartPAD inactive	Stop 1 (on-path)
3	☑🔒	Velocity Monitoring	Hand guiding device active	Cartesian velocity monitoring (100) First kinematic	-	Stop 1 (on-path)

Figure 19. *Non-configurable KUKA safety Configuration.*

Figure 19 gives the non-configurable *KUKA* safety configuration. This assignment is inherent. It cannot be changed but only complimented by user defined safety measures. This could either be done in the script of the Robot Offline Programme directly (Program 1 given next) or by using inherent *KUKA* configurable customer safety configuration (Shown in Figure 20).



Configurable customer safety configuration						(8/100)
Row	Active	Category	AMF 1	AMF 2	AMF 3	Reaction
7	☐	Velocity Monitoring	Cartesian velocity monitoring (1) First kinematic system	-	-	Stop 1 (on-path)
8	☐	Collision detection	Collision detection (2) First kinematic	Cartesian protected space monitoring (1) First kinematic	-	Stop 1

Figure 20. *Configurable KUKA customer safety configuration.*

Both of these configurations are based on same methodologies. Each row correlates to 3 AMF columns. Based on these AMFs a reaction (Stop, lowering the speed etc.) is generated. For instance, row no.3 corresponds to velocity monitoring. Safety measures related to velocity monitoring are determined first by checking AMF1 i.e. whether the hand guiding device is active or not (every AMF has a separate criterion to ensure safe operation). If the set safety criterion is not met, then a reaction is generated right away. If not, then it checks the AMF2 i.e. Cartesian velocity monitoring of the first kinematic chain (has different safety criterion than AMF1). If the set safety criterion is not met, then a reaction is generated right away. Otherwise, it checks the next column which is AMF3. Here, the AMF is not assigned (these are ignored inherently), therefore, it resumes the normal robot operation. Hence, it can be stated that every category is checked against an AMF in a successive order. A reaction, to ensure safety, is generated right away if any of these AMFs is violated against its respective set criterion.

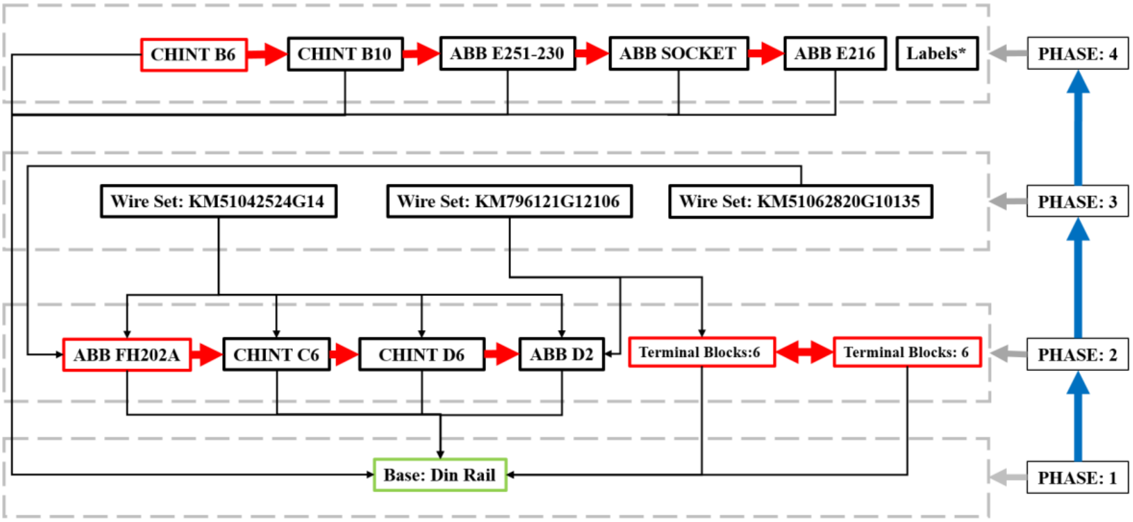
```
CartesianImpedanceControlMode comp_Mode = new CartesianImpedanceCon-
trolMode(); // Instantiating the class to specify the control mode

comp_Mode.parametrize(CartDOF.Z).setStiffness(800); /* To set stiff-
ness values for z-axis of the TCP */

comp_Mode.parametrize(CartDOF.Y).setStiffness(800); /* To set stiff-
ness values for y - axis of the TCP */

comp_Mode.parametrize(CartDOF.X).setStiffness(800); /* To set stiff-
ness values for x - axis of the TCP */

gripper_1.move(Lin(frame_Pick).setCartVelocity(100).setMode(
comp_Mode)); /* For moving the end effector (gripper_1) linearly in
compliant mode with maximum Cartesian velocity of 100 mm/sec */
```

Program 1. *Cartesian impedance control mode for compliant behavior*

5. APPLICATION - HUMAN ROBOT COLLABORATIVE ASSEMBLY

5.1 Assembly Stage Decomposition Model

The assembly stage model, shown in Figure 21, gives a brief overview regarding the assembly sequence. And it gives a bottom-up directional approach for the assembly process of the product given in Figure 11.

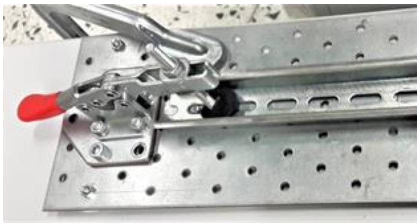


* *To be placed on all the assembled components*

Figure 21. *The assembly stage decomposition model. Based on [16].*
Note: Black arrows represent the direct connection between parts. Whereas, red arrows point (originate from the items outlined in red) towards the next assembly item in the sequence.

Phase 1 starts with picking up the DIN rail from the inventory and securing it onto the assembly table with the help of a toggle clamp (presented in Table 11).

Table 11. *Phase 1 of the assembly stage decomposition model.*

S/No.	Type	Component Details	Quantity	Pictorial Description
1	DIN rail	N/A	1	

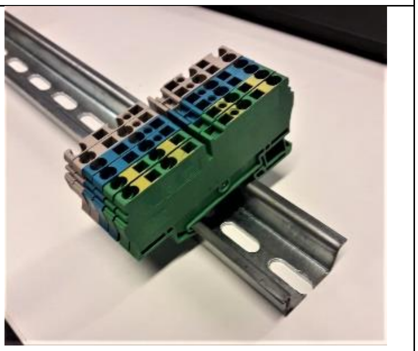
During phase two, there are a total of 16 electrical components that need to be assembled on top of the base i.e. DIN rail. These are divided into two types of groups; based on structural and functional similarities. These are categorized as followed:

1. Terminal Blocks
2. Circuit Breakers/Switches/Sockets

During phase two of assembly, the terminal blocks are fitted near the opposite ends of the rail with same configuration (mirrored assembly). Hence, if the order (given in Table 12) is correct, the assembly of terminal blocks does not depend on which side of the rail is chosen first. This makes enough space for the rest of the circuit breakers/switches to be assembled on the rail.

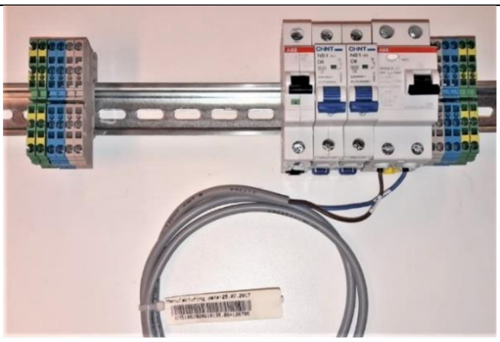
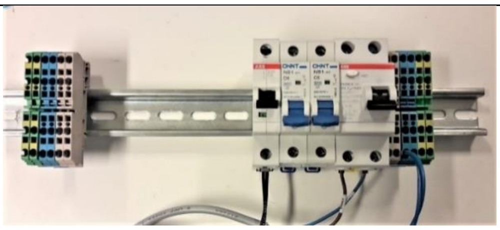
However, for the case of circuit breakers/switches, the assembly starts with the component outlined in red. And the sequence follows the red arrows till the end; up to the last component in the sequence (as shown in Figure 21).

Table 12. *Phase 2 of the assembly stage decomposition model.*

S/No.	Type	Component Details	Quantity	Pictorial Description
1	Terminal Blocks	2 × ZDU 2.5/4AN (GREY); 2 × ZDU 2.5/4AN BL; 2 × ZPE 2.5/4AN (GREEN);	6	
2	Terminal Blocks	2 × ZDU 2.5/4AN (GREY); 2 × ZDU 2.5/4AN BL; 2 × ZPE 2.5/4AN (GREEN);	6	
3	Circuit Breakers and switches	ABB FH202 A; CHINT C6; CHINT D6; ABB D2;	4	

Phase 3 involves attaching 3 types of wire sets to the already assembled components. The wire endings are secured in the terminals with the help of an electric screwdriver. The process is given in Table 13.

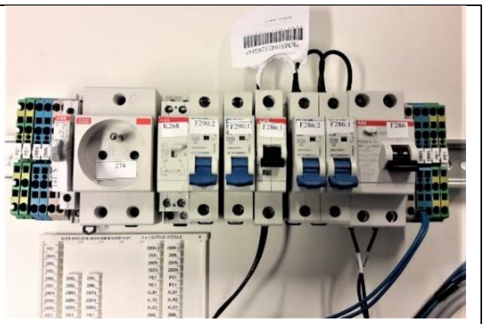
Table 13. *Phase 3 of the assembly stage decomposition model.*

S/No.	**Type**	**Component Details**	**Quantity**	**Pictorial Description**
1	Wire Set	KM51062820G10135	1	
2	Wire Set	KM796121G12106	1	
3	Wire Set	KM51042524G14	1	

Phase 4, given in Table 14, starts with the assembly of switches/circuit breakers/sockets and ends with the placement of labels on the already assembled components. This phase marks the end of the assembly process.

Table 14. *Phase 4 of the assembly stage decomposition model.*

S/No.	**Type**	**Component Details**	**Quantity**	**Pictorial Description**
1	Circuit Breakers and switches	CHINT B6; CHINT B10; ABB E251-230; ABB Socket; ABB E216;	5	

2	Labels	On all the assembled electrical components according to their respective electrical drawings.	21	

5.2 Product Design Analysis – DFA Methodology

Design for assembly methodology was used to analyze the design of the product (shown in Figure 11). Assembly process plan and different task assignments, between human and the robot, are based on the findings of this analysis. DFA methodology and its tools, mentioned earlier in the text, are used to determine the following in the product under study.

1. The joining methods.
2. Necessary parts.
3. Assembly directions.
4. Available assembly stage customizations.
5. Quantifiable features of the product assembly.

5.2.1 Joining Methods

Joining methods of the assembly items were identified during the DFA analysis of the product under investigation. And these are given next in Table 15.

Table 15. *Details of Joining methods*

S/No.	Assembly item	Joining Method
1	DIN rail	N/A (Base - clamped via toggle clamp)
2	Terminal Blocks	Snap fit
3	Switches/Sockets/Circuit breakers	Snap fit
4	Wire Set	Screw terminal connection (Switches/Sockets/Circuit breakers)
		Spring Terminal connection. (Terminal blocks)
5	Labels	Adhesive Joining technique
		Snap fit

DIN rail is secured onto the assembly table with the help of the toggle clamp. All the terminal blocks are snap fitted onto the DIN rail. Similarly, all the switches/sockets/circuit breakers are also snap fitted onto the DIN rail. Wiring of terminal blocks utilizes spring terminal connections. Whereas, the wiring of switches/sockets/circuit breakers utilizes screw terminal connections. Labels are attached on switches/sockets/circuit breakers via adhesive joining technique. However, for the case of Terminal block labels, special snap fitting labels are provided by the manufacturer (Weidmüller Interface GmbH & Co. KG for the case under study).

5.2.2 Necessary parts

For the case under study, the minimum necessary number of parts were identified on the basis of two factors:

1. Completion of electric circuit.
2. Structural integrity.

Except for the labels, it was analyzed that all the other mentioned parts (DIN rail, switches and the terminal blocks) bear equal importance; due to structural and functional properties of the product. Exclusion of any of these parts leads to an open circuit or an overall dis-integration of the product.

5.2.3 Assembly Directions

Table 16 gives an overview of the angle of symmetry along with individual alpha and beta angles for assembly items. These values were utilized during the planning of the assembly sequence and also during Robot Offline Programme.

Table 16. *Angle of symmetry of the assembly items*

S/No.	**Assembly item**	**α Alpha angle (Degrees)**	**β Beta angle (Degrees)**	**α+β Angle of symmetry (Degrees)**
1	DIN rail	180	360	540
2	Terminal Blocks	360	360	720
3	Switch/Socket/Circuit breaker	360	360	720
4	Wire Set	360	0	360
5	Labels	360	360	720

After careful analysis, it can be stated that out of all the mentioned items, only DIN rail has identical configuration; if it is rotated 180 degrees about the alpha axis. All the rest of the components need a 360 degrees rotation to have the same identical configuration. For the case of Beta angle rotations, only wire sets are independent of this rotation i.e. it has same configuration on all the rotations around beta axis. However, for the rest of the components, a 360 degrees rotation around the beta axis is required to achieve the same configuration.

5.2.4 Available assembly stage customizations

From Figure 21, it is examined that the following stages offer room for customizations with regards to division of tasks among the robot and the human assembly worker:

1. Phase 2
2. Phase 3
3. Phase 4

This is also evident from Table 11-14. During phase 2, for instance, the terminal blocks and the switches can be placed by the human worker and the robot simultaneously. During phase 3, the human worker could, similarly, house the wires into the terminals. While the robot holds the screwdriver in compliant mode for securing the wires. During the last stage, the robot could assemble the rest of the DIN rail components from the shelf; while the human prepares and puts the labels on all the already assembled components.

In case, there is any clearance between the assembled components then it can be removed by pushing them to either side of the DIN rail. It can be done by the robot in compliant mode. Otherwise, it can always be done by the human assembly worker. The same applies if the parts are not assembled well.

5.2.5 Quantifiable features of the product assembly

In order to mitigate the previously mentioned risks and to increase the human assembly worker's awareness, two-digit manual assembly codes were generated on the basis of conditional logic. Logical conditions were identified by analyzing assembly stage customization options and assembly stage decomposition diagram.

Table 17. *Conditional assignment of the first digit of the manual assembly code.*

S/No.	Condition	First Digit
1	The direction of approach is opposite to the Robot.	1
2	The direction of approach is opposite to the human assembly worker.	0

Table 17 and 18 give the key for the determination of manual assembly codes. For instance, in case of a wire set, where the direction of approach towards the DIN rail is opposite to the robot; the manual assembly code would be *'01'*.

Table 18. *Conditional assignment of the second digit of the manual assembly code.*

S/No.	Condition	Second Digit
1	Electrical Component / DIN rail / Label	1
2	Wire Set	0

5.3 Overview of the laboratory setup

The commissioned collaborative workstation is shown in Figure 22. It can be seen that the human assembly worker shares the workspace with the collaborative robot setup. The robot, here, is assembling the DIN rail components from the rack. Whereas, the human assembler prepares the wire sets to be secured in their respective terminals.

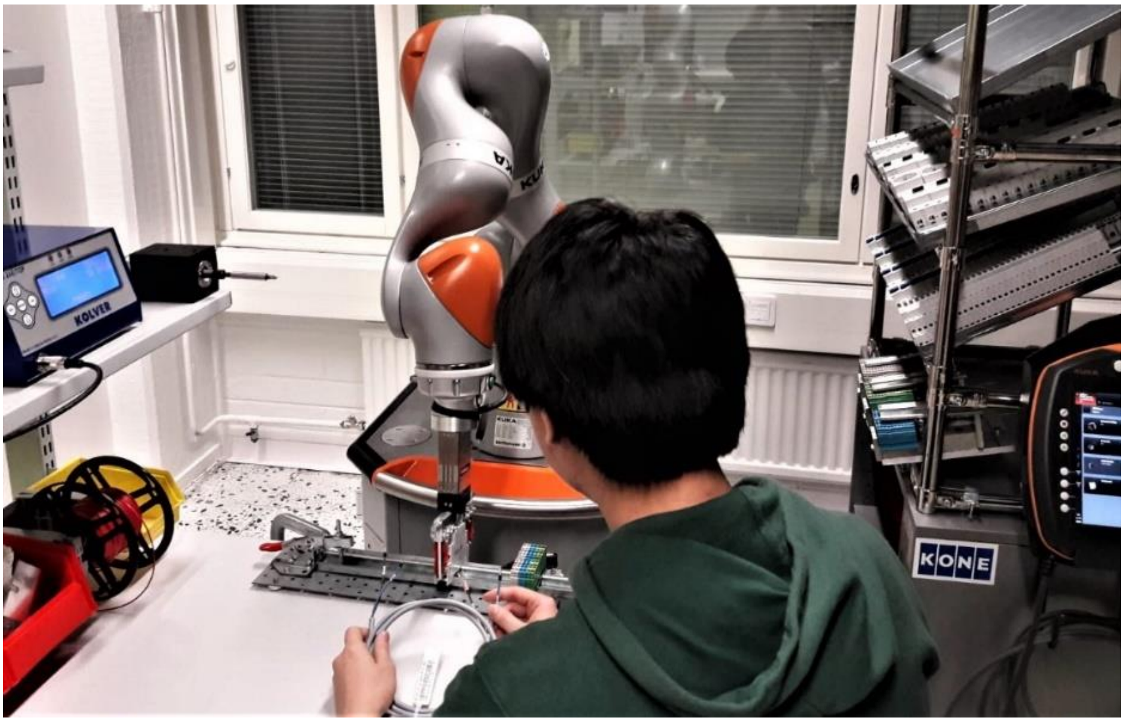


Figure 22. *The commissioned collaborative workstation.*

The end effector details are given in Table 19. The gripper fingers are covered with industrial grade cotton fabric to achieve the necessary grip.

Table 19. *Manipulator end effector details*

Item type	**Detail**	**Explanation**				
		Clearance between the gripper fingers (mm)			**Gripping Force (N)**	**Pictorial Description**
Gripper	Schunk EGP 50-N-N-B	**Fully Open**	**Fully Closed**	**Difference**		
		88.55	72.3	16.25	215	

The width (distance between the planes/ends where the grasping force acts normally) of all the Switches/Sockets/Circuit breakers is 85 mm. Similarly, for the terminal blocks it is 79.5mm.

Table 20. *Component feeder details*

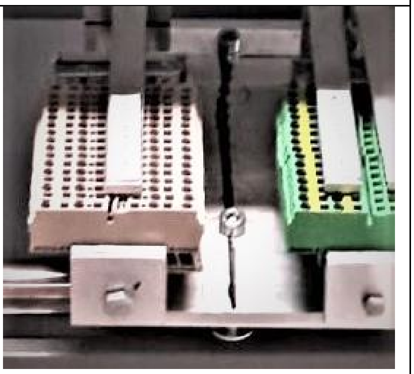
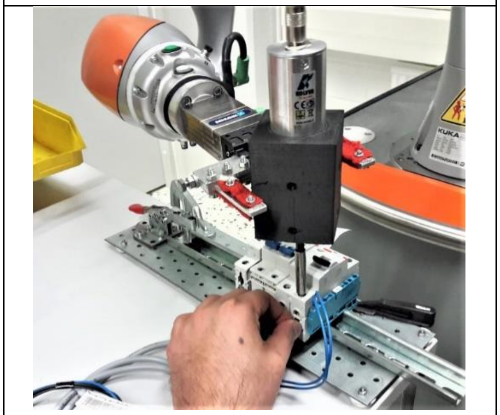
S/No.	Feeder Type	Detail	Pictorial Description
1	Gravity Type feeder	For Switch/Circuit Breakers/Sockets	
2	Magazine Type Feeder	For Terminal Blocks	

Table 20 gives the overview of inventory rack's feeders. Feeder no. 1 is a gravity type feeder. The components slide under the influence of gravity. The concept here is the same as a body sliding on an inclined plane under the influence of gravity. Therefore, the angle of inclination along with the static and dynamic frictions influence the feeding abilities of the setup. The magazine type feeders (feeder no.2) on the other hand works on the similar concept here; except for the difference that these are spring loaded mechanisms.

Table 21 gives the details regarding the industrial electric screw driver. It offers configurable programs which can be readily activated/deactivated via *KUKA Sunrise.OS*. Digital inputs and outputs were utilized after the terminals were properly mapped in the *KUKA Sunrise.OS (via KUKA.WorkVisual* software*).*

Table 21. *Industrial electric screwdriver details*

Item	Detail	Pictorial Description
Kolver EDU 2AE/TOP Electric screw driver	8 configurable programmes for fastening applications	 KR C I/Os KR C Variables PLC Fieldbusses Sunrise I/Os Sunrise I/O groups MediaFlange FlexFellow RobotiQ KolverScrewdriverInputs KolverScrewdriverOutputs
		

The aluminum cased screwdriver is housed in a 3D printed carbon fiber case. This ensures it to be grasped by the robot's gripper without damaging it. The screw driver programs offer a variety of configurable parameters e.g. Torque, Speed, number of allowed rejects etc. [26]

5.4 Collaborative Assembly Tests

A total of three tests were carried out to determine the collaborative assembly cycle times with the task assignments given in Table 22. Moreover, the DFA methodology-based worksheets for these tests are given in 'APPENDIX B' for detailed study.

Table 22. *Task assignment between Human and the Robot*

S/No.	Component	Phase	Task Assignment
1	DIN rail	1	Human
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	Human
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	Human
4	Terminal Block: ZDU 2.5/4AN BL	2	Human
5	Terminal Block: ZDU 2.5/4AN BL	2	Human
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	Human
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	Human
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	Human
9	Terminal Block: ZDU 2.5/4AN (Grey)	2	Human
10	Terminal Block: ZDU 2.5/4AN BL	2	Human

11	Terminal Block: ZDU 2.5/4AN BL	2	Human
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	Human
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	Human
14	ABB FH202 A	2	COBOT
15	CHINT C6	2	COBOT
16	CHINT D6	2	COBOT
17	ABB D2	2	COBOT
18	Wire Set: KM51062820G10135	3	Human + COBOT
19	Wire Set: KM796121G12106	3	Human + COBOT
20	Wire Set: KM51042524G14	3	Human + COBOT
21	CHINT B6	4	COBOT
22	CHINT B10	4	COBOT
23	ABB Socket	4	COBOT
24	ABB E251-230	4	COBOT
25	ABB E216	4	COBOT
26	Labels	4	Human

These task assignments are based on the product analysis. The analysis was based on the findings of assembly stage decomposition model and DFA analysis. Phase 1 is carried out by the human assembly worker. Terminal block assembly of Phase 2 is carried out by the human assembly worker alongside COBOT. COBOT here assembles the Switch/Socket/Circuit breakers in between the terminal blocks. Phase 3 is carried out together by the human and the COBOT. As mentioned earlier, the COBOT in compliant mode assists the human assembly worker in securing wire connections. During Phase 4, the COBOT assembles the rest of the electrical components; whereas, the human assembly worker puts the labels on the already assembled components. From the tests (given next) it is clear that the cycle times range from 3.0 – 4.0 min. Therefore, the demand of 113 Units/Day can be reached since the Takt time for it is 3.98 min; as presented in the case study. And to reach the highest mentioned demand of 210 Units/Day, the available resources can be doubled.

5.4.1 First Test

The Cartesian velocities of the TCP frame along with stiffness values, for complaint mode, have been given in Table 23.

Table 23. *Details of the collaborative assembly*

S/No.	Type	Value
1	Maximum Cartesian velocity of the TCP	225 mm/s
2	Cartesian Velocity of the TCP during Linear motions	50 mm/s
3	Stiffness Values of TCP’s Z - axis	1000 N/m

Maximum Cartesian velocity of the TCP was set in *KUKA Sunrise Workbench's* safety configuration by utilizing configurable customer safety configuration. Whereas, the Cartesian velocity of the TCP frame during linear motions, along with the stiffness values, were set in the script of Offline Robot Programme. Since the z-axis of the TCP frame is utilized by the end effector to approach or retract during the linear motions; therefore, it is set soft in this direction. The allowable values of stiffness (For x, y and z axis) range from 0 - 5000 N/m. By analyzing Program 2, it is clear that the linear end effector velocity is adjusted to 50 mm/s; by reducing the set speed to 50% of its actual designated value.

```
lbr_Iiwa.getApplicationControl().setApplicationOverride(0.5); /* Speed
reduced by 50% */

gripper_1.move(lin(Frame_orient).setCartVelocity(100));  /* For moving
the end effector (gripper_1) with maximum Cartesian velocity of 50
mm/sec */
```

Program 2. *Application override function to set the Cartesian velocity of the TCP*

Table 24 shows that the total assembly time is 3.88 min. This is the sum total of all the phase timings. Total phase timing is dependent on the bottlenecks. For instance, during phase 2, the COBOT has the higher cycle time; therefore, the total phase 2 time is taken to be that of the COBOT i.e. 81.8 s.

Table 24. *Human Robot Collaborative Assembly timings*

S/No.	Phase	Human	Robot	Total Phase Timings (s)	Total Assembly time (min)
		Time (s)			
1	1	5	N/A	5	3.88
2	2	60	81.8	81.8	
3	3	45		45	
4	4	60	101.2	101.2	

5.4.2 Second Test

Similarly, for the second test, the maximum TCP velocities were assigned along with the stiffness values. And these are given in Table 25.

Table 25. *Details of the collaborative assembly*

S/No.	Type	Value
1	Maximum Cartesian velocity of the TCP	225 mm/s
2	Cartesian Velocity of the TCP during Linear motions	112.5 mm/s
3	Stiffness Value of TCP's Z - axis	1000 N/m

From Table 26, it can be seen that by increasing the Cartesian speeds, during the linear motions, the total assembly cycle time has reduced to 3.598 min.

Table 26. *Human Robot Collaborative Assembly timings*

S/No.	Phase	Human	Robot	Total Phase Timings (s)	Total Assembly time (min)
		Time (s)			
1	1	5	N/A	5	3.598
2	2	60	74.91	74.91	
3	3	45		45	
4	4	60	90.96	90.96	

5.4.3 Third Test

For the third test, the linear velocity of the TCP was increased to 225 mm/s (shown in Table 27). The stiffness value of the TCP frame was, however, lowered to avoid any hazard. This reduces the delivered kinetic energy of the end effector. The idea here is to lower down the inertial properties of the manipulator (kinematic chain including end effector and its load) in case of increase in speed.

Table 27. *Details of the collaborative assembly*

S/No.	Type	Value in mm/s
1	Maximum Cartesian velocity of the TCP	225 mm/s
2	Cartesian Velocity of the TCP during Linear motions	225 mm/s
3	Stiffness Value of TCP’s Z - axis	800 N/m

From Table 28 it can be seen that by doing so the total assembly cycle time has been reduced to 3.332 min.

Table 28. *Human Robot Collaborative Assembly timings*

S/No.	Phase	Human	Robot	Total Phase Timings (s)	Total Assembly time (min)
		Time (s)			
1	1	5	N/A	5	3.332
2	2	60	69.6	69.6	
3	3	45		45	
4	4	60	80.33	80.33	

5.4.4 Operator oriented application design

During the development of this thesis, hand guided frame teaching methodology was utilized for the design of collaborative applications. This relieves the human assembly worker of having the need to be an expert in the programming related knowledge areas.

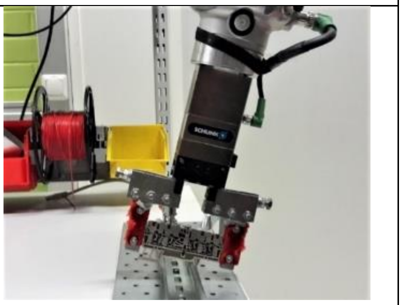
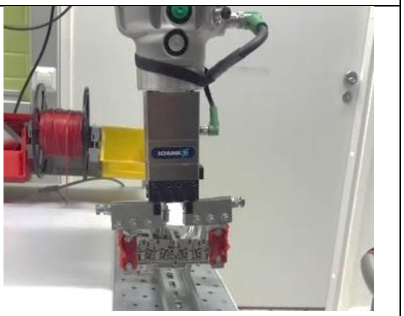
```
Frame Assembly_Approach_Frame = app_Data.getFrame("/Assembly_Table/ap-
proach_Frame_1").copyWithRedundancy(); /* acquiring the frame data
which was recorded during the hand guided frame teaching activity*/

gripper_1.move(ptp(Assembly_Approach_Frame)); /* end effector (TCP)
moves to the taught frame */
```

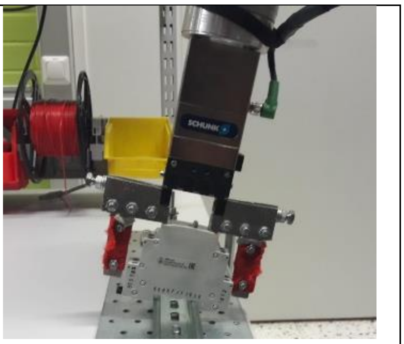
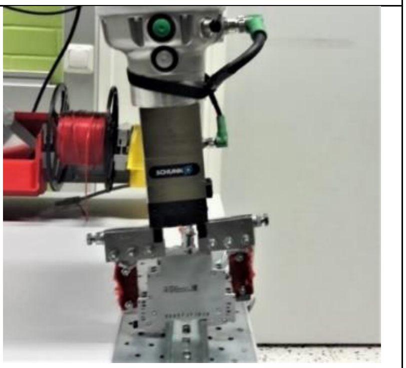
Program 3. *Utilization of a taught frame*

Programme 3 gives the idea of hand guided frame teaching methodology of application design. The frames were taught while utilizing the hand guiding functionality in T1 robot operating mode. Table 29 gives the overview of terminal block and Switch/Socket/Circuit breaker assembly. In this method, all the frames are calibrated with respect to a base frame (World/Origin frame by default). Here (for assembly positions), the base frame was set on the assembly table.

In case of drift errors (loss of repeatability), a recalibration of all the frames can be done by simply teaching the base frame again. It can be done by a human assembly worker who has gone through operator's training. However, it should also be noted here that the repeatability of KUKA LBR iiwa is ±0.1mm (confirms to the tests of ISO 9283:1998) and it is rated for 30,000 hours of operation [24]. This ensures reliability and builds confidence for industrial scale deployment.

Table 29. *Overview of Terminal Block and switch/socket/circuit breaker assembly with COBOT*

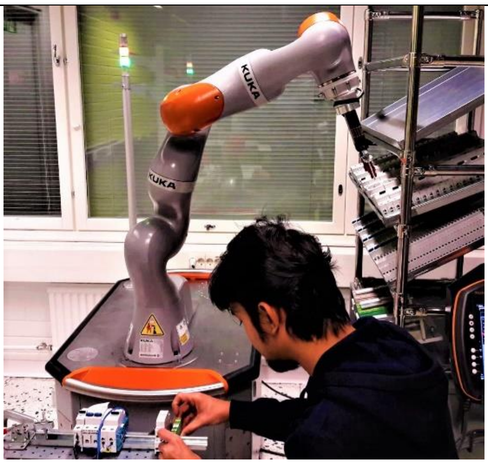
Item	**Detail**	**Pictorial Description**
Terminal Block	Approach Towards the DIN rail	
	End effector's motion to assemble the component.	

Switch/Socket/Circuit breaker	Approach Towards the DIN rail.	
	End effector's motion to assemble the component.	

Program 4 gives the idea of stimulating the collaborative robot with the touch of a human hand. The robot starts a to-and-fro motion along the z axis of the TCP frame when this function is called sequentially in the Robot Offline Programme. The motion is halted when a 15N external force is sensed along the z axis of the TCP. That's when the robot is stimulated to start executing its share of the assigned tasks alongside the human assembly worker. This is pictorially explained in Table 30.

Table 30. *Interactive function for stimulation of COBOT by human touch.*

S/No.	Detail	Pictorial Description
1	Operator Taps the COBOT to initiate the operation.	

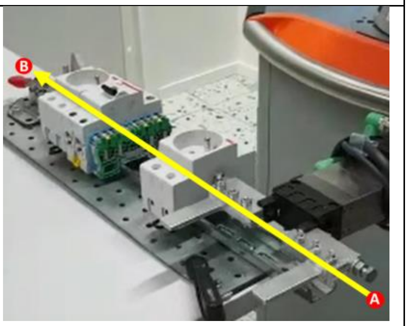
2	COBOT starts to pick components from the Rack, while the human worker assembles the terminal blocks.	

```
private void tap_Function()
{

logger.info("Tap the robot to start"); /* Notifies the operator on
KUKA smartPad */
ForceCondition contact_Start = ForceCondition.createSpatialForceCondi-
tion(gripper_1.getDefaultMotionFrame(), 15); /* 15N force condition
along Spatial Cartesian coordinates of the TCP frame */
for(;;)/* infinite For loop which breaks when the force condition is
not satisfied */
{
IMotionContainer contactMotion_1 = gripper_1.move(linRel(0, 0,
10).setCartVelocity(100).breakWhen(contact_Start)); /* 10 mm Linear
motion of the end effector in positive z direction */

IMotionContainer contactMotion_2 = gripper_1.move(linRel(0, 0, -
10).setCartVelocity(100).breakWhen(contact_Start)); /* 10 mm Linear
motion of the end effector in negative z direction */

if (contactMotion_1.hasFired(contact_Start)||contactMo-
tion_2.hasFired(contact_Start)) /* Conditional logic to break the loop
if force conditions aren’t satisfied */
{
media_Flange.setLEDBlue(false); /* to turn off the blue LED of Media
Flange */

logger.info("The assembly task starts now"); /* notifies the operator
on KUKA smartPad */
break;// breaks the infinite for loop
}
}
}
```

Program 4. *Tap function for collaborative operation.*

Similarly, Program 5 gives the idea of utilizing the collaborative robot for the removal of clearances between the assembled components. Cartesian impedance controller is utilized to lower the stiffness along y-axis (direction of linear motion) of the TCP frame. Cartesian Impedance controller allows deviation from the set path when the motion is obstructed due to the presence of DIN rail components. The TCP does not reach the end frame while moving linearly from the start frame. But it tries to do it by pushing against the obstructions. The linear motion is discontinued if the external force along the TCP frame reaches the set threshold of 90N. The start and end frame are represented by point A and B in Table 31 respectively.

Table 31. *Programmed functionality for removing the clearances between the assembled components.*

S/No.	Detail	Pictorial Description
1	The COBOT's end effector moves linearly from point A to point B to remove the clearances between the assembled components.	 

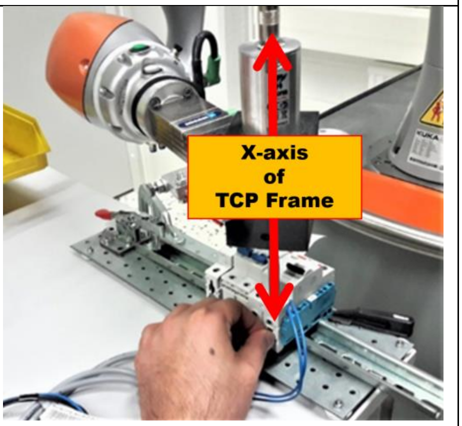
```
private void remove_Clearance()

{
CartesianImpedanceControlMode clearancerob_Push = new CartesianImped-
anceControlMode(); /* Instantiating the class to specify the control
mode */

ForceCondition external_React_Force = ForceCondition.createSpatial-
ForceCondition(gripper_1.getDefaultMotionFrame(), 90);/* 90N force
condition along the Spatial Cartesian coordinates of the TCP frame */

clearancerob_Push.parametrize(CartDOF.Y).setStiffness(500.0); /* To
set stiffness values for Y-Axis of the TCP */

Frame push_Comp_Orient= app_Data.getFrame("/Assembly_Table/ori-
ent_Push_Comp").copyWithRedundancy(); /* frame to orient the end ef-
fector */

```

```
Frame push_Comp_Start= app_Data.getFrame("/Assembly_Ta-
ble/push_Start").copyWithRedundancy(); /* Start frame of the push op-
eration */

Frame push_Comp_End= app_Data.getFrame("/Assembly_Ta-
ble/push_End").copyWithRedundancy(); /* End frame of the push opera-
tion */

gripper_1.move(ptp(push_Comp_Orient)); /* end effector moves to ori-
ent itself before starting the operation */

gripper_1.move(ptp(push_Comp_Start)); /* End effector moves to the
start frame */

gripper_1.move(lin(push_Comp_End).setCartVelocity(100).set-
Mode(clearancerob_Push).breakWhen(external_React_Force)); /* End ef-
fector moves to the end frame in compliant mode with a linear Carte-
sian velocity of 100 mm/sec and discontinues the motion if the set
external force has exceeded*/
}
```

Program 5. *Function for the removal of clearances between the assembled components.*

Program 6 gives the implementation for collaborative fastening operation. Table 32 elaborates the fastening operation and it can be seen that the axis of insertion for screws is parallel to the X-axis of the TCP frame. Gravity also acts in this direction. Therefore, the stiffness value is higher than the other two Cartesian coordinate frames (Y and Z). This enables the manipulator to carry the load at the end effector while allowing hand manipulation. Once the set point is reached the robot can be tapped along the X-axis to start the fastening operation of the screw driver.

Table 32. *Collaborative fastening operation.*

S/No.	Detail	Pictorial Description
1	The human assembly worker houses the wire in the terminal while the COBOT holds the screw driver for fastening operation.	

```
public void fastening(ICondition screw_Done)
{
CartesianImpedanceControlMode fastening = new CartesianImpedanceCon-
trolMode(); /* Instantiating the class to specify the control mode
for hand guiding task*/
fastening.parametrize(CartDOF.X).setStiffness(800.0); /* Gravity
acts in this direction so the stiffness is higher */
fastening.parametrize(CartDOF.Z).setStiffness(100.0); /* Stiffness
lowered to facilitate YZ planar movement */
fastening.parametrize(CartDOF.Y).setStiffness(100.0); /* Stiffness
lowered to facilitate YZ planar movement */
Frame fastening_Pos= app_Data.getFrame("/fastening_Pos").copy-
WithRedundancy(); /* hand guiding position */
gripper_1.move(ptp(fastening_Pos)); /* end effector moves to hand
guiding position */
ForceCondition start_Screw = ForceCondition.createNormalForceCondi-
tion(gripper_1.getDefaultMotionFrame(),CoordinateAxis.X,50); /* 50N
force condition on the X-axis of the TCP */

IMotionContainer hand_Mani = gripper_1.move(positionHold(fastening,
50, TimeUnit.SECONDS).breakWhen(start_Screw)); /* end effector can
be hand guided for 50 seconds unless a 50N force is detected along
X-axis of TCP */
logger.info("The screw has been reached"); /*notification for the
operator*/
if(hand_Mani.hasFired(start_Screw))
{
Kolver_Screw_Driver.start(); //Starts the screwdriver Programme
}
CartesianImpedanceControlMode fastening_Op = new CartesianImped-
anceControlMode(); /* Instantiating the class to specify the control
mode for fastening operation*/
fastening_Op.parametrize(CartDOF.X).setStiffness(5000); /* rigidity
increased as the set point for fastening operation has been
reached*/
fastening_Op.parametrize(CartDOF.Z).setStiffness(5000); /* rigidity
increased as the set point for fastening operation has been
reached*/
fastening_Op.parametrize(CartDOF.Y).setStiffness(5000); /* rigidity
increased as the set point for fastening operation has been
reached*/
fastening_Op.parametrize(CartDOF.C).setDamping(0.7); /* Damping can
be set along the orientation axis C (Angle C: rotation about the X
axis) according to need since the moment acts along X-axis*/
IMotionContainer fastening_Hold = gripper_1.move(positionHold(fas-
tening_Op, 50, TimeUnit.SECONDS).breakWhen(screw_Done)); /* end ef-
fector is rigid for 50 seconds but it breaks the motion mode when
screw has been fastened */
}
```

Program 6. *Collaborative fastening operation*

6. CONCLUSIONS

The objective of this thesis was to explore the concept of Human Robot Collaboration in assembly processes alongside the key technologies involved in it. To achieve this, a total of four research questions were posed. The answers to these questions led to the implementation of a reliable and industry scalable assembly process (as shown in Figure 23).

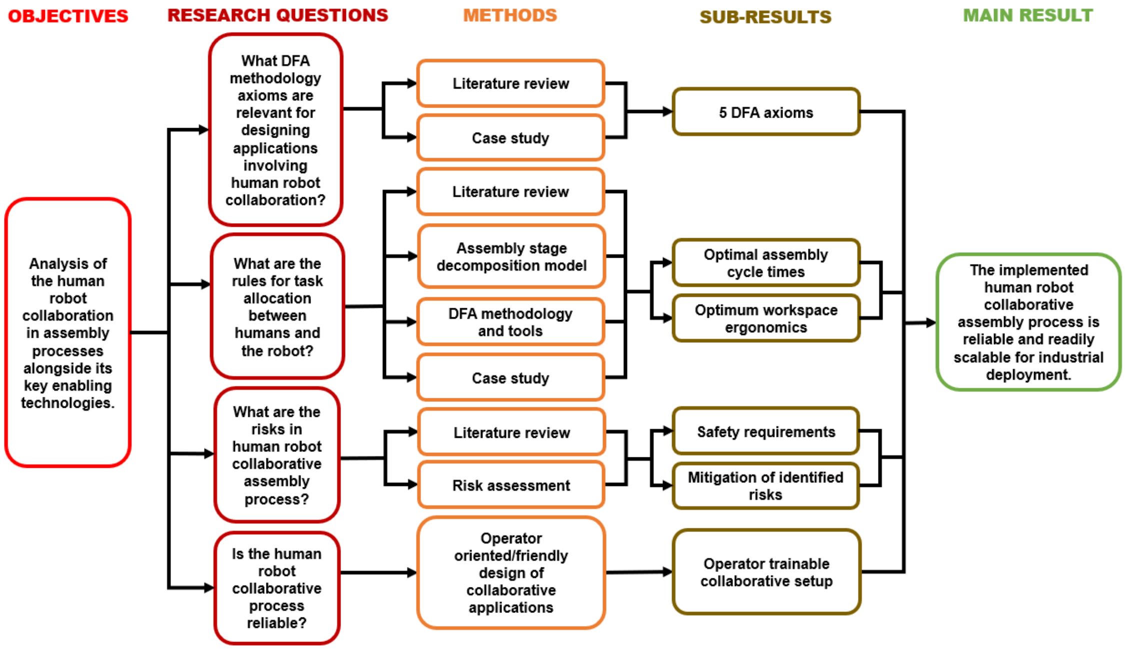


Figure 23. Objectives and research questions along with the obtained results.

To fulfill the requirements of the first research question, a literature review was carried out to explore the significance of DFA methodology and its tools for the analysis of the case under investigation. A total of five axioms were identified to be relevant for the assembly of the given product. These are given in the following text:

1. Identification of the joining methods
2. Identification of Necessary Parts
3. Identification of Assembly Directions
4. Available Assembly Stage Customizations
5. Quantifiable features of the product assembly

A total of four joining methods/techniques were identified for the investigated product and these are: snap fitting, spring terminal connection, screw terminal connection and adhesive joining technique. A total of 25 out of 26 parts were considered important based on structural integrity and completion of electrical circuit requirements. The concept of angle of symmetry aided in determining the assembly directions of the individual parts.

It was utilized in planning the assembly sequence and helped in avoiding confusing/uncertain situations for the human assembly worker. It was also utilized in the preparation of the Robot Offline Programme. Unwanted and extra robotic movements, which only add to the overall entropy of the assembly process, were effectively avoided. This was the result of careful evaluation of the assembly orientation requirements of the individual parts. Availability of the assembly stage customizations offered room for the execution of collaborative tasks. Two-digit manual assembly codes were generated to aid the manual assembly of the parts. These were used to increase the awareness/alertness of the assembly worker during the collaborative operations.

The second research question emphasizes on the rules of task assignment between the human assembly worker and the collaborative robot. Task Assignments between the human and the robot was explored with the following objectives in mind: Optimal assembly cycle times and workspace ergonomics. Literature review facilitated in understanding the needs and concept of HRC. The given product was disintegrated to produce the assembly stage decomposition model. It outlined the phases of assembly alongside the added features/components of the given product. Next, DFA methodology axioms and tools were used to analyze the different phases of the product assembly outlined in the assembly stage decomposition model. 3 out of 4 phases of assembly offered room for collaborative activities between the human and the collaborative robot. The resulting task assignments ensured optimal assembly cycle times and ergonomic operations. The assembly cycle times corresponded with the customer demands presented in the case study of the given product. Different functionalities were added in the Robot Offline Program which ensured an ergonomic assembly process. One of these functionalities involved the robot being stimulated by the touch of the human coworker. Another function allowed the robot to dissipate the unwanted vibrational energy of the industrial screw driver via virtual damper; thus, allowing the human coworker to avoid wrist sprains. It was implemented as part of the compliant behavior of the robot at the TCP frame. The collaborative robot also removed the clearances between the assembled components by pushing against them in compliant mode. These functionalities were readily available (sequential function call when needed) for the human assembly worker during the collaborative assembly process. From the results of the collaborative tests it is evident that the robot always had the higher cycle time during the collaborative tasks. This allowed the human worker to have extra available time while keeping up with the customer demands.

The third research question dealt with the hazards involved in a collaborative assembly operation. Literature review facilitated in instilling awareness alongside necessary knowledge regarding the safety requirements of the collaborative assembly processes. Risk assessment was performed (according to ISO12100) before commissioning the laboratory setup for collaborative assembly. A total of seven use cases were identified along with their associated risks and hazards. Strategies for the mitigation of the identified risks were then formulated and applied during the development of this thesis.

The last research question deals with the reliability of the collaborative process. Operator oriented/friendly approach was taken during the preparation of Robot Offline Program. Hand-guided frame teaching methodology was used during the development of the robotic applications. Apart from this, the collaborative robot is, inherently, rated for 30,000 hours of operation with an accuracy of ±0.1mm. However, in case of drift errors, the collaborative system can be readily trained again by the human coworker; to resume the normal collaborative assembly operation.

To conclude, it can be stated that the results, obtained while addressing the research questions, ensured a reliable and industry scalable implementation of the human robot collaborative assembly process.

7. FUTURE DEVELOPMENTS

There are several steps that could be taken to delve deeper into the topic of Human robot collaborative assembly process. One of them involves mapping of external sensors in KUKA SUNRISE.OS to increase safety and productivity. For instance, the use of 3D perception devices to detect human presence and adjustment of manipulator's speed accordingly; to ensure safe and productive operations.

Another future development would be to test the collaborative assembly process for the biomechanical limit criterions presented in ISO/TS 15066. Determination of ergonomic and psychological aspects of human robot collaborative assembly also offers a lot of room for R&D related to the topic.

Development of a motion planner/visualization platform, that readily generates the Robot Offline Programme, could ease the COBOT commissioning process. In this case, a frame parser needs to be developed which transfers the frames along with redundancy information from the planning software to the *KUKA SUNRISE.OS*.

REFERENCES

[1] International Organization for Standardization, "ISO 10218-2:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 2: Robot systems and integration," [Online]. Available: https://www.iso.org/standard/41571.html.

[2] KUKA Roboter GmbH, KUKA Sunrise.OS 1.11 KUKA Sunrise.Workbench 1.11 Operating and Programming Instructions for System Integrators, 2016.

[3] K. Schwab, "The Fourth Industrial Revolution: what it means, how to respond," World Economic Forum, [Online]. Available: https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/. [Accessed 18 July 2018].

[4] European Commission, "What is an SME?," 01 November 2018. [Online]. Available: http://ec.europa.eu/growth/smes/business-friendly-environment/sme-definition_en.

[5] M. Bortolini, E. Ferrari, M. Gamberi, F. Pilati and M. Faccio, "Assembly system design in the Industry 4.0 era: a general framework," *IFAC-PapersOnLine,* vol. 50, no. 1, pp. 5700-5705, 2017.

[6] euRobotics aisbl, "Robotics 2020 Strategic Research Agenda for Robotics in Europe," 11 October 2013. [Online]. Available: https://ec.europa.eu/research/industrial_technologies/pdf/robotics-ppp-roadmap_en.pdf.

[7] Björn Matthias, ABB Corporate Research, "Risk Assessment for Human-Robot Collaborative Applications," in *Workshop IROS 2015 – Physical Human-Robot Collaboration: Safety, Control, Learning and Applications*, 2015.

[8] R. J. Halme, M. Lanz, J. Kämäräinen, R. Pieters, J. Latokartano and A. Hietanen, "Review of vision-based safety systems for human-robot collaboration," *Procedia CIRP,* vol. 72, pp. 111-116, 2018.

[9] International Organization for Standardization, "ISO 10218-1:2011 Robots and robotic devices -- Safety requirements for industrial robots -- Part 1: Robots," [Online]. Available: https://www.iso.org/standard/51330.html.

[10] KUKA Systems GmbH, Blücherstraße 144, 86165 Augsburg, Germany, "KUKA flexFELLOW," 2018. [Online]. Available: https://www.kuka.com/en-de/products/mobility/mobile-robots/kuka-flexfellow. [Accessed 13 October 2018].

[11] International Organization for Standardization, "ISO/TS 15066:2016 Robots and robotic devices -- Collaborative robots," February 2016. [Online]. Available: https://www.iso.org/standard/62996.html.

[12] S. Fox, A. Kotelba and . I. Niskanen, "Cognitive Factories: Modeling Situated Entropy in Physical Work Carried Out by Humans and Robots," *Entropy,* vol. 20, no. 9, 2018.

[13] VTT Technical Research Centre of Finland Ltd., , "Guidelines to make safe industrial robot systems," Tampere, 2017.

[14] European Commission, "Regulations, Directives and other acts," [Online]. Available: https://europa.eu/european-union/eu-law/legal-acts_en. [Accessed 24 September 2018].

[15] American National Standards Institute (ANSI), "ISO Type A-B-C Structure for Machinery Standards," [Online]. Available: https://blog.ansi.org/2017/10/iso-type-abc-structure-machinery-standards-ansi-b11/#gref. [Accessed 24 September 2018].

[16] M. Lanz, R. V. Osuna and R. Tuokko, "FEATURE-BASED MODELING AND ANALYSIS FOR KNOWLEDGE INTENSIVE CONCURRENT ENGINEERING IN FINAL ASSEMBLY," in *Proceedings of The 6th International Conference on Computer-Aided Industrial Design & Conceptua l Design (CAID&CD 2005), Applications of digital techniques in industrial design engineering CAID&CD*, Delft, the Netherlands., 2005.

[17] G. Boothroyd, Assembly Automation and Product Design, Second Edition., CRC Press, 2005 .

[18] G. Boothroyd, P. Dewhurst and W. A. Knight, Product Design for Manufacture and Assembly, Third Edition., CRC Press, 2010.

[19] G. A. Chang and W. R. Peterson, "Using Design for Assembly Methodology to Improve Product Development and Design Learning at MSU," American Society of Engineering Education., 2012.

[20] KONE Corporation, "Visual components - Tool for 3D Simulation and Manufacturing," in *3D Simulation seminar by Visual Components and Delfoi*, Espoo, 2018.

[21] KONE Industrial Oy, "SWITCH-moduulin VALMISTUSOHJE," Hyvinkää, FI., 2018.

[22] KUKA Roboter GmbH, "14.10.1 Redundancy angle," in *KUKA Sunrise.OS 1.11 KUKA Sunrise.Workbench 1.11 Operating and Programming Instructions for System Integrators*, pp. 320-321.

[23] B. Siciliano, L. Sciavicco , L. Villani and G. Oriolo, in *Robotics Modelling, Planning and Control* , Springer-Verlag London Limited 2010 .

[24] P. Cazottes, "Compliant mechanisms," Institut Jean le Rond d'Alembert, Universite Pierre et Marie Curie, [Online]. Available: http://www.lmm.jussieu.fr/~cazottes/Compliant_mechanisms.html.

[25] International Organization for Standardization, "ISO 12100:2010 Safety of machinery -- General principles for design -- Risk assessment and risk reduction," [Online]. Available: https://www.iso.org/standard/51528.html.

[26] Kolver srl via M. Corner, 19/21 36016 Thiene (VI) - Italy, "Controllers EDU series," [Online]. Available: https://kolver.it/products-list/8-Controllers-EDU-series.

[27] European Commission, "Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC (recast) (Text with EEA relevance)," *Official Journal of the European Union,* 2006.

[28] C. Ott, "Cartesian Impedance Control of Redundant and Flexible-Joint Robots," *Springer Tracts in Advanced Robotics,* vol. 49, 2008.

[29] Statistics Finland, Työpajankatu 13, FI-00580 Helsinki., "Wages, Salaries and Labour Costs," 2 October 2018. [Online]. Available: https://www.stat.fi/tup/suoluk/suoluk_palkat_en.html. [Accessed 23 10 2018].

[30] Weidmüller Interface GmbH & Co. KG, "Spring connection with tension clamp technology," [Online]. Available: https://www.weidmueller.com/int/products/connectivity/klippon--connect-terminal-blocks/universal-range/spring-connection-with-tension-clamp-technology.

[31] KUKA Deutschland GmbH, Zugspitzstraße 140, 86165 Augsburg, Germany, "LBR iiwa," [Online]. Available: https://www.kuka.com/en-de/products/robot-systems/industrial-robots/lbr-iiwa.

APPENDIX A: RISK ASSESSMENT WORKSHEETS

Table 1. *Identification of use cases and the respective actors.*

S/No.	Use Case	Description of the use case	Actors	Frequency
1	Commissioning and robot offline programming	Installation, commissioning, Robot Programming	Trained personal: Usually robot commissioning Engineer.	Rare
2	Assembly Operation – Automatic mode	Robot working in automatic mode	Human Assembly Worker: Typically, having gone through robot operator's training.	High
3	Human Intervention in Robot only operating zone	Reaching the robot only workspace. Usually carried out to correct an error situation. E.g. Correction of problems in the feeding system.	Human Assembly Worker: Typically, having gone through robot operator's training.	Low
4	Foreseeable malpractices in assembly process	Non-authorized personal entering the assembly workstation. E.g. A colleague or a visitor.	Usually an untrained person.	Not known and assumed to be rare.
5	Maintenance/Service of collaborative workstation	Maintenance or service activity carried out to optimize the collaborative operation.	Trained personal: Usually robot commissioning Engineer.	Rare to medium.
6	Cleaning/Housekeeping	Cleaning the workstation and general housekeeping of the workstation.	Human Assembly Worker: Typically, having gone through robot operator's training.	Medium
7	Decommissioning	Dismounting the workstation to ship or dispose the equipment.	Trained personal: Usually robot commissioning Engineer	Rare

Table 2. *Hazard identification with explanations.*

S/No.	**Use Case**	**Type of Hazards**				**Explanation**
		Entering Robot's Workspace	**Transient Contact**	**Quasi-Static Contact**	**Damage to the workstation (All 3 functional zones)**	
1	Commissioning and robot offline programming	YES	YES	YES	YES	During commissioning the operator does enter the robot's workspace, however, it is recommended for the robot to be in T1 and T2 operating modes for programming/teaching and testing of programs. Use of automatic operating mode, during robot commissioning, could expose the human operator and the workstation to dangerous and uncontrollable situations. It is due to the fact that the dead man's switch is absent during automatic operation.
2	Assembly Operation – Automatic mode	YES – Collaborative workspace only	YES	YES	YES	During automatic operation of the robot, the human assembly worker shares the workspace with the human worker. It is therefore, exposed to the mentioned hazards.

3	Human Intervention in Robot only operating zone	YES	YES	YES	YES	During automatic operation of the robot, human worker and the workstation are exposed to the mentioned risks if human violates the robot's workspace.
4	Foreseeable malpractices in assembly process	YES	YES	YES	YES	During automatic operation if someone (unauthorized personal) violates the robot's workspace then the whole work station could be exposed to the mentioned risks.
5	Maintenance/Service of collaborative workstation	YES	YES	YES	YES	During maintenance if the robot is not used in T1 or T2 operating modes then it could expose the whole workstation to the corresponding mentioned risks.
6	Cleaning/Housekeeping	N/A	NO	NO	NO	At the end of the shift the assembly worker clears and cleans up the workstation. Since the robot is nonoperational therefore the corresponding mentioned risks are nonexistent for his case.
7	Decommissioning	N/A	NO	NO	YES	Since the robot is not operational during this scenario, therefore, the corresponding mentioned risks do not exist.

Table 3. *Risk level estimation with HRN System.*

S/No.	Use Case	Hazard Rating Number System (HRN)					Risk Level
		LO	FE	DPH	NP	HRN	
1	Commissioning and robot offline programming	2	0.5	4	1	4	Very Low Risk
2	Assembly Operation – Automatic mode	15	5	0.5	1	37.5	Considerable Risk
3	Human Intervention in Robot only operating zone	2	1	2	1	4	Very Low Risk
4	Foreseeable malpractices in assembly process	1.5	0.5	15	2	22.5	Considerable Risk
5	Maintenance/Service of collaborative workstation	1.5	0.5	0.5	1	0.375	Meaningless risk
6	Cleaning/Housekeeping	1	2.5	0.5	1	1.2	Meaningless risk
7	Decommissioning	1	0.5	0.5	1	0.25	Meaningless risk

Table 4. *Legend for HRN System.*

S/No.	Likelihood of Occurrence (LO)	Frequency of exposure to the hazard (FE)	Degree of Possible Harm (DPH)	Number of Persons (NP)	HRN = LO x FE x DPH x NP Risk Level
1	Almost impossible - possible only under: 0.033 – extreme circumstances	Annually: 0.5	Scratch/bruise: 0.1	1-2 persons: 1	Meaningless Risk: 0-1
2	Highly unlikely - 1	Monthly: 1	Laceration/mild ill-effect: 0.5	3-7 persons: 2	Very Low Risk: 2-5
3	Unlikely - but could occur: 1.5	Weekly: 1.5	Break minor bone or minor illness: 2 – (temporary)	8-15 persons: 4	Low Risk: 6-10

4	Possible - but unusual: 2	Daily: 2.5	Break major bone or major illness: 4 – (temporary)	16-50 persons: 8	Considerable Risk: 11-50
5	Even chance - could happen: 5	Hourly: 4	Loss of one limb, eye, hearing loss: 6 – (permanent)	50+ persons: 12	High Risk: 51-100
6	Probable - not surprising: 8	Constantly: 5	Loss of two limbs, eyes: 10 – (permanent)	-	Very High Risk: 101-500
7	Likely - only to be expected: 10	-	Fatality: 15	-	Extreme Risk: 501-1000
8	Certain - no doubt: 15	-	-	-	Unacceptable Risk: 1000 +

Table 5. *Risk levels and risk mitigation strategies.*

S/No.	**Use Case**	**Risk Level**	**Risk Mitigation Strategy**
1	Commissioning and robot offline programming	Very Low Risk	By always using modes with controlled speeds (e.g. T1 mode during Robot Offline Programming and frame teaching operations)
2	Assembly Operation – Automatic mode	Considerable Risk	By limiting Power and Force (using active compliance). By having controlled speed of the manipulator. Alerting the operator when the robot is in collaborative workspace e.g. Use of flex Fellow's Buzzer System to alert the operator.
3	Human Intervention in Robot only operating zone	Very Low Risk	By having controlled speed of the manipulator. By limiting power and force (using active compliance).

4	Foreseeable malpractices in assembly process	Considerable Risk	By limiting power and force (using active compliance). By having con-trolled speed of the manipulator. By having markings and signs to alert.
5	Maintenance/Service of collaborative workstation	Meaningless risk	Standard Measures
6	Cleaning/Housekeeping	Meaningless risk	Standard Measures
7	Decommissioning	Meaningless risk	Standard Measures

APPENDIX B: DFA ANALYSIS WORKSHEETS

Table 1. *Theoretical minimum part count*

S/No.	Component	Assembly Stage Phase	Theoretical Minimum Part Count
1	DIN rail	1	1
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	1
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	1
4	Terminal Block: ZDU 2.5/4AN BL	2	1
5	Terminal Block: ZDU 2.5/4AN BL	2	1
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	1
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	1
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	1
9	Terminal Block: ZDU 2.5/4AN (Grey)	2	1
10	Terminal Block: ZDU 2.5/4AN BL	2	1
11	Terminal Block: ZDU 2.5/4AN BL	2	1
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	1
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	1
14	ABB FH202 A	2	1
15	CHINT C6	2	1
16	CHINT D6	2	1
17	ABB D2	2	1
18	Wire Set: KM51062820G10135	3	1
19	Wire Set: KM796121G12106	3	1
20	Wire Set: KM51042524G14	3	1
21	CHINT B6	4	1
22	CHINT B10	4	1
23	ABB E251-230	4	1
24	ABB Socket	4	1
25	ABB E216	4	1
26	Labels	4	0
		Total Sum	**25**

Table 2. *Manual assembly code assignments*

S/No.	Component	Assembly Stage Phase	α	β	α+β	Manual assembly code – 2 digit
1	DIN rail	1	180	360	540	11
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	360	360	720	11
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	360	360	720	11
4	Terminal Block: ZDU 2.5/4AN BL	2	360	360	720	11
5	Terminal Block: ZDU 2.5/4AN BL	2	360	360	720	11
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	360	360	720	11
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	360	360	720	11
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	360	360	720	11
9	Terminal Block: ZDU 2.5/4AN (Grey)	2	360	360	720	11
10	Terminal Block: ZDU 2.5/4AN BL	2	360	360	720	11
11	Terminal Block: ZDU 2.5/4AN BL	2	360	360	720	11
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	360	360	720	11
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	360	360	720	11
14	ABB FH202 A	2	360	360	720	11
15	CHINT C6	2	360	360	720	11
16	CHINT D6	2	360	360	720	11
17	ABB D2	2	360	360	720	11
18	Wire Set: KM51062820G10135	3	360	0	360	10
19	Wire Set: KM796121G12106	3	360	0	360	10
20	Wire Set: KM51042524G14	3	360	0	360	00
21	CHINT B6	4	360	360	720	11
22	CHINT B10	4	360	360	720	11
23	ABB E251-230	4	360	360	720	11
24	ABB Socket	4	360	360	720	11
25	ABB E216	4	360	360	720	11
26	Labels	4	360	360	720	11

Table 3. *Individual timings for 1st test*

S/No.	Component	Phase	Time (s)	Manual Assembly codes
1	DIN rail	1	5	11
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
4	Terminal Block: ZDU 2.5/4AN BL	2	5	11
5	Terminal Block: ZDU 2.5/4AN BL	2	5	11
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
9	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
10	Terminal Block: ZDU 2.5/4AN BL	2	5	11
11	Terminal Block: ZDU 2.5/4AN BL	2	5	11
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
14	ABB FH202 A	2	20.3	N/A
15	CHINT C6	2	20.5	N/A
16	CHINT D6	2	20	N/A
17	ABB D2	2	21	N/A
18	Wire Set: KM51062820G10135	3	15	10
19	Wire Set: KM796121G12106	3	15	10
20	Wire Set: KM51042524G14	3	15	00
21	CHINT B6	4	20.4	N/A
22	CHINT B10	4	20.2	N/A
23	ABB E251-230	4	20.3	N/A
24	ABB Socket	4	20.2	N/A
25	ABB E216	4	20.1	N/A
26	Labels	4	60	11

Table 4. *Individual timings for 2nd test*

S/No.	Component	Phase	Time (s)	Manual Assembly codes
1	DIN rail	1	5	11
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11

4	Terminal Block: ZDU 2.5/4AN BL	2	5	11
5	Terminal Block: ZDU 2.5/4AN BL	2	5	11
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
9	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
10	Terminal Block: ZDU 2.5/4AN BL	2	5	11
11	Terminal Block: ZDU 2.5/4AN BL	2	5	11
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
14	ABB FH202 A	2	18.36	N/A
15	CHINT C6	2	18.55	N/A
16	CHINT D6	2	19	N/A
17	ABB D2	2	19	N/A
18	Wire Set: KM51062820G10135	3	15	10
19	Wire Set: KM796121G12106	3	15	10
20	Wire Set: KM51042524G14	3	15	00
21	CHINT B6	4	18.32	N/A
22	CHINT B10	4	18.13	N/A
23	ABB E251-230	4	18.3	N/A
24	ABB Socket	4	18	N/A
25	ABB E216	4	18.21	N/A
26	Labels	4	60	11

Table 5. *Individual timings for 3rd test*

S/No.	**Component**	**Phase**	**Time (s)**	**Manual Assembly codes**
1	DIN rail	1	5	11
2	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
3	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
4	Terminal Block: ZDU 2.5/4AN BL	2	5	11
5	Terminal Block: ZDU 2.5/4AN BL	2	5	11
6	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
7	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
8	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11

9	Terminal Block: ZDU 2.5/4AN (Grey)	2	5	11
10	Terminal Block: ZDU 2.5/4AN BL	2	5	11
11	Terminal Block: ZDU 2.5/4AN BL	2	5	11
12	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
13	Terminal Block: ZPE 2.5/4AN (GREEN)	2	5	11
14	ABB FH202 A	2	16.15	N/A
15	CHINT C6	2	15.95	N/A
16	CHINT D6	2	16.5	N/A
17	ABB D2	2	21	N/A
18	Wire Set: KM51062820G10135	3	15	10
19	Wire Set: KM796121G12106	3	15	10
20	Wire Set: KM51042524G14	3	15	00
21	CHINT B6	4	15.5	N/A
22	CHINT B10	4	16.25	N/A
23	ABB E251-230	4	16.45	N/A
24	ABB Socket	4	15.93	N/A
25	ABB E216	4	16.2	N/A
26	Labels	4	60	11