THREADED PLUG & RING - ASSEMBLY STATION DESIGN

(01-May-2018 to 14-December-2018)

MSc Mechanical Engineering: DPM-1566

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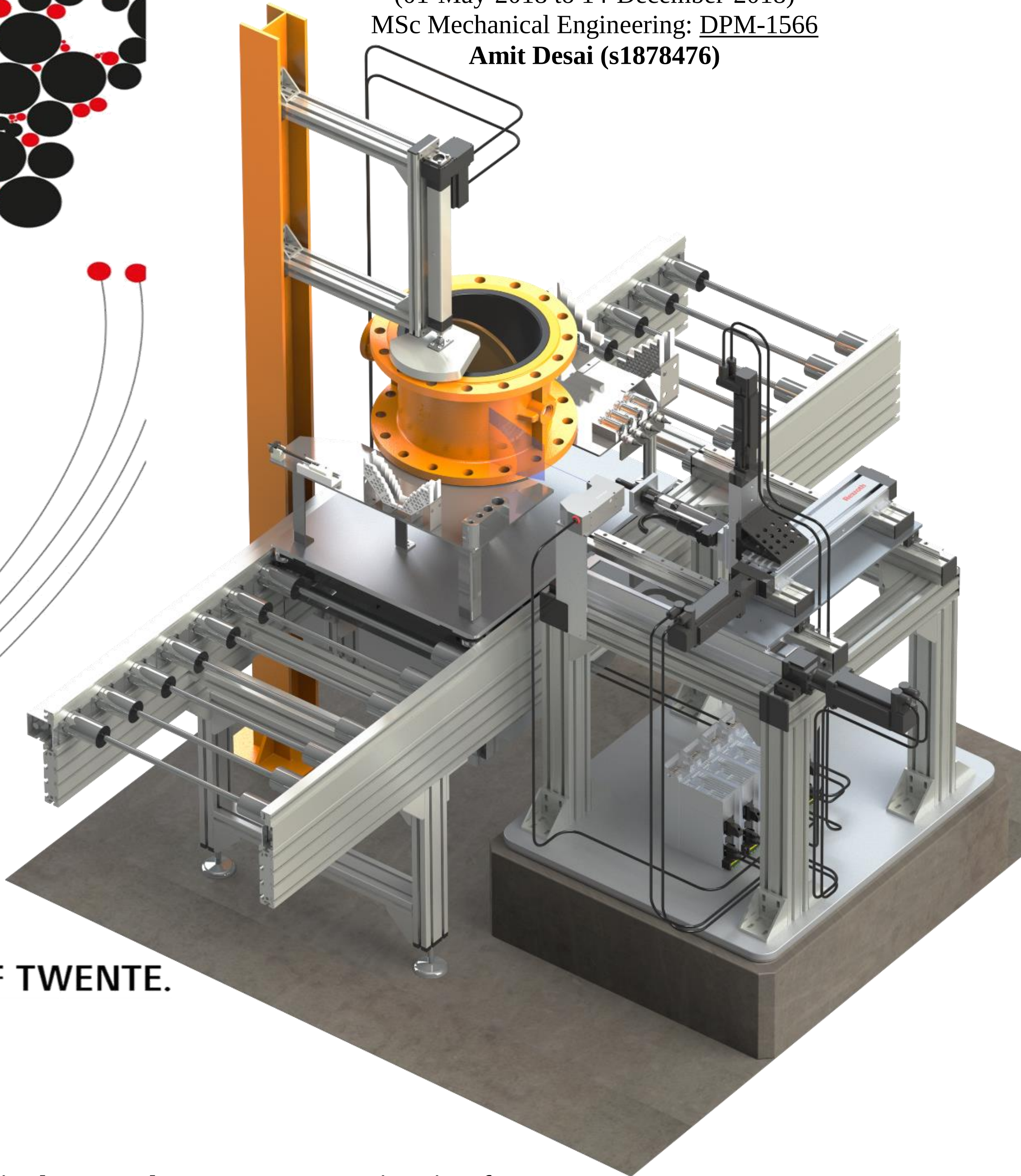

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WOUTER WITZEL VALVE TECHNOLOGY

ACKNOWLEDGMENT

The following report reflects the work I have done on "Threaded Plug & Ring Assembly Station Design." This work is a part of my graduation thesis which was carried out at Wouter Witzel. The completion (theoretically) of the project was not possible without the support, guidance, assistance, and motivation from some special people. Hence, I would take some freedom to convey my gratitude towards them.

Firstly, I would like to thank Tom Vaneker who introduced me to this project and suggested me for having a look if it was within my field of interest. I found the project to be interesting, and he agreed to be my supervisor for the project. It was his support, guidance, and assistance which helped me overcome certain hurdles. Moreover, his critical assessment was beneficial in my overall improvement.

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Amit Desai

PREFACE

I present you my graduation report that would provide you with explicit details of the work I have performed during the period of my thesis. Due to the reduction of the agreed topic of the thesis, the topic was extended with an additional assignment. Thus, the thesis project is divided into two assignments which have been explained in details in two separate sections of the report- part A and part B.

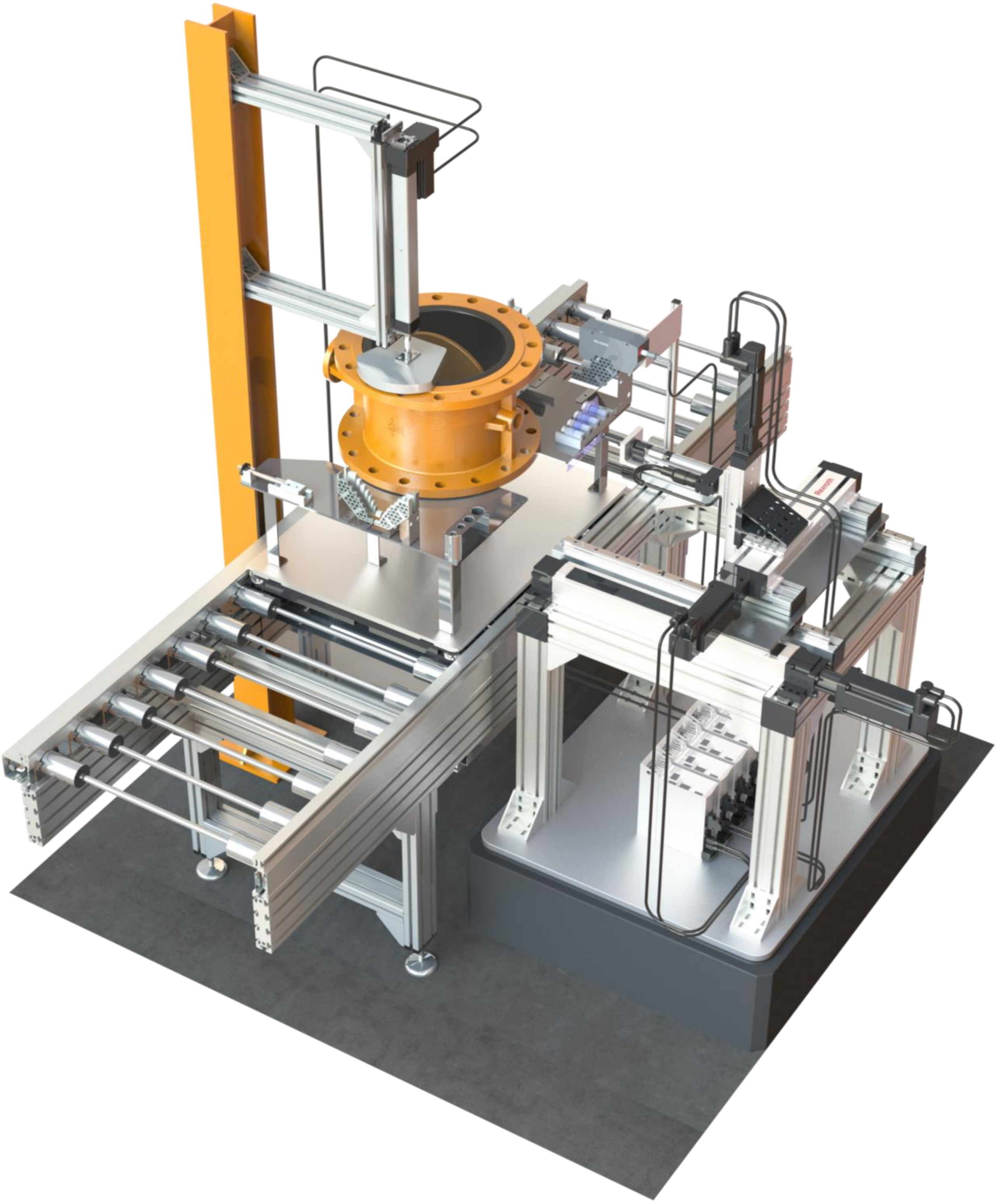
Part A, entitled –"Threaded Plug and Ring-Assembly Station Design" is the main topic of the thesis. It provides elaborated information on the research, designing and development process performed to design a complete assembly station, assigned for assembling the plug & ring (butterfly valve components) in a butterfly valve body.

Part B, entitled-"Machine-Aided Assembly Setup Design" addresses the extended portion of the thesis. It illustrates the preliminary concept designing and prototype development phase of a semi-automated unit for aiding the operators to assemble a butterfly valve completely.

I hope you would find the overview to be interesting.

PART- A

"THREADED PLUG & RING-ASSEMBLY STATION DESIGN"



ABSTRACT

“THREADED PLUG & RING-ASSEMBLY STATION DESIGN”

Wouter Witzel Euro valve is a Dutch company specialized in the production and manual assembly of different sizes and models of the butterfly valve. Currently, Wouter Witzel investigates the technical feasibility of automating the assembly process of these valves.

Previous research was dedicated to the general feasibility of automating the assembly process. It showed that it was economically feasible to automate the process. The next phase of the project led to the detailed system level design of the assembly line. This detailed design included an assembly line layout with several assembly stations, the sequence of the assembly process, type of assembly stations required, cycle time analysis and estimation on implementation cost. This assignment deals with the detailed design of one of those assembly stations; the assembly station for assembling the threaded plug & ring into the valve body. The plug and ring are two critical components of the valve, and their functionality is to provide leak-proof sealing.

The research was focused on the development of two major components of the system - a fixture for placing the plug & ring, and a robotic system to perform the assembly operation. The fixture was designed to place the plug & ring with ease & without changing their orientation using a robotic linear Cartesian system with three translational degrees of freedom. A tightening tool is mounted on the linear system, and the tool is used to pick (from the fixture) and place (tighten) the plug & ring in the valve body.

Finally, a design failure mode and effect analysis has been performed. The critical potential causes of failure and other parameters essential for the operation of the system were considered, and a preliminary control plan has been proposed. A cycle time analysis was carried out to ensure that the system could perform the assembly operation in an envisioned cycle time of 2min. These final checks indicate that the proposed assembly station is capable of fastening the plug & ring to provide a leak-proof sealing in the desired amount of time and at minimal costs.

Keywords: butterfly valve, assembly station, plug & ring, detailed design.

Abbreviations

WW	Wouter Witzel
ScBS	Self-centring Bonded Sealing Ring
BS	Bonded Sealing Ring
RLBV	Rubber Lined Butterfly Valves
EPDM	Ethylene- propylene- dieen- rubber
NBR	Acrylonitrile- butadiene rubber
FKM	Fluor- rubber
VMQ	Silicon- rubber.
SLD	System level design
P&R	Threaded plug & sealing ring
LMD	Linear Motion Designer
CTA	Cycle Time Analysis

CONTENTS

1 Introduction

The following research and development project is the tertiary phase of the RECap project. RECap is an acronym for "Robotics Experience Centre als proeftuin" and EFRO subsidized (initiated by ESPS Almelo). Several other companies and educational institutions (The University of Twente, etc.) are collaboratively working to realize this project. Ever since the project started in 2016, two feasibility studies have been performed on the automation of the assembly process of the butterfly valve (only Rubber lined Euro Valves). After the studies, the subsequent research was performed to propose a technical setup for the assembly. This was done by distributing the process in three phases. Figure 1-1 shows the 3-phase converging to the complete design of an automated assembly station. Phase 1, Phase 2, and some part of phase 3 have been completed earlier. In primary and secondary phase product study, conceptual designing, primary level testing, and system level designing were proposed and evaluated. The next phase was to carry out extensive study and analysis on product level based on proposed system-level design. It is focused on the design of an automated assembly station to assembly plug & ring into the valve body (The components and body are explained further in product study phase).

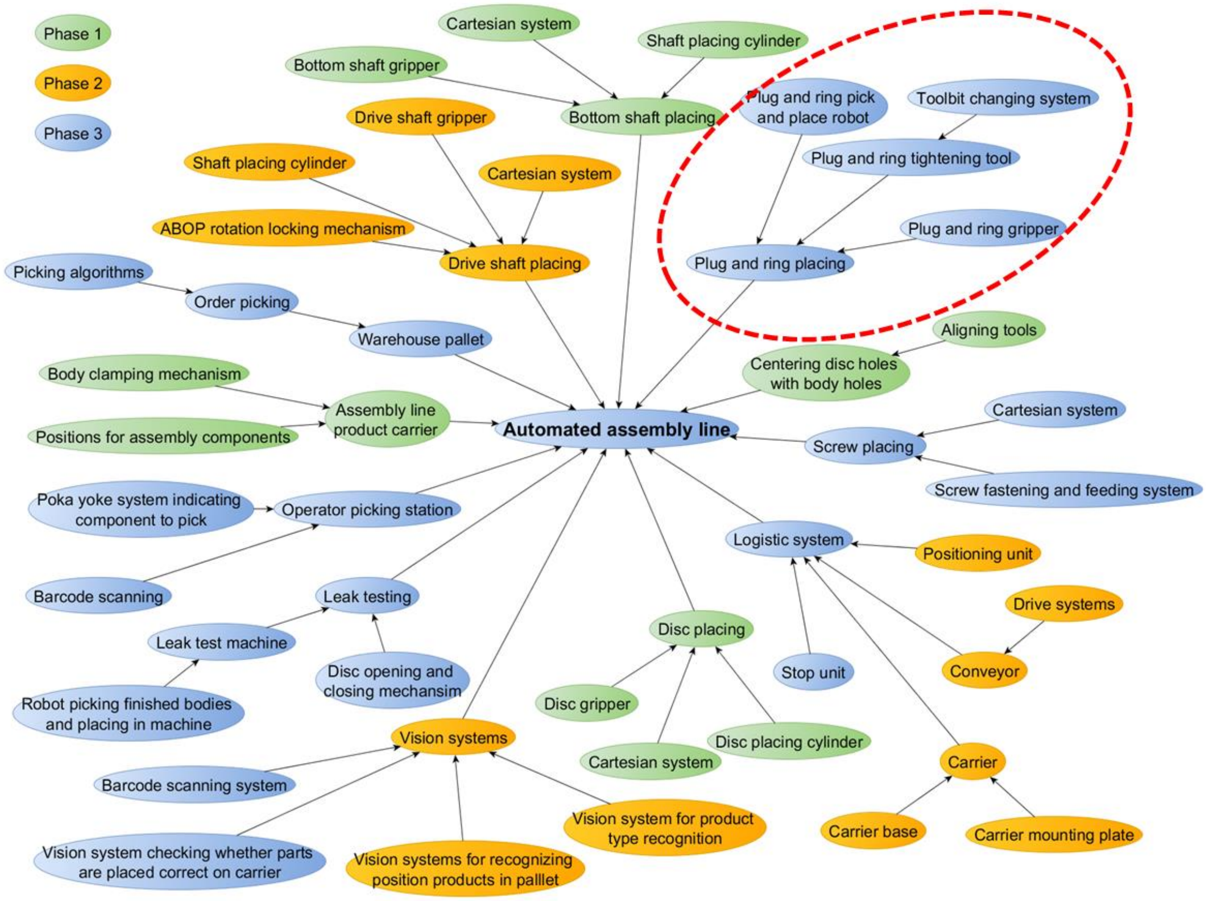


Figure 1-1: Phase Diagram for the automated assembly line [39]

1.1 Wouter Witzel EuroValve BV.

Wouter Witzel founded this Dutch company in 1966 and ever since has been internationally renowned in the field of butterfly valve manufacturing. After selling the company to PCC USA in the year 2000 and later being taken over by AVK group, the company has broadened its technical knowledge and optimized international service.

WW specialize in producing a wide range of butterfly valves and accessories. The products are made as per the market requirement, and in some cases, these are engineered to customer order requirements & specifications. The company produces a full range of manual control devices, actuators, and accessories for specific conditions. Wouter Witzel products conform to the most stringent international quality requirements, and their products have proved to be extremely durable. The valves are primarily manufactured and delivered to customers from seven diverse industries:

- Water Treatment
- Ship Building
- Oil & Gas
- Desalination
- Building Services
- Power stations
- District Cooling

The company is in Losser, De pol Noord and the principal operation at this plant is the assembly of valves along with research and development of new products. External manufacturers supply the components. In total, 11 components are required to complete the assembly of a standard euro valve (EV) (Figure 1-3 shows the different components assembled to make a complete valve) this does not include the actuation mechanism. WW offers a wide range of products which includes *rubber lined butterfly valves (RLBV), high-performance butterfly valves*; *check valves, actuators,* and *automation technology [50]*. The rubber-lined valves are used in various industries for a wide range of application with low to high operating pressure. These are also called as Euro valves or EV range valves. High-performance valves are used for applications with high operating pressure, severe conditions & with abrasive media. Moreover, WW provides actuation mechanism which comprises of hand levers, worm gears, electric, pneumatic, & hydraulic actuation [50].

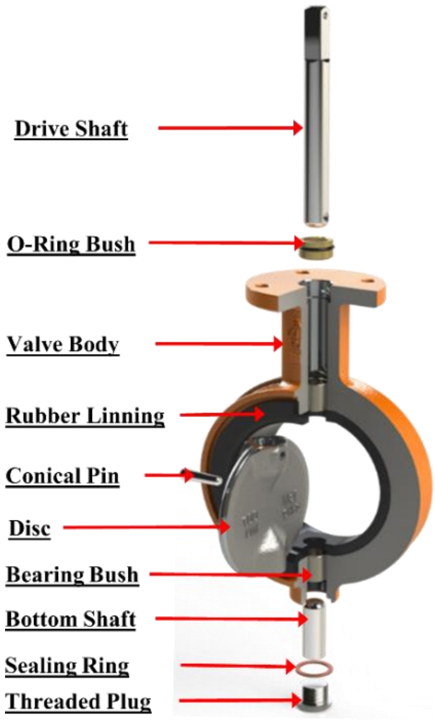


Figure 1-2: Section view of a fully assembled butterfly valve (old design). In December 2017 a decision was made to modify the design of the body, disc, and shaft for the EV range products and planned its gradual implementation from 2018.

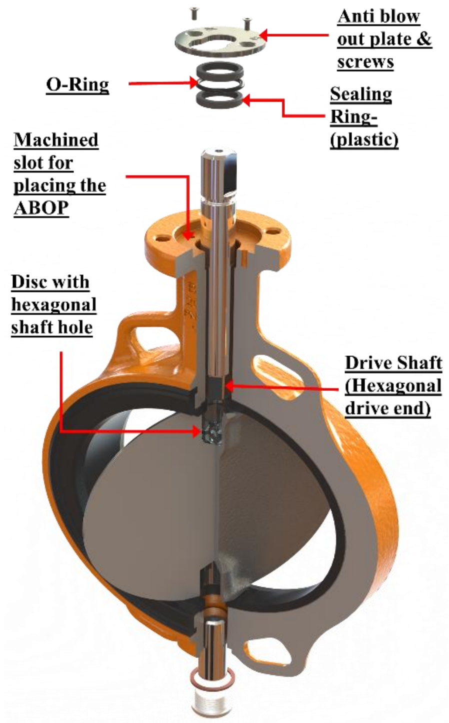


Figure 1-3: New design of the body, drive shaft and disc. The new shaft sub-assembly has an ABOP, o-ring, sealing ring, and the shaft has a hexagonal end. The circular hole in the disc is changed to a hexagonal hole (this eliminates the need for the conical pin). The top flange body is machined to make a slot for placing & tightening the ABOP.

1.2 Background information

This section is assigned to provide insight on what range of products are under consideration, followed by the progress of RECap till date (before the start of this assignment in May-2018). And this would be considered as the starting point to proceed with the assignment. This section is further divided into three subsections, with the 1st section motivating automating the assembly process. Followed by a detailed explanation of the automated assembly line (AAL)- (proposal from the system level design (SLD) phase of RECap) in the 2nd section. Lastly, the third sub-section explains the proposed automated assembly process.

The initiation of the revolutionary step to automate the assembly process of the butterfly valves is focused on starting slow and then widening the perspective. Hence, selection of a specific range of product is made. A limited range of RLBV is considered under the scope of this project, and their size ranges from DN40-DN2200. However, research, development, and implementation for RECap are limited to nine types of valves, available in 11 different sizes (the size & type variants are listed in

Table 1-1). The reason for considering 11 sizes is their high production volume and limited variation in dimensions in comparison to the larger sizes (Detailed information on the type and size of valves is stated in the appendix. A).

Table 1-1: Different type and sizes of valves. The number following the DN is the inner diameter (in mm) of the body of the valve, and all the other dimensions are majorly dependent on the valve type.

9 Types of RLBV		**11 Size Variants of RLBV**	
1.EVS	6.EVTLLS	1.DN40	7.DN150
2.EVCS	7.EVML	2.DN50	8.DN200
3.EVBS	8.EVFS	3.DN65	9.DN250
4.EVBLS	9.EVFL	4.DN80	10.DN300
5.EVTLS		5.DN100	11.DN350
		6.DN125	

1.2.1 The motivation for automating assembly operation.

At WW, the method and process of assembling a butterfly valve have not witnessed any drastic changes. Currently, the valves are assembled manually in a conventional manner and with the aid of some power tools (The detailed overview of steps followed to carry out the valve assembly are described in the appendix. B). Aiding machinery like overhead cranes are used for larger sizes (because of limitation on weights to be lifted by an operator as per Dutch working norms). All the components of the valve except the body, disc, pin, and drive shaft are present on the worktable in kanban bins on the assembly line. The rest are delivered to the operator at assembly line as per the production order (Production order- It is the document stating the type, size, and quantity of valves to be assembled.) The production order varies majorly depending on the type and size of the valve. The carrying out of valve assembly requires the operators to apply higher forces (calculated during SLD) and manufacturing multiple orders in a shift remains a tiresome work. At present operators use grease during the assembly process; use of grease lowers the assembling forces but makes the work environment messy and after assembling this grease needs to be cleaned to eliminate contamination of the medium where the valve would be used. Thus, the heavy-duty work performed by operators in an 8-hour shift has an adverse effect on their health. The health issues compromise operator's attention leading to deteriorated quality of work and increased cases of absenteeism. Moreover, hiring and training a workforce to perform this work is less economical. Moreover, if the assembling process is automated then grease might be excluded from the process. Therefore, WW investigated in the feasibility of automating the assembly process. The fundamental motive was to enhance the efficiency and quality accompanied by throughput time and labor absenteeism reduction. Also, automation of this labor-intensive process helps cost reduction which maintains WW competitive with low-wage countries in the future. The SLD research and analysis showed that "*the current assembly costs are €707,373 per year, and about 95000 valves are produced on average per year. The average assembly costs per valve are, therefore, €7.45 (including actuators), which contributes only to a small part of the total butterfly valve production costs. The total production costs for a small DN50 butterfly valve range from €25 up to €150. The total production costs for a large DN350 butterfly valve range from €250 up to €625. Automating the assembly process can reduce the average assembly costs per butterfly valve* *to €3.59*" [39]. The proposals made during the automation feasibility study, followed by the methodology for automating the assembly process led to system level design (SLD). The SLD was concluded with the proposal for carrying out stepwise assembly of the butterfly valve on the automated assembly line (AAL). The comprehensive explanation on overview of the automated assembly process is explained in the following section.

1.2.2 Proposed semi-automated assembly line

The RECap is the first automation project carried out at WW, and therefore the initial goal of the project was to design a completely automated assembly line for assembling the valves. But business case prepared during the concluding stages of SLD demonstrated that initial investment cost for implementing AAL was high. A solution to this problem was the proposal of making the assembly line semi-automated. With the semi-automated assembly line (SAAL) the picking and placing of all the components on a product carrier(described in Figure 1-5) would be done by an operator present at the start of the line (this task was expected to be done by an articulated robot in AAL, and the cost of such a robot was extremely high). With the approval for SAAL, the layout for the assembly line and corresponding assembling steps proposal was made. (Figure 1-4 shows the SAAL and the location of all the assembly station)

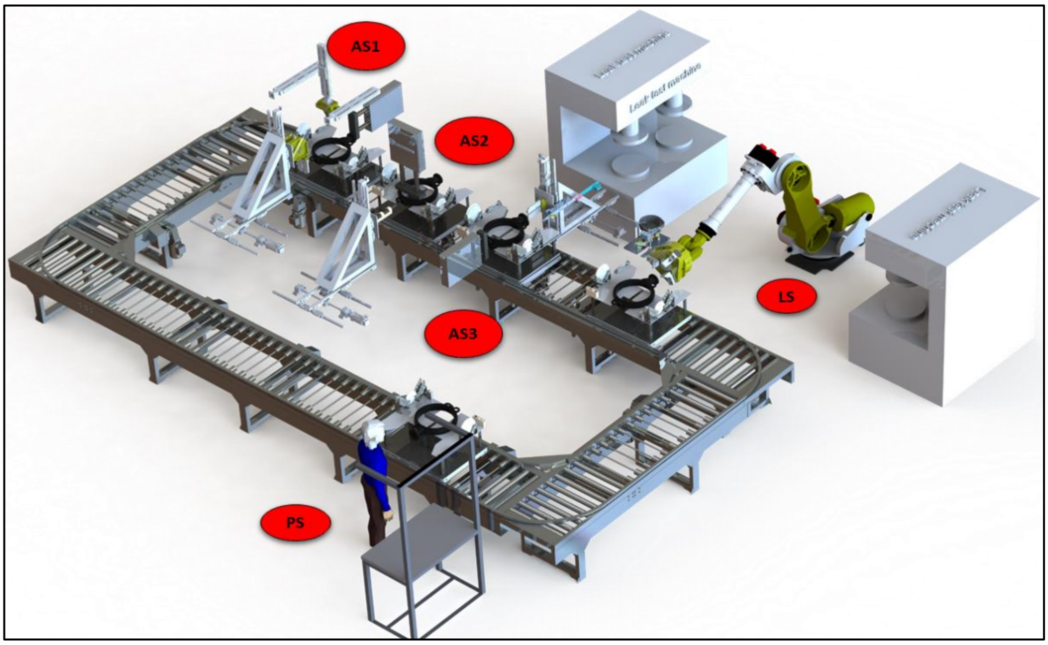


Figure 1-4: The semi-automated assembly line (SAAL) as developed during the system level design phase [39]. The line shows the positioning of all the assembly stations about the conveyor unit. The line starts from the pick & place station, operated by an operator (PS). The next assembly station is for assembling the disc and bottom shaft (AS1), followed by plug & ring assembly station (AS2), and drive shaft sub-assembly station (AS3). Lastly, the leak testing station (LS) tests the valves for leakage.

1. ***Pick & place station (PS):*** An operator standing at this station picks and places all the component on the product carrier.
2. ***Assembly station 1 (AS1):*** This station is for assembling disc and drive shaft.
3. ***Assembly station 2 (AS1):*** The station is for assembling the plug & ring in the threaded hole of the body.
4. ***Assembly station 3 (AS3):*** The drive shaft sub-assembly is assembled on this station.
5. ***Leak test station (LS):*** The fully assembled valve is transferred to leak testing machine.

The SAAL is to be equipped with 16 product carriers (Figure 1-5 shows the product carrier with all the fixtures). It is a unit equipped with different fixtures, and the detailed design had been carried out in system-level design (SLD). At a given point of time, each station has a product carrier and remaining are in buffer [39].

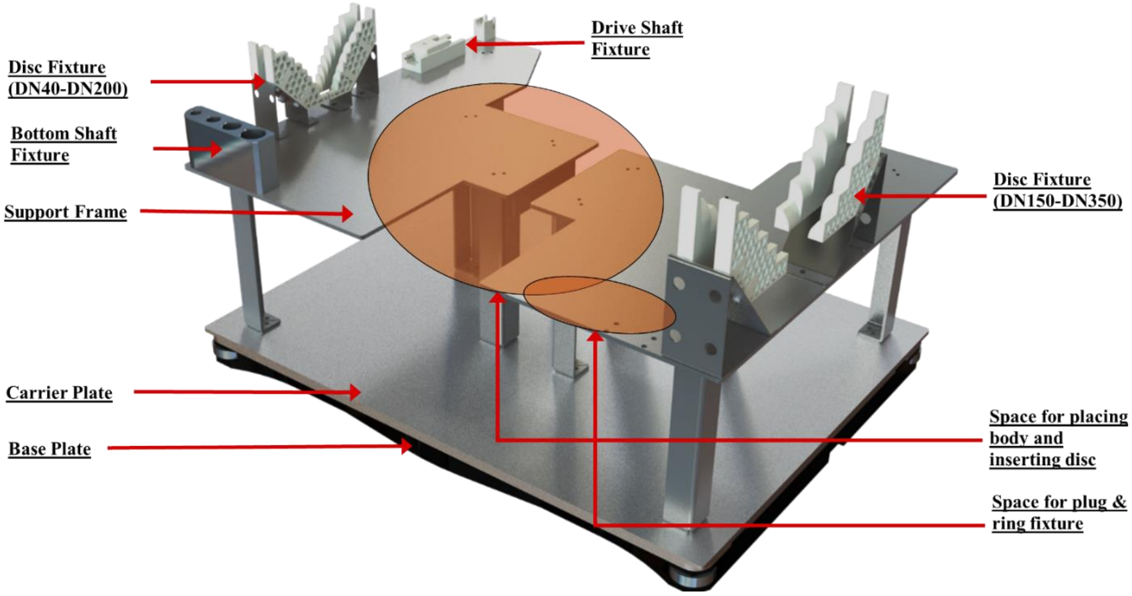


Figure 1-5: Product carrier [39] The figure shows all the different fixtures placed on the PC. Each component has an assigned location on the carrier, and there is ample space available for placing the plug & ring fixture.

1.2.3 Semi-automated assembly process.

The prior section provided a general overview of the SAAL layout and the proposal made for performing the assembly operation. This section explains the sequential assembly operation by illustrating the functionality of each assembly station. These steps are the outcome of study and analysis done during the prior stage research on system level design (Studied and referred to the proposal made for the automated process in [39]).

Initially, the body and disc are stored in the warehouse, picked as per the received order, and carried to SAAL by a warehouse operator. Other components of the valve would be stored and refilled at S1 in different kanban bins (part of current kanban system) as per their size, type, and material (Figure 1-6 the kanban system implemented in current assembly process) PS. Each component would have a distinct identification code, which would be helpful in choosing the component based on the received order. The body and disc arriving at the line would have a printed order sheet on which the individual identification code of each component as per the size, type, material, pressure class, and other necessary details are printed. Once all the components are at PS, the subsequent step would be to initiate the assembly process. The assembly of the entire valve is carried out as explained in the following steps.

Figure 1-6: Uniquely identified kanban bins for all the plugs (1), sealing rings (2), bottom shafts (3), and o-ring bushing (4). The black strips on the bins have a unique article number, used for identification of components as per production order.

1. The product carrier would be present on the conveyor system in front of the pick & place station. A trained operator present at the station acknowledges the delivery of the correct order from the warehouse.
2. Next, the body is placed centered on the product carrier. The operator is responsible for assuring centered placement of the body onto the product carrier because it is crucial for the functional accuracy of all the automated stations.

3. The subsequent step is to place the disc in the disc fixture (an integrated part of the product carrier.).
4. Then, the operator prepares the drive shaft sub-assembly by mounting the anti-blowout plate, O-rings, and sealing ring on the drive shaft. This is followed by placing the drive shaft sub-assembly, bottom shaft, sealing ring & bottom plug. Each of these components is placed in their respective fixtures.
5. After placing all the component, the product carrier moves forward on the conveyor.
6. At the first assembly station (AS1) a robotic system picks the disc from its fixture and assembles it into the body. Next, the bottom shaft is picked from its fixture and inserted in the bottom hole of the body.
7. On second assembly station, a robotic system picks the plug & sealing ring from the fixture and then fastens it into the bottom hole of the body.
8. The partly assembled valve then moves to third assembly station (AS3), where the drive shaft subassembly is assembled into the body, and two screws are fastened into the anti-blowout plate to complete the assembly.
9. The product carries then moves to the last station where a robotic system picks the completely assembled valve and moves the disc to close position. And, the assembled valve is placed into the leak testing machine for performing the leak test.
10. Lastly, the valves finished with testing are placed by the robot in the exit conveyor.

Based on the proposed steps rigorous analysis was done on the takt time and cycle time of the entire assembly line. The study was done with all considerations of downtime, operational time, yearly production volume, operating cost, etc. The analysis showed that apparently, **2min** is the optimum cycle time for the SAAL. Thus, further design and calculations of assembling plug & ring at the assembly station would be done in accordance with proposed cycle time. This does not mean the station would take 2mins to perform the assembly, but a relevant study would be done and corresponding optimum cycle time would be proposed (this could be either lesser or equal to 2min.).

1.3 Goal description & research topic

The current status of RECap is a result of consecutive studies, testing, evaluations, and proposals made by three graduate students who were working on this project. The background information provided in the previous section constructs the foundation for determining the goals of this design assignment. The SLD was concluded with a proposal for SAAL design layout and the corresponding assembly stations. And, detailed operational sequence and functionality of each assembly station have been determined. There is a broad spectrum of sizes for the valves under consideration. Moreover, an overview was given on what kind of mechanisms could be used to carry out the assembly.

The design and layout overview of all the stations of the line (except AS2) was done. Thus, the primary & general question arising from the background information is: How to automate the assembly operation of fastening the plug & sealing ring in the bottom hole of the valve body? Hence, this assignment is focused on the detailed design of the assembly station 2. For this report, the bottom plug & ring assembly station would be denoted as assembly station, and reference to any other station of the assembly line would be done concerning the operation it is assigned, e.g., Disc & bottom shaft assembly station, etc.

The general question of how to automate is extended to how to design an effective, efficient and robust assembly station. This would be addressed in the sequence of multiple questions (listed below).

1. What is the purpose of the assembly station and how are such systems designed?
   a. How is the assembly of PR done manually?
   b. What components of the valve must be assembled on this station?
   c. How are mechatronic systems designed & developed?
   d. Quality checks to be performed.
2. What are the requirements for designing the station?

a. What components make up a mechatronic system and which of them would be required for the assembly station.
b. What is the tightening torque required to fasten a plug to ensure leak-proof sealing?
c. How the plug & ring should be placed on the product carrier?

3. What components should be designed to build and evaluate the assembly station?
   a. How would the plug & ring be made available for the operation?
   b. What would be the configuration of the robotic system?
   c. What would be the sequence of operation?
   d. What would be the cycle time for the assembly station?
   e. What parameters could lead to the failure of the system and how to eliminate them?

1.4 Structure and Approach

The research represents a state of art assembly station and exclusively designed to address the design problem with a structured approach. Stepwise study and analysis would be done to address the research question and based on the exploration decisions would be made to attain the final goal. An elaborate knowledge had to be gained to conceive an efficient design of the assembly station. This station is a unique mechatronic station, which must be designed in a way that all the requirements of the system are met with limited or no constraints. For providing a design that could be readily implemented, it is necessary to dig into some specific factors that must be addressed in detail. These are distributed over eight different chapters and are summarized as follows:

- ***Chapter 1*: Background information**: The Initial chapter provided the introduction and background information on RECap and its status at the commencement of this assignment. This was concluded with defining the research questions and scope for the assignment.
- ***Chapter* 2: Research of the manual assembly step.** A primary stage study would be performed to understand how the plug & ring are assembled manually. The study would clarify which steps and actions must be automated. Simultaneously research and knowledge acquisition work would be done on Mechatronic System Design.
- ***Chapter* 3: Identification of modular solutions.** This chapter would illustrate the second phase study of the product and its components (i.e., valve body, plug and sealing ring). Based on the study necessary testing setup would be designed and tested. Followed by studying different system components that might be needed to design the station. And by the end of the chapter, a detailed summary would be provided on what exactly is the design problem at the system level, and the learnings would be used to steer the subsequent phase of conceptual design.
- ***Chapter* 4: Conceptual design at the system level for the assembly station**. This chapter acknowledges the conceptual design phase where learnings from chapter 2 &3 would be used to ideate conceptual designs for addressing the design problem. These designs would then be evaluated and graded to filter out the most suitable design concept.
- ***Chapter* 5: Detailed design of the assembly station**. Next, the 5th chapter illustrates the detailed design of the selected conceptual design. Here, one can find the calculations done to determine forces on the system and cycle time analysis. The intermediate stage of the chapter concerns the selection of appropriate components for developing the final assembly station. And it would be concluded with cycle time analysis followed by the proposal of DFMEA and preliminary control plan.
- ***Chapter 6:* System Validation.** The chapter gives a brief explanation on the cycle time analysis and 2D sensor testing, performed to validate the feasibility and functionality of the designed system.
- ***Chapter* 7: Evaluation:** This concluding chapter would consist of an evaluation of the proposed design based on the comparison of the costing of the designed setup and the estimation made during the system level design.
- ***Chapter* 8: Discussion, Conclusion, and Recommendations:** The research project would be momentarily concluded by discussing the outcomes of the research with the derived conclusions and providing value adding recommendations.

2 Research of manual assembly steps

Before digging into how the assembly station would look like, it is necessary to understand, what must be done and only then, proposals could be made on how it could be done. Initially, insight and knowledge are acquired on how a mechatronic system is designed. Following that research, the components, and parameters of the process which drive and affect the operation of the entire station are studied. Components of the system are defined as the parts of the valve that would be assembled on this station, i.e., plug and sealing ring. Later the components needed for designing the station would be studied.

2.1 Mechatronic system design

The following section illustrates what is meant by a mechatronic system, how it is different from the traditional method of system design, what are its essential components, and how it is designed. Each question is studied to get an idea of the system. The knowledge gained would then be translated to the design of the assembly station.

Traditionally development of product or system required separate & individual input from mechanical, electrical, information technology, etc. Firstly, the skeleton of the system was designed which use to be the functional mechanical components, this was followed by providing muscles to it which was part of electrical systems, then came the nervous system which was taken care by electronic systems and lastly the system was provided with brains by the control system. This method of development had limited interaction with other subsystems. Thus, the system was developed as homogeneous sub-systems according to their respective disciplines. Lastly, every sub-system was put together to form the final functional system. Thus, starting with basic design & manufacturing phase processing, parameters at each phase are optimized to produce a quality product in shortened cycle time [3]

On the other hand, the Mechatronic system design methodology leads to the optimal design of electromechanical systems. It is based on a concurrent, instead of sequential, approach to discipline design, which results in more synergistic products. It is not only limited to producing high-quality products but also considers their maintenance. Important parameters like failure rate, time, cost, modularity of design, onboard diagnostics, future compatibility with the current design, etc. are also taken into consideration [42]

A basic mechatronic system comprises of an overall functional system, array of sensors, actuators, control units, & information processing units. Such intelligent system includes the use of intelligent sensors & actuators which are integrated with signal converters and processors. The choice of components for such a system depends on the flows, which are mainly material flow, energy flow & information flow. The material flow is the movement of solids, liquids, or gases through the system which could be measured, monitored, analyzed, and monitored. Similarly, energy flow is the flow of thermal, mechanical, electrical, or any other form of energy. Also, forces, currents, and torques are a part of it. Lastly, information flow is about how different units communicate for a collaborative operation [42].

The design process for a mechatronic system is divided into 3 phases: modeling, simulation, prototyping, & deployment. Modeling is sub-divided in a simple model which illustrates the fundamental behavior of the system and a detailed model which is an extension of the simple model which gives elaborated functionality and accuracy than the prior model.

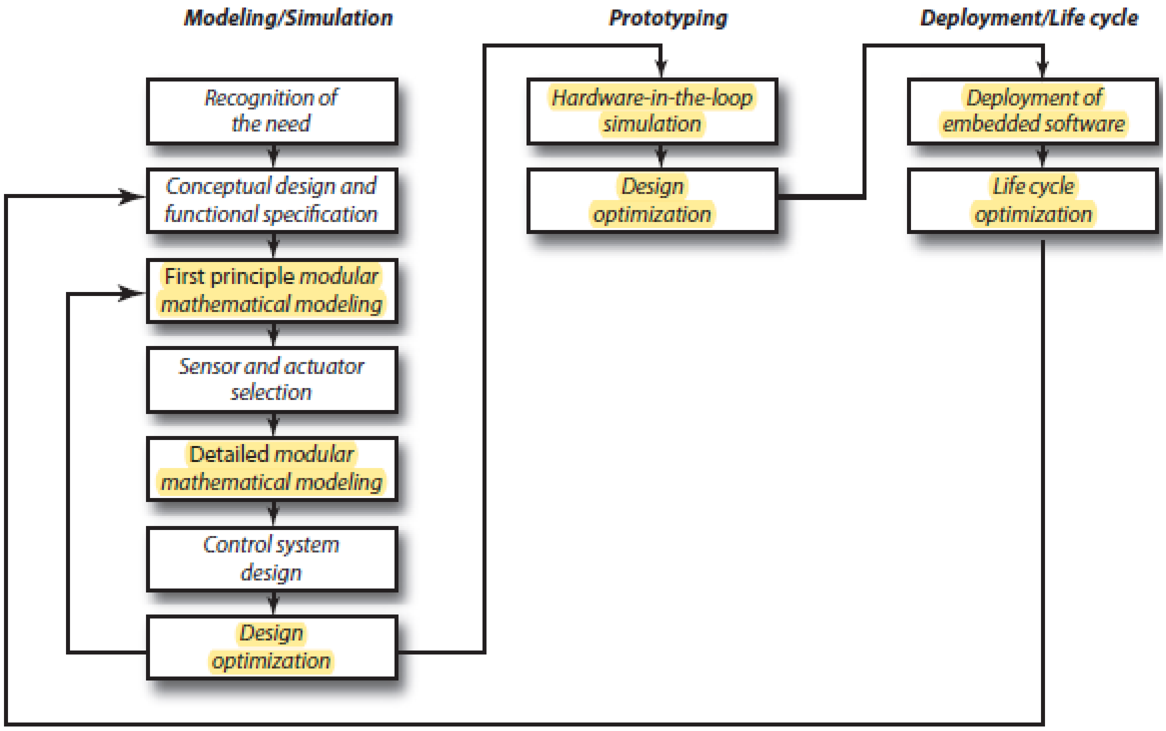


Figure 2-1: Mechatronic Design process overview [42].

Modeling uses a set of mathematical equations and logic to represent the behavior of a real system. Models could be static or dynamic, where static denotes models with no energy transfer, and hence no resultant motion and the dynamic models are precisely opposite. The dynamic models have a cause & effect structure where some specific signals give the desired output, and these are represented by block diagrams. Once the modeling is done, the next phase of simulation starts. Here, the simulation takes place in 3 steps: initialization, iteration, and termination. The obtained results are in the form of graphs, meter readout, animation, etc. and are used for presenting and posting output process.

Next phase is of optimization, where the aim is to get an optimal system configuration. Using which aspects like identification of optimal trajectories, control system design, model parameter, etc. are addressed.

The flow structure described in Figure 2-1 shows the complete process of development. However, due to lack of resources and knowledge in mechatronics, this research project would only address the following aspects of the process (Fields highlighted in Figure 2-1 are excluded from the scope of this project.):

1. Recognition of the need: Determine the requirements for the system design
2. Conceptual design & functional specifications
3. Sensors and actuator selection
4. Control system design: Detailed design is kept out from the scope of this project; only preliminary proposals would be made.

2.2 Manual assembly of plug & ring

This section is dedicated to comprehending how the plug & ring are manually assembled. The understanding would be used to define requirements for the automated process. The detailed manual assembly process is described in the appendix B. However, the concentration of this research is limited to step no.5. (Tightening of the threaded plug & sealing ring). It is necessary to recognize the set of steps followed by an operator for this operation and only then a suitable system could be designed which closely imitates a human.

After assembling the disc & bottom shaft, (step 1-4 in the appendix. B) The valve is in partially assembled form, and this is exactly like the set of operation carried out on AAL at the disc & bottom shaft assembly station. The subsequent step is assembling the plug & ring (PR). The stepwise operation performed by the operator is illustrated in Figure 2-2

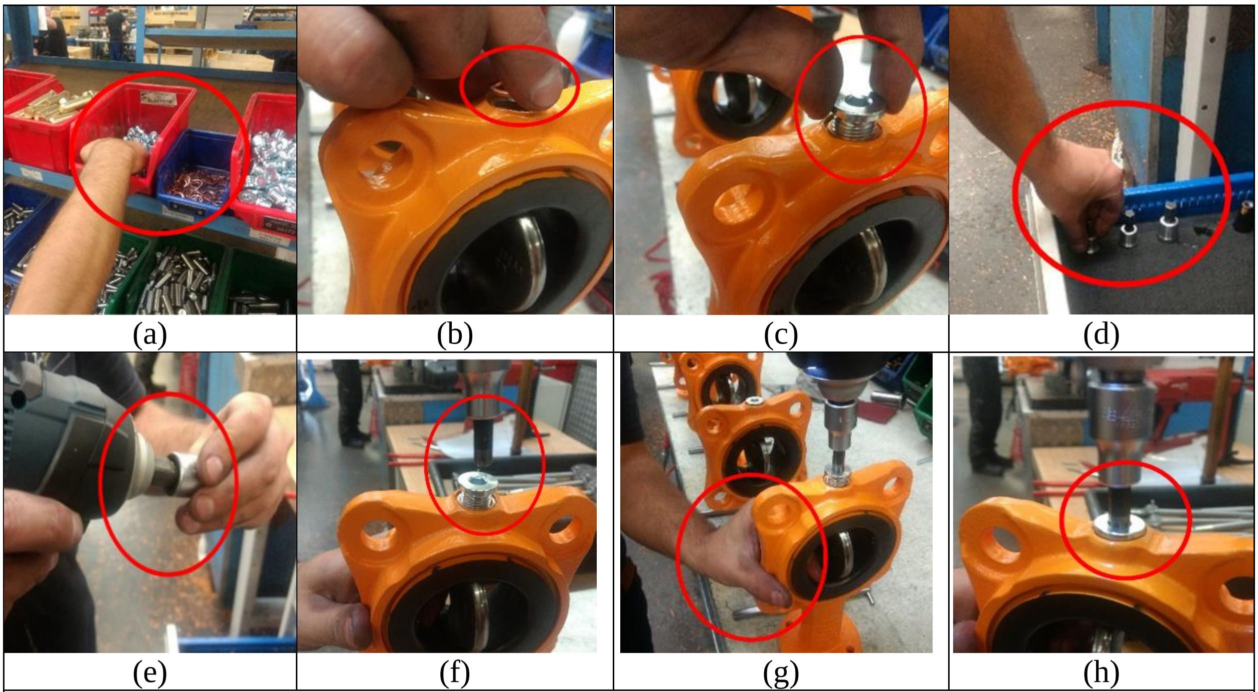


Figure 2-2: The steps followed (a to h) by the operator to assemble the plug & ring in the bottom hole of the partly assembled valve.

The detailed illustration of steps carried out by the operator to assemble plug & ring as shown in Figure 2-2 (a) to (h) is as follows:

- ***Picking the plug & sealing ring:*** Firstly, the operator picks up the right size of the plug & sealing ring. The appropriate size is mentioned in the production order in the form of article number.
- ***Placing the sealing ring*:** Initially, the operator places the partly assembled body on the table resting on the top flange and inserts the sealing ring in a counterbored hole at the bottom end of the body.
- ***Inserting the threaded plug*:** Next, he puts the threaded plug in the threaded hole and performs 2-3 turns to engage the threads.
- ***Selecting the tool bit***: He selects hexagonal tool extension/adaptor from the toolbox as per the size of the plug.
- ***Tool bit change*:** The tool extension is mounted on the impact gun by py pressing the ball socket end of the gun against the tool bit.
- ***Aligning & inserting the tool in the plug***: The ready tool for operation is inserted inside the hexagonal end of the plug.
- ***Performing the tightening operation***: Lastly, the operator holds the valve body with his hand and tightens the plug until the plug cannot be tightened any further.

2.2.1 The outcome of studying the manual process.

The fore stated points portray the operation, but there are more intermediate steps to this operation. Before placing the Plug and Ring (PR), the operator must check and identify the size of the body, as the size of the body decides the size of the PR to be used. Thus, using a correct size is desirable. The plug and rings are stored in kanban bins on the worktable of the operator and are appropriately identified. Hence, a similar arrangement must be made at the station such that the correct plug and ring could be made readily available for the robotic mechanism that performs the operation.

Secondly, the operator must select the correct size tool for tightening and for that purpose, they are provided with a well-identified and easy to access toolboxes. This could be translated as a requirement for tool change unit at the assembly station.

Lastly, a noticeable step is, the operator firmly holds the body while tightening the plug. This is done to restrict the rotation of the entire valve about its geometric vertical axis due to applied tightening torque. Therefore, a similar counter torque mechanism must be installed which holds the body and prohibits rotation.

From this section a following set of conclusions are made on the requirements of the system:

1. A robust system must be designed to fasten the threaded plug with the sealing ring in the bottom hole of the body.
2. Fixture- Designing a unit/fixture to hold/ deliver the plug and ring.
3. Tool change station- System to select and change to required tool extension as per the size of the plug.
4. Investigating and selecting an appropriate tightening tool.
5. Mounting of different sized tool extensions on the tightening tool
6. Determining the torque required for fastening different size plugs.
7. A mechanism to counteract the torque by holding the body in position

3 Modular solution identification

3.1 Product components Study and Analysis

Following sub-section of the research addresses the study of variation in the size of components. This study would define parameters to be tested and thus resulting in the design of the test setup. The knowledge gained from study and testing would be then used to develop concepts

3.1.1 Threaded Plug (DIN-908-Metric Thread Plugs)

The threaded plug is the most crucial part and components of the station. Design of the whole system is profoundly influenced by the variation in the size of the plugs under consideration. During the system level design phase, four sizes of plugs were being used for all the different variants and sizes of bodies. However, at the preliminary stage of the detailed design phase, the shaft sizes used in bodies from DN40-DN350 changed from four to five (earlier the shaft sizes were not as per the ISO standard). Thus, the plug sizes also changed to five. A detailed overview of the variation in sizes is made and could be found in the appendix. C.1 (Table. C-1)

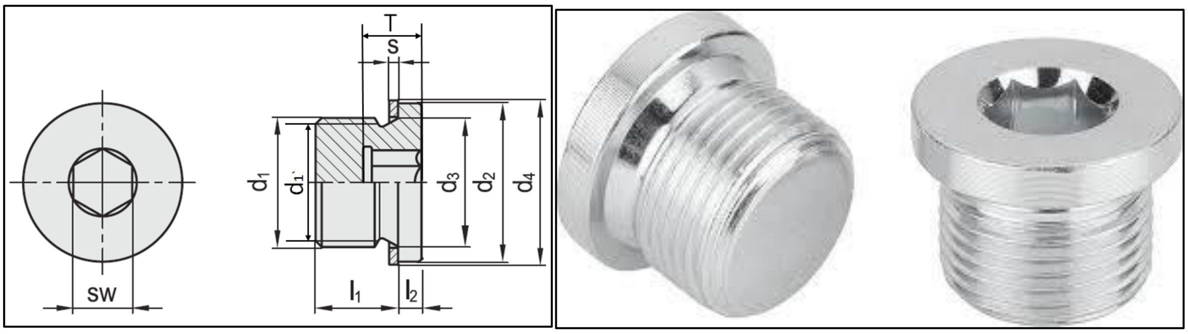


Figure 3-1: DIN-908 Plug Annotation [25].

Figure 3-1 shows the threaded plug annotation. The variation in 'SW' dimension governs the type of tool needed; the 'l_1' dimension helps determine if the plug is completely installed and other dimensions are crucial for the design of the fixture.

3.1.2 Sealing ring

The sealing ring is the second crucial component to be assembled at the assembly station. The valves are designed to provide sealing at three levels. The primary sealing is the disc which is in contact with the flowing medium. The secondary sealing is the contact between flat end circumference of the disc and the vulcanized rubber on the body. Lastly, the tertiary sealing is provided by the plug & sealing ring. In case of failure of both the primary and secondary sealing, the medium under pressure is exposed to tertiary sealing. Hence, the sealing ring should assure leak-tight seating, and this is assured if the plug is tightened correctly. Presently Wouter Witzel is using copper rings as tertiary seals, compressed in between the bottom hole and the flange of the bottom plug during tightening. Tests were performed during the SLD with the copper sealing rings to determine the torque needed to ensure a leak-tight seal. Testing showed that even after tightening the M36 plug with a torque of 300-330 Nm the sealing was not leak tight [39]. Thus, it was clear that the copper ring does not assure a full proof sealing (Figure 3-2 shows the leakage past the sealing ring).

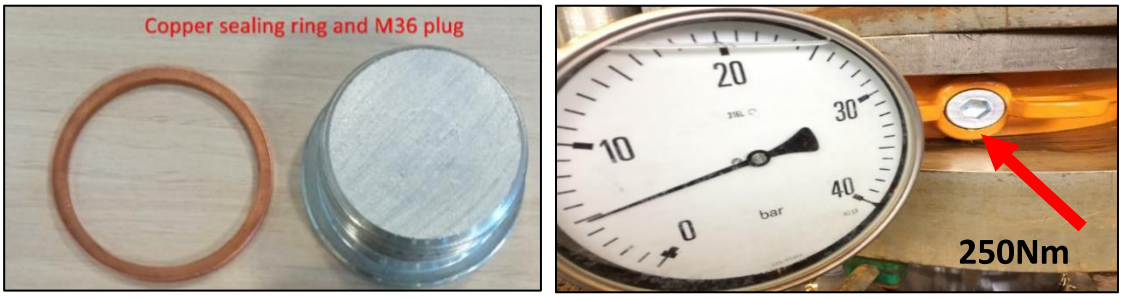


Figure 3-2: Leak past the copper sealing ring and plug even after applying a tightening torque of 300-330-Nm [39]

Hence, a solution was proposed to replace the copper sealing rings with bonded sealing rings (BS rings). The BS rings design has an additional rubber ring (Cross section-trapezium) cured on a metal ring [38]. The applied torque compresses the rubber before it could compress the metal ring, and this compression provides more effective sealing as compared to conventional copper rings (Figure 3-3 shows the functionality of a BS ring). Tests performed on BS ring show that the torque required to tighten the plug to assure leak-tight sealing is as low as 50Nm (as shown in Figure 3-4).

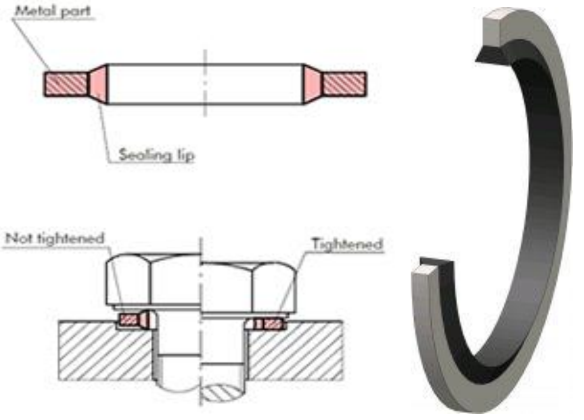


Figure 3-3: Sealing obtained by compressing the rubber ring of a BS [8][38]

Figure 3-4: No leakage past the bonded sealing ring and plug when the plug is tightened with a torque of 50-Nm [39]

Hence, a decision was to be made on which type of sealing ring must be used in the future. Because it directly affects the following:

- The size and rating of the tightening tool/mechanism: (Required torque would be reduced considerably)
- The type of robotic system: Lower torque results in lower reaction forces on the system and thus low torques required for the movement of robotic systems.
- The design of the PR fixture (size and type of sealing are governing parameters).

After conducting a meeting with logistic/warehouse, engineering, work preparation department it was determined that it is more logical to use a bonded seal than the copper rings.

The tightening operation had to be carried out with plug and ring in horizontal operation (this orientation is a result of research from SLD which led to the decision of placing bodies flat on the rubber face on the product carrier.). One significant drawback with both the bonded sealing rings and the copper ring was their loose fit over the plug. Moreover, with a slight inclination (when in the horizontal position), the sealing ring could slide off from the other end of the plug. Moreover, in the horizontal orientation, the rings were non-concentric to the plug (Figure 3-5 & Figure 3-6). When the PR would be fastened with a non-concentric ring over the plug, it would jeopardize the sealing of the valve.

Figure 3-5: M36 Plug with sealing ring of copper in non-concentric orientation about the plug.

Figure 3-6: M36 plug with a bonded sealing ring with a non-concentric orientation about the plug.

An alternative for this was a self-centering bonded seal (ScBS). These are derivative of the bonded seals with an additional rubber ring; this ensures the ring is always concentric to the plug (Figure 3-7 shows the inner ring profile of ScBS rings).

Another notable difference in the sealing rings was of the dimensions of the rings. The size of the ScBS was larger than the copper rings. In the bodies spot face diameter was machined according to the size of the copper rings, and opting to use ScBS means changing the spot face diameter of the body. A summary of dimensions for all the three types of sealing rings was prepared, and it was used to check the change in dimensions of the body (The variation in dimensions of the ring are summarized in Table. C-2). Also, this would help in designing the test setup for determining the tightening torque.

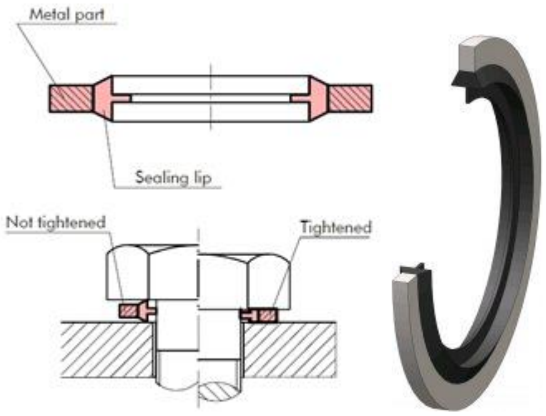


Figure 3-7: Centering of the ScBS ring around the fastener and providing sealing with compression [8][38]

3.1.3 Valve Body (Position of Thread Hole).

There is a substantial variation in size and type of bodies and must be carefully analyzed, as this affects the positioning of the tool, fixture, and the movement of the system which ultimately governs the cycle time of the system. Figure 3-8 displays an example to illustrate the position where the bottom hole with respect to the product carrier, for EVFL DN350 it is 94mm from the edge and 146.5mm high with respect to the support frame; whereas for an EVS DN40 body the bottom hole position is 266.8mm from the edge and 22.5mm above the support frame. A detailed summary depicting the position of the bottom hole for different sizes and types of bodies could be found in Appendix C.3 under Figure. C-6

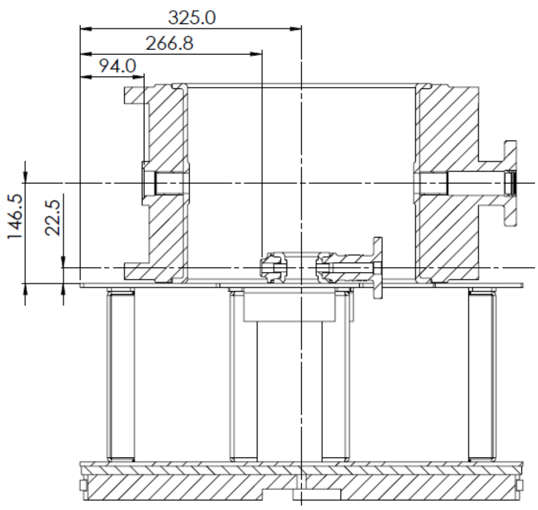


Figure 3-8: Position of the bottom hole from the center of the product carrier, for different sized bodies

3.2 System component study

This section is assigned to provide details on components of the assembly station such as the selection of a tool for the assembling the plugs, the type of sensors that could be used and the components which would build up the Cartesian system.

3.2.1 Tightening Tool

Based on the test results of the torque requirement for different plug sizes, a tightening tool had to be selected which could deliver the required torque. Typically, three types of power tools are used to perform the tightening operation. These are called Nutrunner and are pneumatically, hydraulically, and servo powered tools. Each variant has its pros & cons, and their selection is made based on the usage condition. Hence, selecting an appropriate tool is crucial for this system as it drastically influences the global design of the system. The three variants of power tools were researched and based on evaluation the final tool option was selected. Table 3.1 shows the comparison parameters and the corresponding evaluation.

Table 3.1: Comparing different tightening tools based on their characteristics.

Comparison Characteristics	Pneumatic	Hydraulic	Electric
Medium	Pressurised gas	Pressurised fluid	Electric drive
Power / Torque delivered	High	High	Moderate
Tool size	Small	Small	large
System size (power unit & Auxiliary system)	Large	Moderate to large	Compact
Cost	High	High	Moderate
Maintenance	Moderate	High	Moderate
Support mechanism	Required	Required	Required
Input Power Requirement	High	High	Low
Tool weight	Moderate	low	Moderate
Noise	Moderate	Moderate	Low

Based on the comparison, it could be stated that the servo driven & pneumatic tools are great options to work with, but the requirement of an auxiliary compressor unit for the tool is a drawback for the pneumatic tool. Hence, it is more appropriate to choose an electric Nutrunner. A variety of Nutrunner is available in the market. These differ in total length, tool offset and most importantly the torque range. For this application, both offset and straight tools were appropriate. Choosing an offset tool means, the reaction support structure needed would be small, but a lengthier tool extension would be needed to tighten the plug for smaller sized bodies. Whereas with a straight version the tool extension length is reduced. A variety of nutrunners were compared based on the torque delivered, their size, weight and the length (comparison matrix could be found in the appendix.G). The important parameter for the choice of the tool was the length and weight of the tool, as it governs the overall design of the system. Based on the comparison, a CFT-401RS1-SL tool from 'FEC Automation Systems' [27] was selected.

Figure 3-9: CFT-401RS1-SL Nutrunner [27]

3.2.2 Sensors:

Sensors are the crucial components of the entire system, without these, the system is blinded. A general approximation is made on required sensors; this is based on an estimate of what parameters need to be analyzed. Sensors would be needed to:

- Detect the arrival and departure of the product carrier in and out from the station.
- Detect the position and orientation of the PR in the fixture.
- Monitor the tightening torque and angle of rotation during each tightening cycle.
- Monitoring the complete assembly of the PR into the body

Presence or absence of an object can be detected by contact or non-contact sensing device. These sensors produce output in the form of an electrical signal which is then used to control the sequential operations.

- *Limit Switches*: These are mechanically activated, contact type switches, i.e., the functionality of the switches depends on their physical contact with the object. They have an arm, lever, knob or a plunger at one end which is activated when in contact with the object to be detected. After contacting it eventually moves the actuator to its limit where the contacts change state and indicate the presence of an object. Their benefits are: could be used in any industrial environment, precise in accuracy and repeatability, consume less power, could switch loads with high inductance and can control multiple loads and high switching frequency, repeatability, and accuracy. Their limitations being: restricted to equipment operating at relatively lower speeds, must make direct contact with the object and the mechanical parts wore off.

- <u>*Proximity sensors*</u>*:* These detect the presence of objects in their close vicinity without any need of physical contact with the object. There are four types of such sensors, capacitive, optical, inductive, and ultrasonic. Selection could be made based on the operational requirements. The fundamental operation involves calculating the distance based on the difference in transmitted and received signals. These have benefits like non-contact sensing & no backlash; no mechanical moving parts; compact, robust, withstands vibrations and mechanical shocks; long lasting (no wear) and maintenance free. However, their only limitation is, some variants have limited sensing distance.
- <u>*2D sensor:*</u> These are quite advanced sensors which are very accurate and precise in determining the shape, position, and orientation of an object under their field of vision. The measurement principle concerns projection of light in the shape of a horizontal line, which is diffusely reflected by the target object. 'The reflected light is formed on the HSE^3-CMOS (High-*Speed Enhanced Eye Emulation-Complimentary Metal Oxide Semiconductor*) and by detecting changes in position and shape displacement and shapes are measured'[31]. These sensors could be used for stationary as well as moving targets.

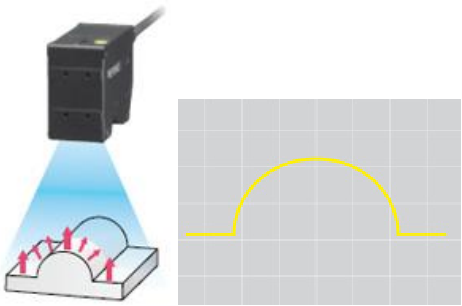


Figure 3-10: Profile sensing by a 2D [31]

- <u>*Torque Sensor*</u>*:* These are widely used in digital power tools to determine and control the torque applied. It works on the principle of measuring the shear stress induced in a strain gauge when torque is applied. This sensor is incorporated in nutrunner and thus, not have to be mounted/incorporated separately.

The sensors mentioned above would be incorporated into the design based on their specific need. If the demand is fulfilled by any conventional control method, then these sensors could be skipped. This decision is made in a later phase in the detailed design section.

3.2.3 Conveyor with positioning unit and stop gate

The assembly station is to be designed around a conveyor system (TS 5 4.0 Longitudinal conveyor) which has been selected during the SLD. The conveyor system (CS) is equipped with a stop gate (Figure 3-12) and a positioning unit (Figure 3-11). These are selected based on the load to be carried and the size of the conveyor. The positioning of the PC changes while moving on the CS. Thus, a positioning unit is used in conjugation with a stop gate to stop and position the product carrier (PC) on the CS. The stop gate is placed after the positioning unit (PU) and has provisions for mounting a proximity sensor. The stop gate is in open position to stop the PC and signals the PU to engage. The PU is also equipped with a proximity sensor to determine the position of the PC over it accurately. Once, the PC is in the position its baseplate holes are in alignment with the four pins of the PU. When actuated the PU engages its pin in the baseplate and lifts it by 5mm with a positioning accuracy of 0.3mm. The positioning unit plays a vital role in positioning, and thus it affects the operation of the entire system.

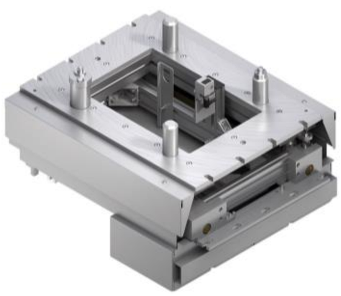


Figure 3-11: PE 5 positioning unit for TS 5 longitudinal conveyor [14]

Figure 3-12: VE5/200 stop gate for TS 5 longitudinal conveyor [14]

3.2.4 Components for Cartesian system

This section highlights the components of the Cartesian system. All the movements of the system are linear, and hence the Cartesian robotic system is the most suitable configuration to use (deduced from the conclusion made on the type of system to use [39]). The Cartesian system is made up of different modules; it could either be a guide rail system or a compact linear module. Both the systems are discussed, and appropriate overview is provided. These would be later evaluated during the detailed design phase to decide whether to use linear modules or linear guide systems or a combination of both. There are well-known manufacturers of linear motion systems, like SKF, Thomson linear motion, Bosch Rexroth, PBC linear, etc. and are widely used for automation projects. For this research, products from Bosch Rexroth (BR) are studied and considered. The reason being the TS5 conveyor system along with the product carrier selected and studied during the system level design is from Bosch Rexroth. Moreover, it was assumed that considering the system components from Bosch Rexroth would be cost efficient from ordering, installing & maintenance perspective. Moreover, having components from a single manufacturer would enhance the compatibility of controls with drive units. Also, BR has a more explicit, more detailed elaboration and explanation provided for selecting and building a linear system as compared to others. Software like 'LMD' & 'LIN Select' provided by BR is excellent for operation-specific component study and selection. Lastly, ESPS is a supplier of linear motion technology components from BR and also is a part of this RECap project. This gives an added advantage on support and services in the near future. However, at the concluding phase of the detailed design, a brief study would be performed to investigate for better alternatives for selected products (this would be helpful from cost, capacity and performance point of view).

There are two approaches to building a linear Cartesian system. In the first approach, a designer could develop the system from scratch, mostly called as a DIY approach. On the other hand, with the second approach pre-engineered assemblies (linear modules) could be purchased and assembled. The choice of approach is governed by the details of the engineering process [21]. Both approaches have certain advantages & disadvantages, these are discussed in the following sub-section.

3.2.4.1 Profiled Rail System / DIY Linear motion solutions

Profiled rail systems are linear systems made for fulfilling specific translational requirements. This type of systems can carry an enormous load over the desired distance. This approach of developing linear system offers the option to customize every detail of the machine. Thus, each component would be selected based on end process requirements. Moreover, it is considered more effective in meeting desired accuracy and precision requirements or dimensional or environmental parameters. However, considering the time required to develop the system from scratch, it is considered as a bit expensive approach.

It is comprised of a guide block, guide rail & drive unit. Figure 3-13 shows a general configuration of a linear guide rail (LGR) unit.

Runner blocks: A compact unit that encloses the rolling elements, sealing slips, lubrication ports. It is designed in a manner that the rolling elements are in constant contact with the guide rail. The rolling motion of the elements facilitates translational motion along the length.

Guide Rail: An extruded and later machined element on which the runner block is mounted. This acts a path for the runner block to move along. It has high standards for mounting and installation to assure smooth operation.

Drive Unit: The driving mechanism of the entire system is the drive unit which comprises of a lead screw with a linear bearing which is enclosed in a housing. The lead screw is supported with two end bearings, and a servo motor drives the screw via a coupling. The linear bearing houses rolling element which move in a closed loop to translate the housing over the length of the screw.

Base Platform: It is like a carrier plate on which the load to be carried is mounted. The plate is attached to the runner blocks and the carriage unit of the drive unit. In this manner, the runner blocks are driven by the drive unit.

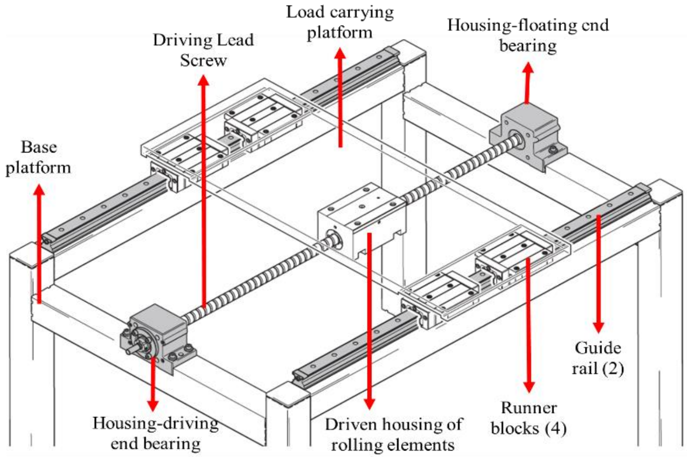
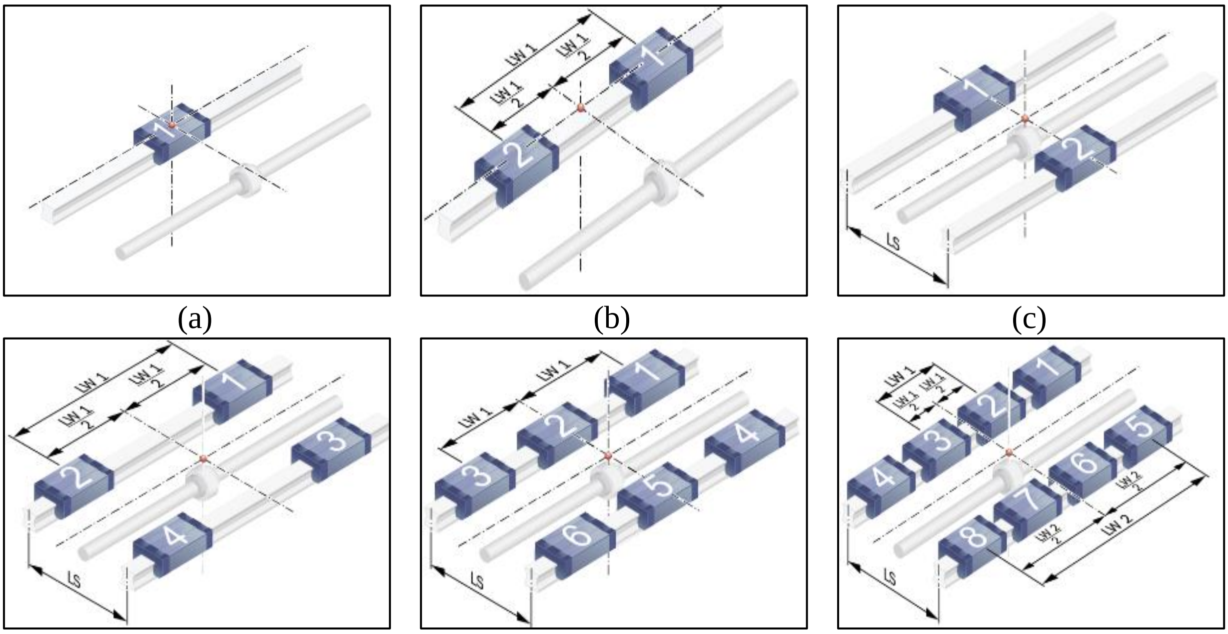


Figure 3-13: Basic linear guide rail system [13]

A linear guide rail system can have different configurations (Figure 3-14 (a)-(f) show the possible configurations of the system). From the possible configuration, a suitable one is chosen during the detailed design phase. The dimensioning and performance of the drive unit is decided by the stroke, load to be carried and other operational forces. The selection of linear guides is made according to DIN 637 guideline [10] (The flow sequence for selection is provided in the appendix. D Figure. D-1).

The forces acting on the entire system are the weight of all the components, their inertia forces and the tightening torque of the tool. These forces govern the selection of the guide blocks. A wide variety of runner blocks are available that could be used to make a linear guide and thus selecting one which best suits the requirement is essential. Whereas the guide rails are mostly standard for the different size of runner blocks, and therefore a general guide rail could be selected. The runner blocks are available with cylinders and balls as the rolling element. In comparison to spherical balls, the cylindrical rolling elements are well known for their high load carrying capacity. However, for this scenario, it is assumed that the load on the system would not be in higher range (around 2000-5000N) and balls as rolling elements would be a suitable option to commence the design process. The detailed selection procedure based on calculations is described in the appendix. H

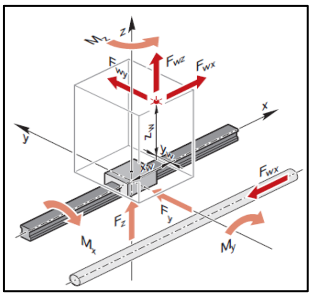


(a) (b) (c)

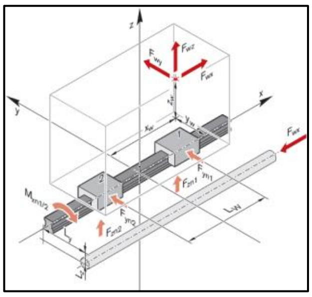
(d) (e) (f)

Figure 3-14: Possible combinations of the runner block and a drive unit to make a linear guide system [33]

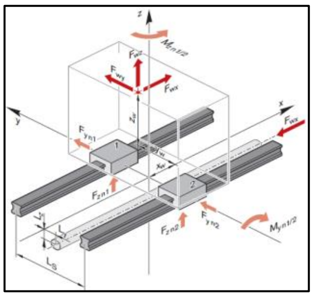
Each configuration of the guide rail system could be selected based on the loading and application. Figure 21.7 (a) – (d) show the different reaction forces experienced by the runner blocks depending on the configuration.



(a)



(b)



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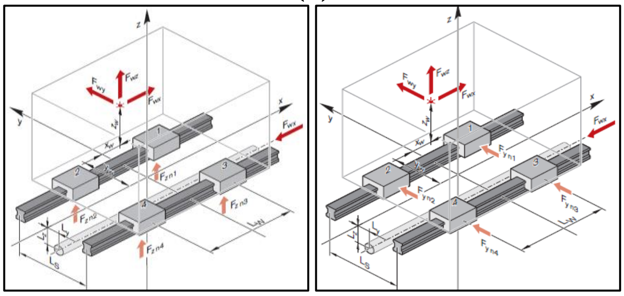


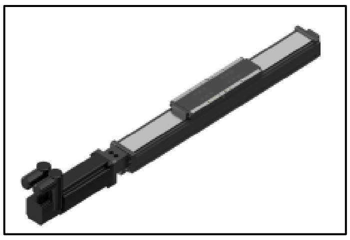
(d)

Figure 3-15: The reaction forces & moment on the runner blocks depending on their number and configuration [33]

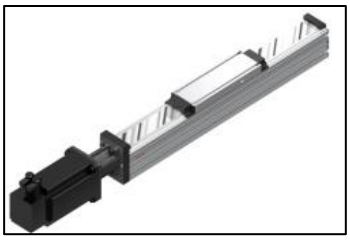
The single runner block unit (Figure 3-15 (a)) experiences a normal & transverse reaction force and moments about all three-principle axis. Whereas 2 runner blocks on single rail experience moment only about the x-axis and the reaction forces. Similarly, single runner block on two rails experience moment about y & z-axis and the reaction force. On the contrary, other rail & block combinations only, experience reaction forces and no moment. The 4/6/8 blocks and two rail system are considered suitable for the assembly station (because these configurations do not have a resultant moment load acting on the system). This detailing on the configuration would be performed during the detailed design of the system.

3.2.4.2 Linear Motion Systems / Hybrid linear designs (Modules)

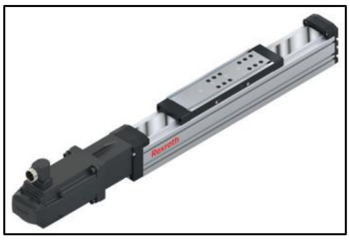
The second possible unit for linear motion is linear modules (LM). These modules are precise, ready-to-install guide and drive systems with high-performance features. These are linear guide systems which are compactly embodied into a casing with the drive system as an integral part. These pre-engineered setups provide the freedom to mix and match parts of the system. Similar to LGR units, it has guide blocks which are attached to the driving nut on the lead screw, and these guide blocks are guided on rails. These are also available in various configuration and selection is done based on stroke length, load carrying capacity, required precision and required sizing. The components of the assembly are predefined and have documented capacities. Moreover, these modules come with manufacturer's warranty and service assistance. However, the lower the level of customization is the main disadvantage. In some cases, modules with higher capacities than required are needed and might be costly.



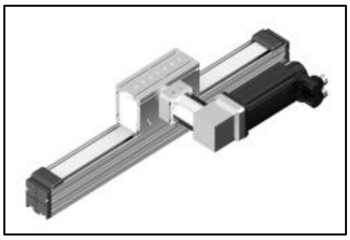
(a)-Precision modules



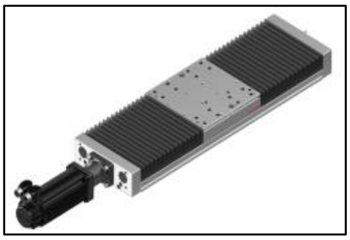
(b)-Function Modules



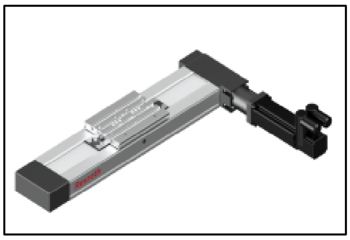
(c)-Linear Modules



(d)-Omega Modules



(e)-Ball rail tables



(f)-Compact Modules

Figure 3-16: Available varients of linear modules [11][19][17][12][9][15]

The variants as shown in Figure 3-16 were compared based on their dimensions, dynamic load capacity, functionality, and repeatability (the table for these parameters is available in the appendix. D Table. D-1). The comparison showed that function modules (b) have repeatability of 0.015 mm as compared to other variants with repeatability value of 0.005mm. Omega modules (d) and ball rail tables (e) are comparatively wider, higher and have a higher dynamic load carrying capacity (denoted by C) in comparison to precision modules (a), linear modules (c), and compact modules (f). Also, precision modules and linear modules if considered for a particular size (for instance width between 80-90mm), have excessively higher values of 'C.' Thus, instead of choosing modules with higher 'C' in the initial stage of design, it was thought wise to select variant with comparatively lower 'C.' If the selected module would result in functional failure, then a different variant would be selected. Therefore, compact modules (CCK) was considered as an initial unit for the iterative process of calculation.

The decision on using a linear module or guide rail system could only be made after detailed calculation. This is done in the detailed design phase in section.

3.2.4.3 Motors

The motors are responsible for actuation of the electromechanical system. Generally, a mechatronic system can have a different type of motors; but traditional stepper and a servo-based system are widely used. The reason for their wide usage is their high torque delivery, positioning accuracy and resolution. Steppers typically use 50 to 100 pole brushless motors while typical servo motors have only 4 to 12 poles [1]. A stepper motor performs accurate incremental steps between its poles using pulse input and thus, does not require an encoder. Whereas servo motors need an encoder to keep track of their position. Thus, it reads the difference between the motor's encoder and the commanded position and adjusts the current required to move [1]. Both motor types are suitable for this particular application. But the modules discussed in the previous section are only available with servo motors. Their operation based on a feedback loop is the reason for their choice. This feedback provides positional accuracy and could be efficiently controlled by control systems. The modules are available with different servo drives and the decision on selecting the appropriate drive would be done in the detailed design phase.

3.3 Confirmations & quality checks.

This section presents the preliminary overview of various checks that might have to be done to assure the desired operation. Prior to this section, the components of the system were discussed, and an essential link in the operation of semi-automated assembly is the operator. The operator places all the components of the valve on the product carrier in their respective fixtures. The placement and orientation of the components influence the assembly process. For this station, the body, bottom plug, and ring placement are of prime concern. Therefore, it must be checked that the right size plug and ring are placed in the fixture and that too at their assigned position. During the SLD, it had been discussed that necessary sensors would be installed on the manual station to assure correct placement of all the components. These sensors and the manual operational platform would be worked out in the future phase of RECap; it could be assumed that there is no need of performing a check at the assembly station for the presence of parts at the exact location. However, considering the continuous operation of the line, it is difficult for the operator to keep the body centered on the PC and the PR with a consistent orientation through his working shift. Tentatively a sensor at the manual station identifies incorrect placement (out of center) of the body and informs the operator to makes the corrections. There are possibilities that the positioning could be slightly altered during assembly operations and movement over the conveyor. Thus, a check must be performed to identify the position of the bottom hole of the body and check the orientation of the plug & ring

The second check is concerned with the tool changing. The plugs are of five varying sizes and consequently would be the tools needed to tighten them. These tools would be picked from some tool change unit, and after the tightening operation, it must be placed back in its corresponding position. Thus, checking and confirmation is needed to assure tool change and replacement.

Lastly, a check needs to be performed to assure that the plug is fully tightened into the body. There might be an instance where the plug might be stuck in the threaded hole of the body, and a false signal is generated to the system about attaining predefined tightening torque value. In such a scenario, the assembly is incomplete, and it is necessary to assure that the system can cope up with such abnormality. Therefore, a check on the desired completion of assembly must be performed.

The checking and confirmation of the above-stated parameters would be discussed and briefed during the detailed design phase.

3.4 Initial testing for determining the tightening torque

This section describes the test performed to determine the tightening torque required for each size of the plug. Based on the dimensions of the plug and the sealing rings a test ring was designed to determine the torque required to attain leak-tight sealing.

These test rings were initially designed during the system level design and tested with copper sealing rings. However, the failure of copper sealing rings led to the proposal of BS rings. The ring was redesigned and tested for the M36 plug. For the current phase, all the different plug sizes and rings had to be tested. Hence the rings were designed with slight modification. In comparison to the prior design, the new design of rings had two different types of threaded holes (12 holes in total). It had six holes with a counterbore hole with a chamfer on its edge and had a close fit around the outer diameter of the sealing ring. The other six threaded holes had a loose fit around the outer diameter of the sealing ring and no unique feature. The intention was to check if the chamfered edge could guide and center the bonded sealing ring about the plug and assure minimum clearance resulting in effective sealing.

The purpose of using a test ring instead of the actual body was:

- At a time only one plug could be tested.
- The bodies spot face diameter for the sealing ring was smaller than the one required for the new rings and machining the bodies only for the test purpose was not economical.
- Also, there was a risk of causing damage to the bodies.

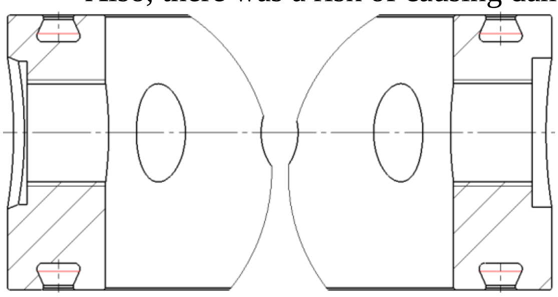


Figure 3-17: Two different types of threaded holes in the test ring. The hole on the left side has a chamfered edge.

Figure 3-18: Tightening the plug & ring in the test ring at 10 Nm torque.

Figure 3-19: Testing the assembled ring at 37.5 bar pressure for 10mins to check for visible leakage.

The rings were tested with their respective sizes with water pressurized at 37.5bar. The largest size in the scope of the project is DN350 of pressure class PN25 (i.e., it can withstand a maximum pressure of 25bar), and as per WW testing methodology. The bodies are tested at 1.5 times their pressure class. Therefore, the rings were tested at the maximum pressure of 37.5bar. The plug and rings were tightened with a starting torque of 10 Nm and gradually increased. The tightening torque at which there was no visible leakage was considered as an optimum torque for attaining a leak-proof sealing. The testing methodology and the test procedure is described in the Figure. E-3.)

Test results show that if plug sizes M16, M18, M22, M27 & M30 are tightened at 15Nm, 15Nm, 15Nm. 20Nm & 25Nm torque respectively, then a leak-proof sealing could be attained which abides by the leak-proof criteria of WW. However, the plug should be tightened with torque values greater than the determined values to ensure that the sealing is always leak tight.

A significant finding from the test was, both the rings provided leak-proof sealing when the centering of the rings about the plug is accurate. As stated earlier, the ScBS rings have excellent centering over the BS rings. Thus a larger counterbore diameter hole for the threaded hole on the body would not affect the sealing. Whereas, for BS rings the fit should be close around the circumference of the ring to assure the ring is concentric about the plug. But a smaller diameter means when the plug and ring are held in a horizontal orientation the ring is eccentric. Thus, it could get stuck between the flange of the plug and body causing hindrance in tightening operation (Figure. E-7). From the test, it was seen that the chamfer on edge guided the eccentric ring into the hole and assured concentricity. From this observation, it could be concluded that the ScBS provide error proofed leak-tight sealing without any special design alteration in the valve body.

3.5 Conclusions

Based on the research performed in chapter 2 & 3, various set of parameters are determined, and conclusions are derived. These would be the driving aspects of the subsequent chapters and phases of the design.

1. From, the basic structure of a mechatronic system it was deduced that this assembly station would comprise actuators, drive units, sensors, and controls.
2. Study of the manual process helped to figure out the steps that must be performed by the system as listed:
3. Making available the plug & ring.
4. Tool extension/tool bit to fasten different sized plugs
5. Placing the ring and plug in the bottom hole followed by fastening operation.
6. Holding the body during tightening operation.
7. There is a broad spectrum of products for automation, and depending on the type, 30 different positions are possible for the bottom hole, with five types of plug & rings. Thus, the system should be designed to perform the tightening operation for all the types & sizes. Based, on the study it was realized that a 3DOF translational system was needed.
8. A fastening power tool, components for fastening the plugs.

These findings are used for defining concepts for the plug & ring fixture and station overview. All the concepts would then be evaluated and graded to decide on which design must be worked out in detail for the final phase.

4 Conceptual design

This chapter illustrates the stepwise procedure followed for conceptual design. As concluded from previous chapters, the first requirement is to design a fixture to hold the different sized PR such that these could be picked and fastened into the body. Secondarily, concepts must be proposed on how the tightening operation would be carried out, and this would define the overall structural overview of the assembly station. The concepts are developed based on morphological scheme and then evaluated for detail designing.

4.1 Plug and ring fixture design

Design problem

The whole station is to be designed for leak-proof tightening of the plug & sealing rings. Five sizes (M16, M18, M22, M27, and M36) of the bottom plugs are to be used in the entire assembly line. These must be readily made available at the station to carry out the fastening operation. The PR is placed in a fixture by the operator at the manual station. The problem to be addressed is the PR should be placed in such a fixture that it is convenient for the operator to place it in, and it should be easy to pick and assemble by the robotic system at the assembly station. The fixture should contain the parts firmly in a way that their orientation/position is unaffected by the forces experienced by the product carrier on the conveyor. This signifies the concept and operating principle of the entire station are directly dependent on the orientation of the plug and hence the design of the fixture. The design concept for the fixture and station go hand in hand. Hence, based on this idea a set of requirements were listed for the fixture.

Requirements:

- Robust design-No/minimum damage under regular usage.
- Universal: Fit in all five sizes
- Ease of operation: For picking and placing by the operator as well as the automated system.
- Stability: No change in orientation due to external forces.
- Cost Manufacturing feasibility & maintenance (replacement)

Wishes:

- Poka-yoke design
- Compatible with different sizes. (If possible single fixture for all sizes, or else different positions to hold different sizes.)

Functions

- Position in the fixture: The fixture must prevent linear/rotational movement of the PR inside the fixture.
- Keeping plug and rings together as a single unit.
- Picking feasibility (Ease of access for picking the unit).

Morphological chart

A morphological overview was made to generate ideas for the design of the fixture. Figure 4-1 shows the morphological chart for the plug and ring fixture design problem.

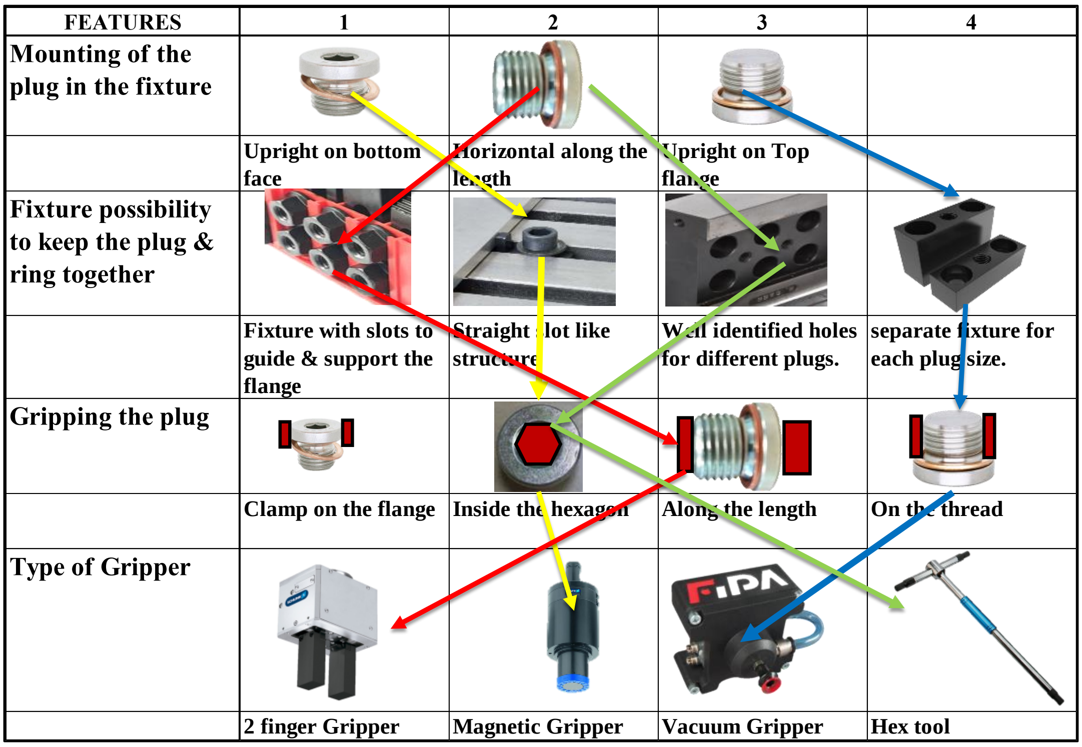


Figure 4-1: Morphological chart for the plug & ring fixture design. The development of the concepts is indicated with colored lines. Redline- concept#1 , Greenline- concept #2, Blue line- Concept#3, and Yellow line-Concept#4.

Defining the concepts

From the morphological chart, four concepts were derived. Figure 4-2 to Figure 4-5 are the sketches of the four concepts. In all the concepts, the plugs are positioned in a separate position in the fixture. As per concept 1 & 2, the plugs are positioned horizontally. With this orientation, the plugs could be placed and removed from the fixture by clamping it on the flat faces or holding it inside the hexagon. With concept, 3 & 4 the plug and ring are placed vertically. With concept 3 the removal and placement of the components would be possible by holding it on the threads or the flat end, and concept 4 allows picking of the units inside the hexagon or on the flange of the plug along with the centering ring.

Table 4.1: Conceptual designs of plug and ring fixture.

Concept #1	Concept #2

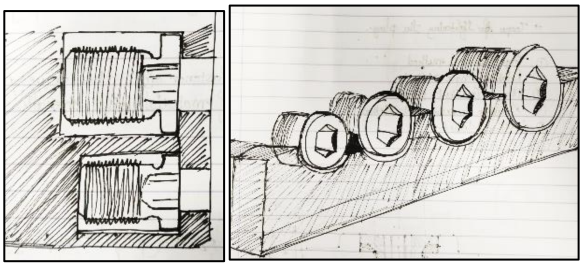
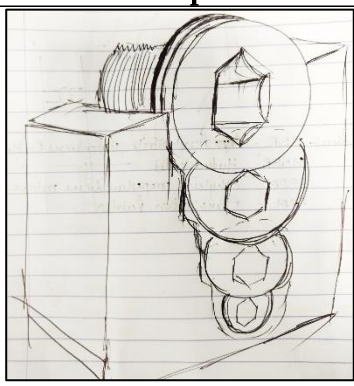
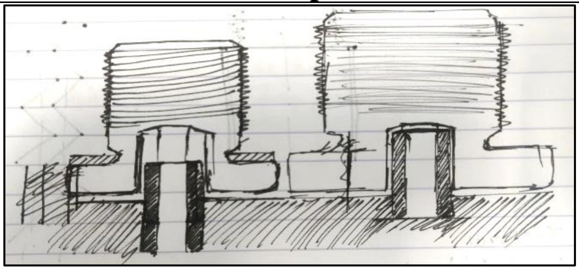
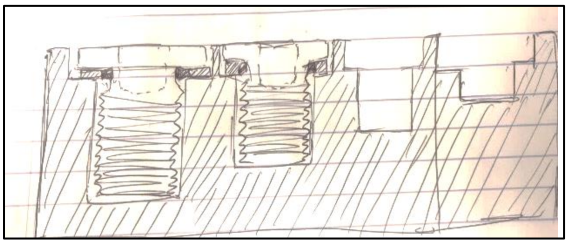

	

Figure 4-2: The plugs and ring are placed in slots made in the block. The cut out in the block holds the plug along its length and restricts movement.	*Figure 4-3: Compact vertical block with concentric slots. Stepped slots are made such that each plug rests at on different step.*

Concept #3	Concept #4
 *Figure 4-4: Fixture with hexagonal shafts. The bottom plug rests on the shaft inside the hexagon.*	 *Figure 4-5: Fixture with counterbored holes. The PR is inserted in the hole, and it rests against the copper ring and the top flange.*

Concept grading and choice

The proposed concepts were evaluated to decide on the fixture for detailed design. The evaluation matrix is filled with grades by process engineer (Assembly department), Manager (Work preparation department), & two graduation students (working on this RECap project). The grading factors are stability, ease of use, compatibility, robustness, and manufacturability. These grading factors are the result of a discussion with the RECap project team members. Stability is defined as a feature of the fixture to hold the plugs steadily without affecting their orientation and is of the most desired aspect. Ease of use is defined as that it is easy for the operator to place the subassembly manually in the fixture and as well as for a robotic system to pick the subassembly from the fixture. The fixture is considered compatible if all different PR sizes could be placed into it without any modular changes. Robustness is defined as the property of the fixture to withstand forces experienced during its lifecycle with minimum deviation in its functionality.

Table 3.2: Score matrix for the plug and ring fixture design concepts.

		Concept			
Requirements (5=good, 1=bad)	**Weight factor**	**1**	**2**	**3**	**4**
Stability	5	2.0	4.0	4.0	4.0
Ease of use (operator & Cartesian system)	4	3.0	4.7	2.0	1.7
Compatibility (different plug and ring sizes)	4	3.0	5.0	3.7	3.0
Robustness	3	2.0	4.7	3.7	4.0
Manufacturability	3	3.7	3.3	3.0	4.3
Total concept scores		53.0	**87.7**	69.7	70.7

From the grading, it follows that concept 2 (horizontal orientation and vertically stacked) had the highest score and was considered for working out in detail.

4.2 Assembly Operation Concept

Design problem

As stated earlier the design concept for fixture and station are co-related, different conditions and orientation of the plug were considered with respect to the operation of the assembling. The problem to be addressed here is how convenient is it for the robotic system to retrieve the plug from the fixture and fasten it in the bottom hole. Based on this, specific requirements, wishes, and functionality were stated.

Requirements:

- Simplicity: No complicated steps to perform the tightening operation.
- Robustness: The system should withstand the assembly forces and moments. Simultaneously it should not damage the system components.
- Accuracy & precision: The system component should be precise and accurate to perform the desired operation.

Wishes

- Low cost
- Similar system as used in other stations (robotic system)

Functions

- Picking the PR from the fixture: No difficulty in picking and no changes in orientation.
- The operation should be done within minimum no. of steps.
- The tightening tool: Tool carried by the system (this affects the sizing and load carrying capacity of the system).
- Type of sensor: For detection and quality checks

Morphological chart

Figure 4-6 shows the morphological chart for the plug and ring fixture design problem.

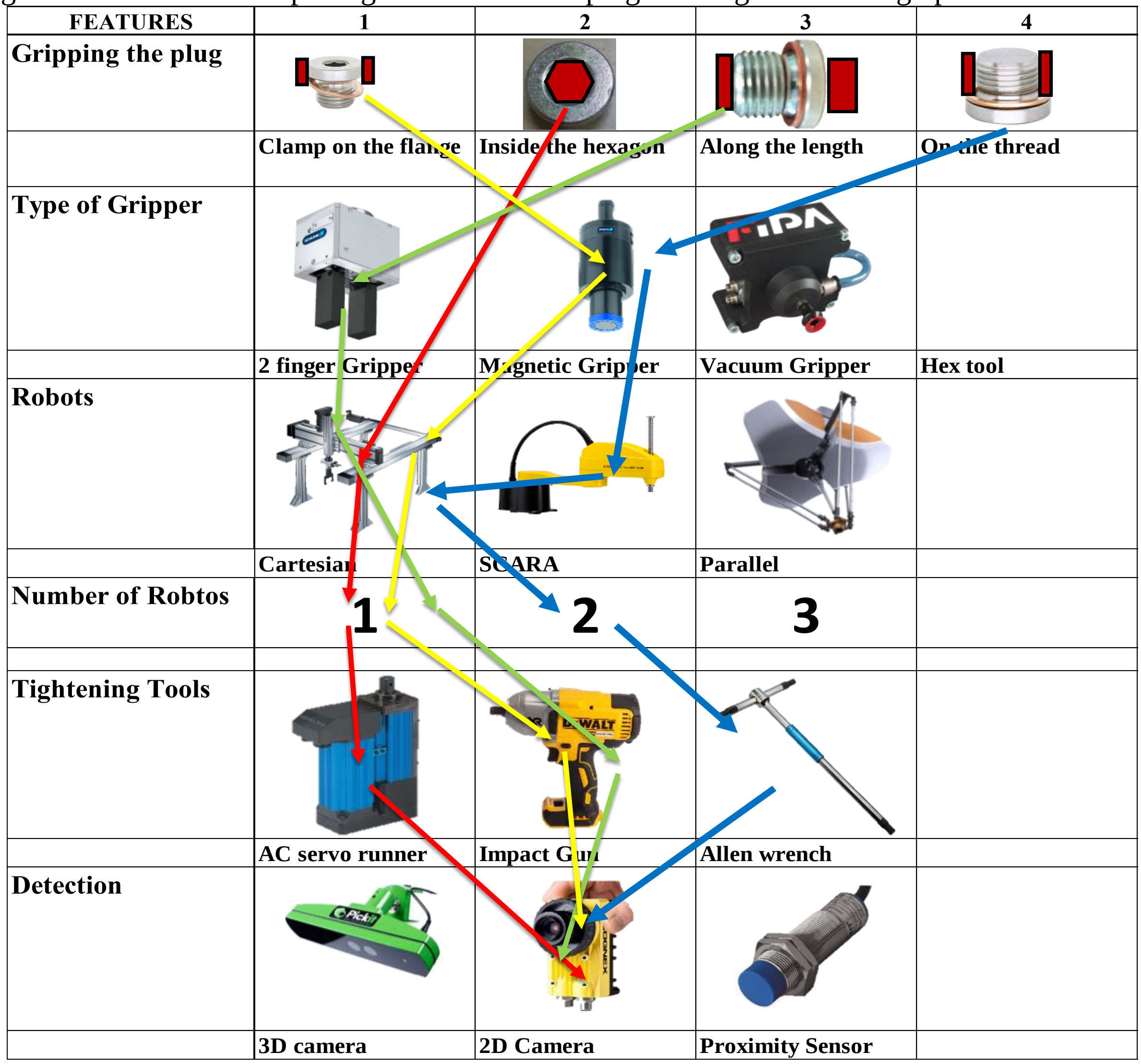


Figure 4-6: Morphological chart for assembly operation layout & system configuration. The development of the concepts is indicated with colored lines. Redline- concept#1, Blue line - concept #2, Greenline -Concept#3, and Yellow line-Concept#4.

Defining concepts

From the morphological chart, four concepts were derived. Figure 4-7 to Figure 4-10 show sketches of the four concepts. In all the concepts, the plugs are positioned in a separate position in the fixture. As per concept 1 & 2, the plugs are positioned horizontally. With this orientation, the plugs could be placed and removed from the fixture by clamping it on the flat faces or holding it inside the hexagon. With concept, 3 & 4 the plug and ring are placed vertically. With concept three the removal and placement of the component is possible by holding it on the threads or the flat end, and concept 4 allows picking of the units inside the hexagon or on the flange of the plug along with the centering ring.

Table 3.3: Conceptual designs for the assembly station.

Concept #1	Concept #2

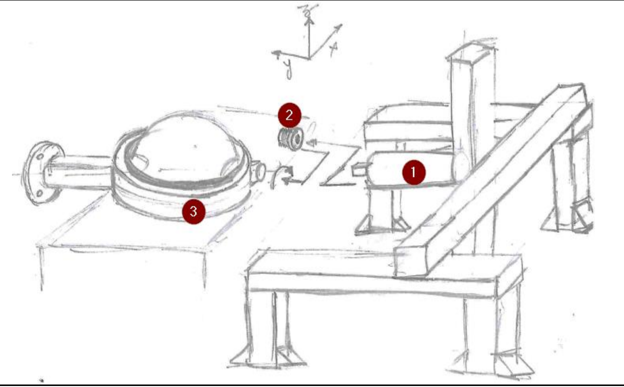
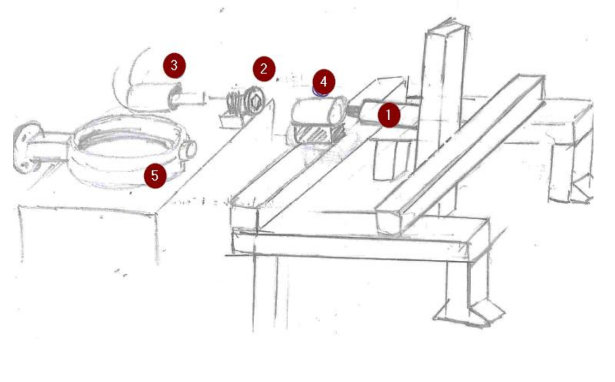

	

Figure 4-7: Tightening tool(1) mounted on a Cartesian system (3 degrees of freedom). The plug & ring (2) is picked up by the tightening tool and is positioned (following the path shown with arrows) in alignment with the bottom hole of the body (3), followed by fastening operation.	*Figure 4-8: Tightening tool (1) mounted on a cartesian system with 2 degrees of freedom along z & y-axis (as per the coordinate system in the figure). The plug and ring(2) would be picked (pushed inside by a mechanism(3)) & carried by guiding tube/block(4) to bring it in alignment with the tightening tool(1). Next, the tool would remove the plug & ring from the tube & fasten it into the valve body (5)*
Concept #3	Concept #4

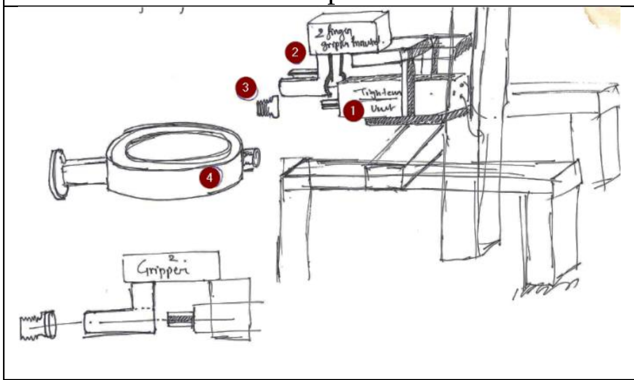
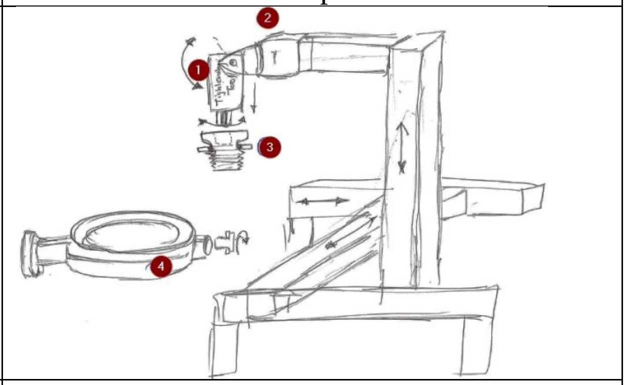

	

Figure 4-9: Tightening tool(1) & a 2 finger gripper mounted(2) on a 3-degree of freedom cartesian system. The gripper(2) picks the plug & ring (3) and acts as a guide for the tightening tool (1) to drive the components into the body (4).	*Figure 4-10: Tightening tool(1) mounted on an end effector(2) with a rotational degree of freedom onto a cartesian system with three degrees of freedom. The plug & ring (3) would be picked by the tool and then fastened int the valve body (4).*

Concept grading and choice

These concepts were also graded for deciding on the concept to be worked on for the final design. The evaluating factors were, the simplicity of the system- this addressed the number of different steps the system had to carry out to complete the tightening operation, Accuracy & repeatability of the system is the ability to operate with least deviation from the desired values and for a prolonged period. Robustness of the system meant it should withstand and overcome adverse conditions to operate in the desired manner. It was an essential factor due to the variation of the forces and moments experienced by the system because of variable sizes. Based on these factors, concept 1 & 3 turned out to be more promising. Even though the 1st concept had better grading than 3rd, it lagged in rating for robustness in comparison to the 3rd concept. However, concept 1 offers more straightforward operation principle which lowers the cost for the system. Whereas the concept 3 offered better robustness with an added disadvantage of complicated operation. The robustness of the first concept is doubted because PR is to be picked by the tool and if the mounting is not correct, then the assembly operation cannot be carried out effectively. However, the design could be worked out to enhance robustness to provide accuracy for repetitive operations. Therefore, the decision was made to work out the detailed design of concept 1 and then re-evaluate to check the robustness of the system. Even then, if the robustness is a shortcoming, then modifications would be suggested based on the learnings.

Table 4-1: Score matrix assembly operation concepts.

		Concepts			
Requirements (5=good, 1=bad)	Weight factor	1	2	3	4
Simplicity of the system	4	5.0	1.75	3.0	2.5
Accuracy & Repeatability	5	4.0	3.25	4.5	3.0
Robustness	5	3.5	3.5	4.25	2.5
Cost	4	5.0	3.0	3.5	2.5
Manufacturing & Maintenance Feasibility	3	4.75	2.5	4.0	3.0
Total concept scores		**91.75**	60.25	81.75	56.5

It could be seen that all the concepts are comprised of a linear system. The choice of a linear system is derived from the proposal made on such systems during SLD, and it was because all the movements in operation are linear. Also, the proposed systems for other assembly stations are also linear; this makes it more efficient to choose a similar system from investment and maintenance point of view [39].

The evaluation of the proposed concepts resulted in the choice of concept 2 (Figure 4-3) for the detailed design of PR fixture, and concept 1(Figure 4-7) for the assembly station functionality. These selected concepts would be designed in detail in the subsequent chapter.

5 Detailed Design

This chapter describes the detailed calculations followed by the modeling of the assembly station. Moreover, prior to the detailed calculations, the designed and tested PR fixture would be discussed. This is followed by details on the change in the design of the fixture. In the concluding phase of the detailed design, a cycle time analysis would be performed with a subsequent proposal for an FMEA and corresponding control plan.

5.1 Detailed design & testing of the fixture

Concept 2 as sketched in Figure 4-3 was worked out in detail. And Figure 5-1 shows the detailed design of the fixture based on the various sizes of plugs. The fixture block is placed near the edge of the product carrier which reduces the stroke length for the picking mechanism. The fixture facilitates stacking of the plug, which ensures that each plug retains its separate position and this reduces the scope of error. And the orientation of the plugs makes the fixture smaller and compact. And open ends facilitate the placement of the plug by the operator, and the picking mechanism can pick the plug from the open end by holding it inside the hexagon. A prototype of this fixture was with Selective Laser Sintering (SLS, a 3D printing technique).

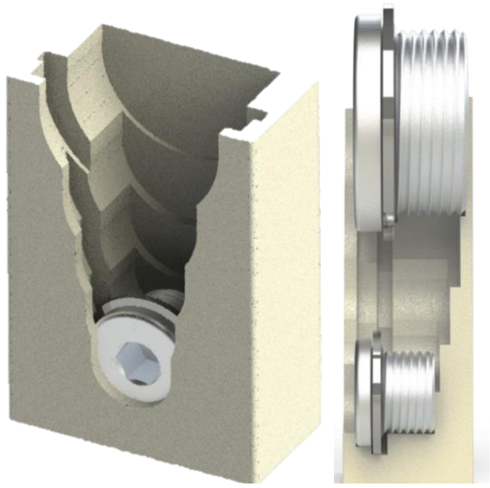


Figure 5-1: Plug and ring fixture

The prototype was tested to confirm the fulfillment of the stated requirements, and the observations made were as follows.

1. As seen in Figure 5-1 (section view) the plug is in perfectly horizontal. But testing revealed the plug sit in slightly tilted because of a clearance fit.
2. The uncertain orientation of the hexagon: The plug is kept in its respective slots in the fixture, and the placing action does not assure orientation of the hexagon. The plug had to be kept carefully with a slight adjustment to attain the desired orientation.
3. Difficulty in placing the smallest size plug: The opening of the designed fixture has converging access, and the plug is kept inside by grasping it on its flange. The converging opening makes it inconvenient for placement.

As seen from the concept design of system operation, the orientation of the plug and ring is essential for the tool to carry out picking operation or else the results are undesirable. The fact that operator places them in the fixture makes it more difficult because every time the operator would have to check and correct the orientation. This is time-consuming, and also there is no assurance on how the orientation of the plugs might change during actual operation. Thus, it turned out that the selected, designed fixture was not fulfilling the stated requirements. To address the problem, secondary research was performed which addressed the following:

- How are shaft and hole assemblies carried out in robotic systems?
- What is the feasibility of using sensors to determine orientation?
- What type of tool could be used to pick the plug such that altered orientation is not a problem?

The research on this study is illustrated in the appendix F. The research showed that such hole and shaft assemblies are addressed as peg & hole problem. For such assemblies contact based method is used to determine the position & orientation of holes. This methodology uses complex matrices to formulate and utilize the data obtained from force sensors mounted on end effectors. In another approach, the assembly is carried out with assistance from a vision system, which accurately determines the orientation and location of the hole. Lastly, a cheaper approach was to use a ball ended hex tool which could be inserted at an angle and thus overcoming the orientation problem.

The force sensor and a vision system are an extremely costly alternative. And, even though the ball end hex tool is a cheaper and promising alternative, it is available in limited sizes (not available for M27 & M36 plug size) and with comparatively degraded strength in comparison to straight hex tools. Thus, it was evident that the orientation of the plug inside the fixture dramatically affects the overall operation of the system. And with the requirement of tool change operation for different sizes, the problem gets more critical. Hence, to overcome the orientation problem, the design of the plug and ring fixture was reconsidered with a design for assembly approach.

5.1.1 Redesign of Plug & Ring Fixture.

The initial design of the fixture aided the operator in placing the PR inside the fixture, which was later removed by the tightening unit. The significant drawback with that design was the probable rotational instability of the plug which presented a problem with orientation. The earlier concepts were reconsidered to come up with an alternative design and overcome the uncertain orientation problem. From the four concepts, only concept 3 assured fixed orientation and concept 1 provided ease of operation. Therefore, concept 3 & concept 1 were combined to get a new fixture design.

With this new fixture, the plugs with the ring were to be placed on a fixture at different pre-assigned positions. A hexagonal tool bit (Figure 5-2) which fits inside the hexagonal shape of the plug would secure the PR in place. The tool bits are separate components, but these would always be present in the fixture. Each tool bit is assigned to one size of the plug. With this combination of the fixture & tool bit, the orientation of the plug could never change. The operator would have to mount the PR onto the tip of the tool bit. The smallest plug size (M16) has a hexagonal hole of the depth of 7.5mm and is deep enough to prevent it from falling off the tool bit (when in horizontal orientation). The fixture supports the PR and keeps the tool bit in position. The bit has two cut sections which eliminate its possibility of rotation inside the fixture. An important thing is even though there are 5 different plug sizes; the fixture has a place for only four. This is because dimensions of the hexagon for M16 & M18 plug is the same and the tolerances between the sizes of the ring are small.

A principal advantage of this fixture and tool bit design is that it eliminates the requirement for a tool change station. The only possibility of error was the orientation of the tool after performing assembly operation. The tool can make the same number of rotations as done during tightening but in reverse direction and thus prior orientation could be achieved, and the tool is placed back in the fixture. The design of the tool bit assures that it is consistently in the desired orientation. Moreover, the tool bit is marked with size and so are their respective position in the fixture, this facilitates easy identification for the operator. However, the design of the bit is different from the readily available tool adapters and thus, need to be custom made.

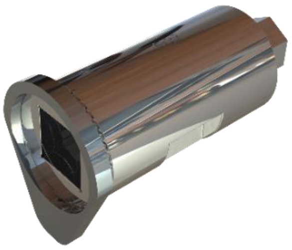


Figure 5-2: Tightening tool bit.

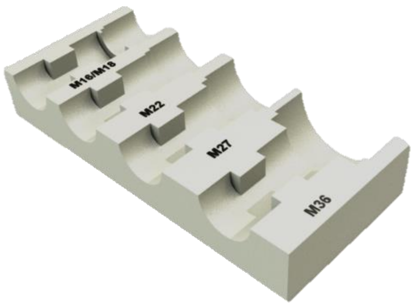


Figure 5-3: Plug-Ring & tool fixture.

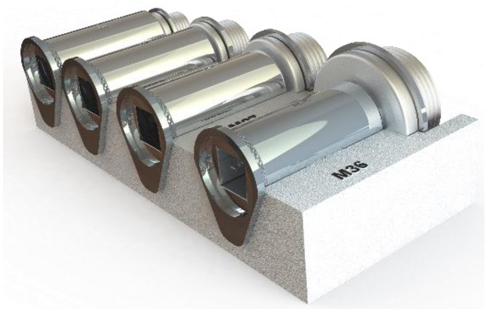
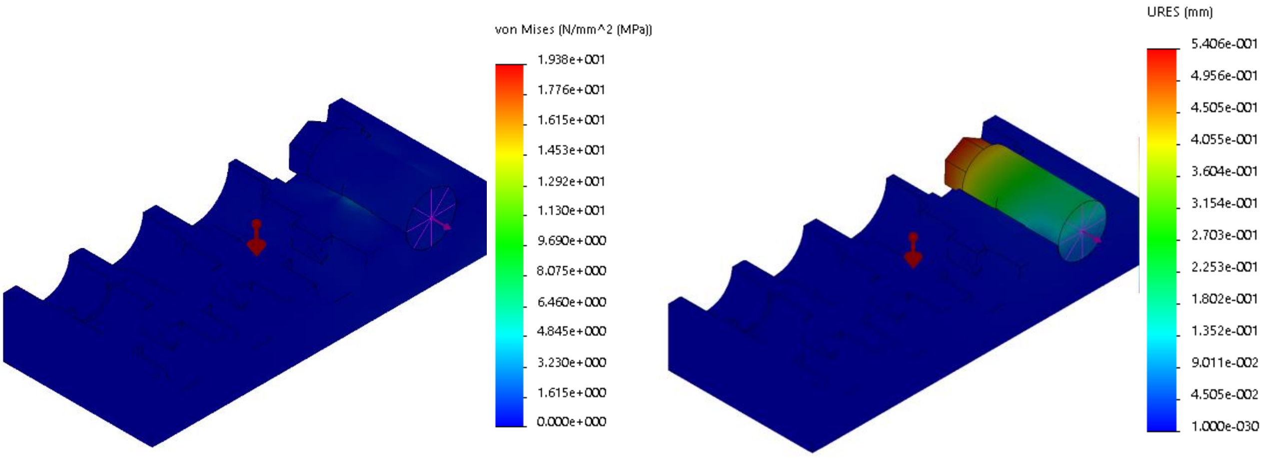


Figure 5-4: Plug-Ring and tool bit in the fixture at their respective positions as per identification.

The designed fixture is a distinct unit with intricate shape, and manufacturing such a fixture with conventional machining is a challenging job. Therefore, the most convenient and affordable method was to manufacture it out of nylon-PA12(because of its better mechanical properties in comparison with PLA, ABS, and Resin) with the SLS process. After tightening operation, the tool bit is placed back inside the fixture by detaching it from the fastening unit. This exerts a pull force on the fixture, and it had to be made sure that the fixture does not fail because of this force. Therefore, a test is performed to determine the force required to unmount a standard ½-inch square drive tool from a ½-inch socket adapter. The test was performed for standard tool bit extension required for the M36 plug, and it resulted in a force within the range of 75N-91N. Thus, considering a factor of safety of 2 and rounding the value to 200N, a simulation was performed to check for deformation and stresses. For simulation purpose, the fixture was assigned a linear elastic orthotropic material in SolidWorks (because the fixture would be 3D printed). The material properties were retrieved from [35]. The detailed test setup and material properties are described in appendix F.



(a) (b)

Figure 5-5: Fixture tested for integrity when a 200N detaching force is applied at the end face of the tool bit resulted in stress (a) of $1.938e^{+001}N/m^2$ and deformation (b) of $5.406e^{-001}$mm.

The simulation result shows the stress distribution and deformation, which gives an understanding that the fixture is robust. However, the yield strength values for a PA-12 made from SLS is unavailable; thus, it is inappropriate and illogical to comment over the strength of the fixture. And hence, prototype testing is highly recommended.

5.2 Detailed design of the assembly station

This section describes the procedure followed and decisions made for attaining a detailed design of the system based on the chosen concept. Initially, the critical components and parameters of the system are defined. Followed by the detailed elaboration on the components which makeup, the system. Analytical calculations are made to decide on which components must be incorporated into the system.

5.2.1 Coordinate system:

Defining a coordinate system is essential to get accurate positioning. In the system, two significant components are moving relative to one another, first being the product carrier and second is the linear system. The linear system must move relative to the body on the product carrier, and it is assumed that the body is positioned accurately on the product carrier.

The coordinate system (Figure 5-6) is defined on the product carrier with its origin on the support frame, starting from the edge of the product carrier. With ±x along the edge, ±y directed towards the center plane of the product carrier and +z-axis along the height. As per this, the body would be precisely at the center of the product carrier, and thus the bottom hole position could be accurately determined.

All the dimensions of the body are measured with respect to the coordinate system-1. The position of the bottom hole of the body is of primary concern. The x-y-z coordinate of the center point of the bottom hole varies with respect to the size and type of body. With prior assumption, it is safe to assume the value of x would always be zero, and only y and z must be determined.

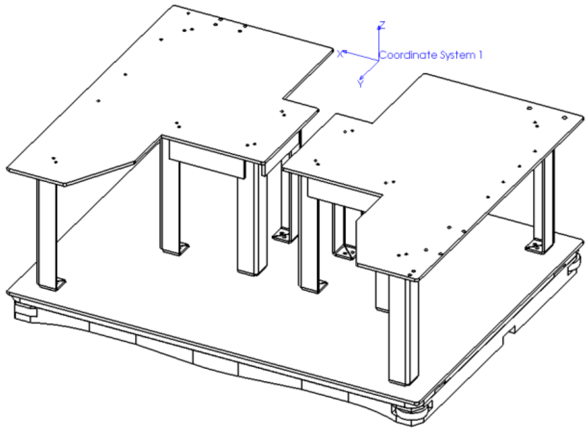


Figure 5-6: Coordinate system-1 with respect to the product carrier. The reference point for determining the position of all the components.

5.2.2 Detailing the tightening operation

The operation of concept 1 which qualified for detail design has been discussed in detail. Figure 5-7 to Figure 5-12 illustrates on steps that would be carried out to perform the assembly operation. The exact flow and operation sequence are discussed further ahead in the report.

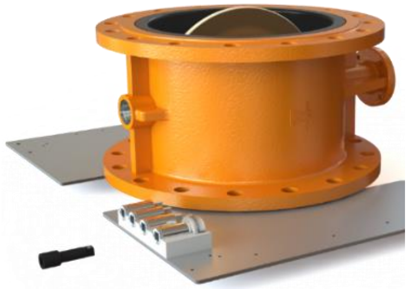


Figure 5-7: Tightening tool positioned in axial alignment with the tool bit, plug & ring in the x-z plane.

Figure 5-8: Linear system moves along the Y axis to fit the tool inside the tool bit.

Figure 5-9: The linear system moves along Z-axis to remove the plug & ring mounted on tool bit, from the fixture.

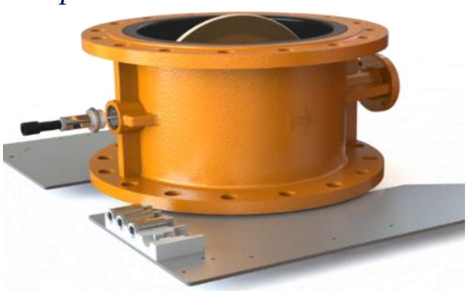


Figure 5-10: The system moves along x-axis & positions the components in alignment with the bottom hole of the body

Figure 5-11: Movement along the y-axis is done to insert & fasten the plug & ring in the hole

Figure 5-12: The system retracts & follows the prior steps in reverse order to place the tool bit back inside the fixture and go back to its home position

5.2.3 Counter torque mechanism

In manual assembly, the applied tightening torque tries to rotate the body about its central axis. The operator holds the body by his hands to counteract the torque. For the automated process, an auxiliary system must be used to hold the body in place.

For the force application, a servo driven force applicator unit was selected. The choice of servo drive unit was made during the system level design phase based on the comparison between pneumatic, hydraulic, and electric drives (The comparison and conclusion have been deduced from [39]). Due to their specific characteristics, they offer advantages in terms of accuracy, dynamics, and controllability. Therefore, not only help to shorten cycle times but also to increase flexibility and quality in the manufacturing process. Their compact design makes them ideal for use in tightly confined spaces [16].

The stroke length and the force requirement governs the selection of force applicator unit. In this case, the force required varies as per the tightening torque. However, a force which can counteract the maximum torque could be applied on each body, and this would not damage the body. The stroke length is the difference between the face-to-face dimension of a DN40 (45.1mm) & DN350 (293.1mm) which is 248mm. Based on the requirement a set of electromechanical cylinders were looked for, and EMC-32 with a ball screw assembly of 12mm (diameter) x 10 mm (pitch) was selected. This was the smallest version of the cylinder available with delivered force close to the requirement. It could be seen from the Figure 5-14 that EMC exerts around 750N force for S_{max} (maximum stroke length). S_{max} (mm), i.e., the maximum stroke length of the cylinder is effective stroke length (248mm) plus excess travel length which is 4 times the pitch of the screw (10mm). Therefore, S_{max} is 288mm which could be approximated to 300mm.

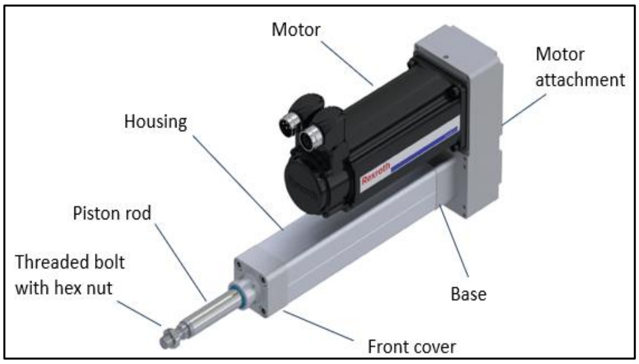


Figure 5-13: Electromechanical cylinder for force application to counteract the tightening torque [16]

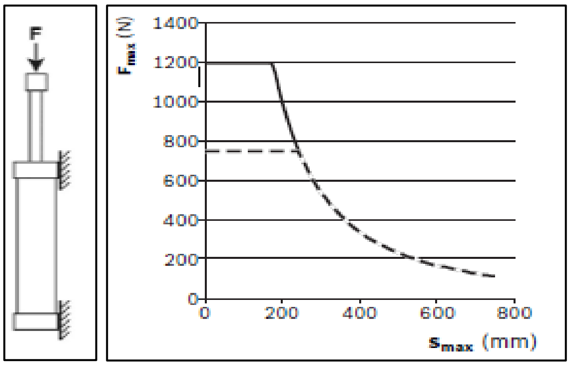


Figure 5-14: With ends fixed, the EMC-32 (12x10) can deliver a maximum force of 750N for a stroke length up to 300mm (shown by dotted curve) [16].

And as it is clear that the variable sizes of the body cause an issue, thus there was an option to either position the mechanism with respect to the outer edge of the body. And this could have been done using a small linear module, but it is uneconomical. Therefore, instead of positioning the mechanism at different positions, it could be fixed at one single position, and an attachment could be made which could cover the variation in sizes. The unit is positioned in a manner that the force plate remains clear from the DN 350 convex disc and yet it can hold the smallest DN 40 body in position (the area covered by force applicator could be seen in Figure 5-15). The lower surface of the plate is covered with a rubber strip to prevent it from damaging the body

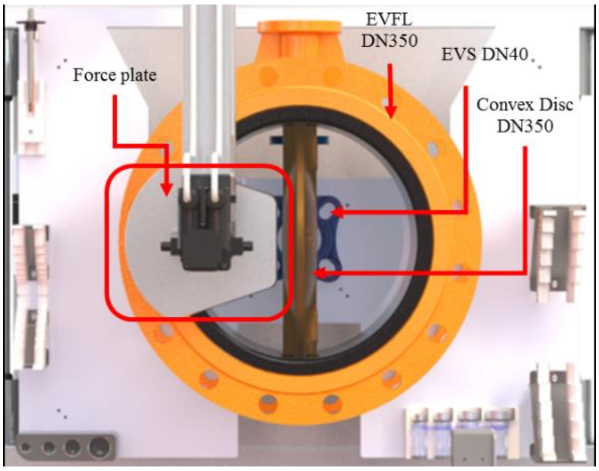


Figure 5-15: Counter torque mechanism could apply force on sizes from DN40(blue body)-DN350(orange body) because of the wider force plate.

5.2.4 Modular robotic system

This section illustrates the steps followed to design the assembly station. The details on calculations and methodology are explained in further detail in the appendix. H. The controller units are not in the scope of this research phase and hence will not be discussed in detail (only the suitable control system would be mentioned.). Some components like the positioning unit, conveyor system, and product carrier had been worked out during the SLD phase and are readily used as part of the assembly station. These components are used for dimensioning and positioning of the Cartesian system. The detailed study and analysis of the drive system are carried out based on static and dynamic forces acting on the system during the entire assembly process. Based on the calculations appropriate modules and components were selected.

The station requires to have a system with three translational DOF, and therefore linear guide systems are used to design the system. Figure 5-16 shows the assumed stage orientation of the Cartesian system for the assembly station.

Stage 1 (S1). The stationary element for holding the tightening tool.
Stage 2 (S2). The translational unit to move the tool vertically along the z-axis.
Stage 3 (S3). A unit for advancing the system along the x-axis.
Stage 4 (S4). A unit for positioning the system along the y-axis.

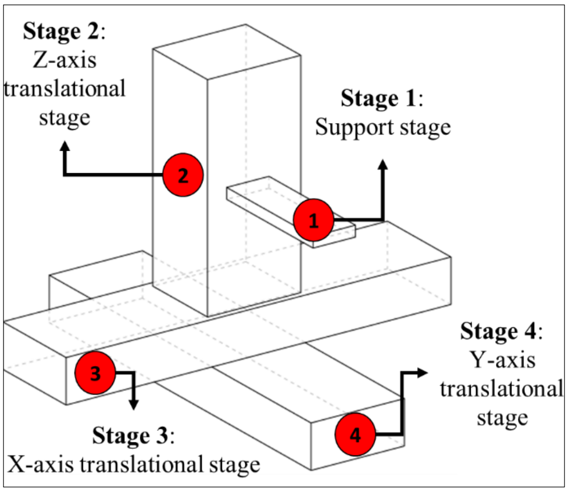


Figure 5-16: Assumed stage orientation of the Cartesian system

The tightening operation causes the most prominent load on the system. And the influence of this force is studied on the system. Stage 1 (S1) which holds the tightening tool is the primary system component which experiences the forces. Hence, S1 is designed first followed by stage 2 (S2), stage 3 (S3) and stage 4 (S4) sequentially as these experience reaction forces from the stage to which they are connected.

5.2.4.1 Operational cycle of a linear system

Before the detailed design of the Cartesian system, an understanding of translational motion was needed. Thus, this section offers a brief description of the operational cycle of translational motion. The translational motion of an object could be simplified as moving towards a destination (forward stroke), being at rest after reaching the destination (dwell phase.), and ultimately returning to the initial position (reverse stroke). The forward & reverse strokes are further sub-divided in 3 phases of acceleration, uniform motion, and deceleration. For simplification, the motion is treated with a linear curve and is assumed symmetrical. Figure 5-17 shows the seven phases of translation for a linear system, where phase T1-T3 & T5-T7 show the forward & reverse stroke respectively. During the forward stroke, phase 1 depicts acceleration, phase 2 uniform motion, and phase 3 deceleration, and same is the case for reverse stroke. The 4th phase is the dwell phase in which the translational system is at a standstill because other translational units are in motion and the tightening operation is being carried out. These 7 phases are applicable for all the 3 translational units. And even though it is assumed that all units are driven at 0.1m/s, the operational time in each phase is different for every module because of different stroke lengths. The difference in stroke lengths indicates different values for acceleration and deceleration for each translational unit, which results in different inertia forces and would ultimately affect the overall design of the system.

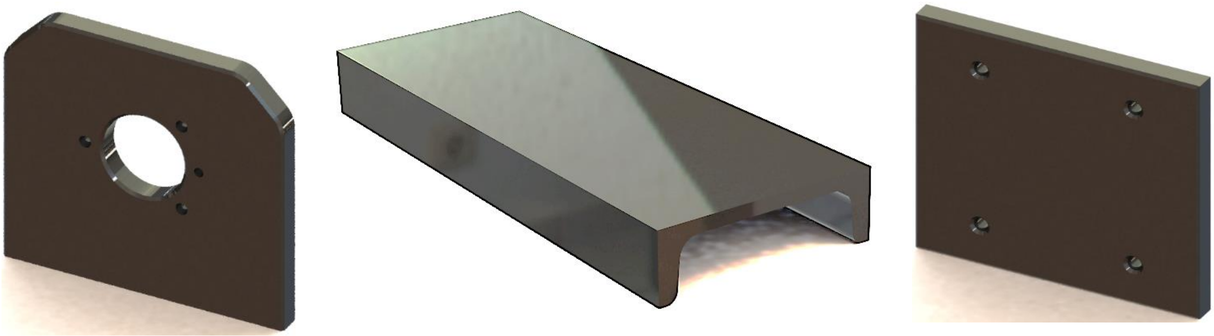
Figure 5-17: Velocity vs. time graph, showing the 7 different phases during translation. T1-T3 depicts forward stroke, T4 is the dwell phase, and finally, T5-T7 is the reverse stroke [33]

With the understanding of operational phases and their impact on the operation of the system, the subsequent step was to design the stages of the linear system.

5.2.4.2 Stage S1: Fixture for nutrunner

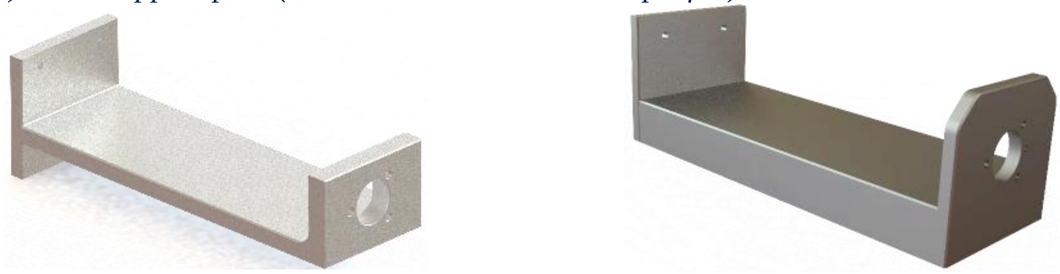
The test results for maximum required torque for tightening M36 plug is 30 Nm, and CFT-401RS1-SL nutrunner from FEC has been selected for the operation (Section. 3.2.1). The tool is 285mm in length, 60mm in diameter and weighs approximately 2 kg (including support profiles, fasteners, and other accessories). It is a fixtured type-tightening tool, which means it needs to be mounted on the fixed support for carrying out the desired tightening operation. The support is required to counteract the tightening torque and is also called as reaction arm (addressed as stage 1 for this report). The stage is treated as a cantilever beam which is acted upon by a distributed load (weight of the tool), and the tightening torque is treated as moment acting at the tip of the tool. The purpose of using reaction arm is to fix the nutrunner in a position such that its positional accuracy is retained. Thus, the deciding criteria for dimensioning were to have a lightweight structure with minimum deformation and torsional stress.

The preliminary design of the fixture (shown in Figure 5-19 (a)) was made by welding together plain strips of aluminum (for a lightweight structure). The design was checked for variable thickness and widths of the fixture (in the form of a cantilever plate), and the most desirable dimensions were selected for the final design. The stress and deformation were calculated for a plate with three different variants of width (80mm, 90mm, and 100mm) and thickness (5mm, 10mm, and 15mm). The analytical calculation shows, at a constant thickness, the change in the width of the plate has a fractional effect on the values of deformation and torsional shear stress (The detailed calculation and analysis performed for different dimensions of the structure are described in the appendix H.1.). Moreover, a simulation was performed to check for the stress distribution in the designed fixture, with a width of 90mm and thickness of 15mm. The simulation demonstrates, a large distribution of torsional stress. Thus, a factor of concern was the stresses induced in the structure due to torsion, and the increased cost because of aluminum. Thus, the design was modified for enhanced torsional stiffness and was made from standard C-profile of steel. The result was a 100mm wide fixture (shown in Figure 5-19 (b)) with deformation of 0.314mm and weighing approximately 3.25kg. The simulation results for the new design are given in the appendix Figure. H-1.



(a) *(b)* *(c)*

Figure 5-18: The fixture support is made by welding (a) the front plate (which is fastened to the nutrunner),(b) the central support plate, and (c) the rear plate (for mounting on the linear system) to the support plate(standard 100mmx50mm U profile).



(a) *(b)*

Figure 5-19: (a)Preliminary design of the support fixture (made out of aluminum), (b) Optimized design of the support fixture

5.2.4.3 Stage S2: Z-Translation Unit

Stage 2 (S2): The second stage of the mechanism has a translational degree of freedom to position the tool in alignment with the bottom hole, along the z-axis. And, is directly acted upon by the reaction forces from stage 1. The stage is simplified as a platform with one DOF, thus could be treated as a beam with roller supports. The forces acting on this stage comprised of the weight of the tightening tool, the fixture arm, and the reaction of tightening torque. The reaction forces are calculated by translating the model into a free body diagram. Assuming, the roller supports are 500mm apart, the normal and transverse reaction forces are calculated as.

$R_{Cy} = - R_{Dy}$

$R_{Cy}\,(0.5) + M_B + M_{Ty} = 0$

$R_{Cy} = - 51.5\text{ N},\ R_{Dy} = 51.5\text{ N}$

$R_{Cx} = - R_{Dx}$

$R_{Cx}\,(0.5) - T = 0$

$R_{Cx} = 100\text{ N},\ R_{Dx} = -100\text{ N}$

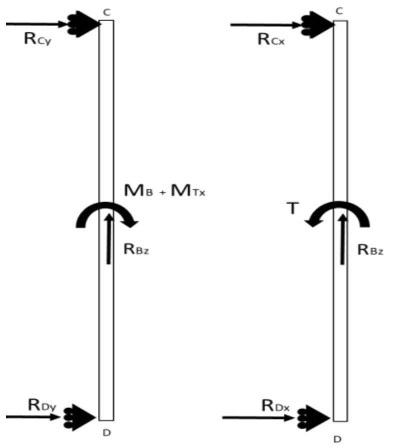


Figure 5-20: FBD for a vertically oriented module.

This simple beam model is then translated to a guide rail system to verify the authenticity of the calculations. As described and concluded in section 3.2.4, a 2 guide rails with 4/6/8 runner block model is best suited for a linear system because of no moment loads. Since the system is not carrying a heavy load, a 4-block combination would suffice. Thus, a similar guide system with vertical orientation is considered.

Based on the model (Figure 5-21) normal (P_N) and transverse (P_T) reaction forces on the runner block are calculated. These values are checked for different values of L_s (distance between guide rails) and L_w (distance between runner blocks) to determine what is the optimum configuration. This is crucial for sizing of the system. The detailed calculation procedure and formulation is given in the appendix H.

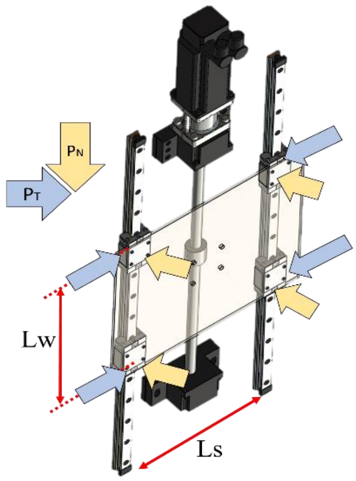


Figure 5-21: 4 block 2 rail linear guide rail system.

Table 5-1: Initial analysis to determine the normal and transverse reaction forces on runner blocks.

Distance between the rails along "Y"	Distance between the rails along "X"	Weight (3Kg)	Coordinates of application of "mg"			Torque Load	Coordinates of application of "Ft"			Reaction forces							
Lw (m)	Ls (m)	mg (N)	x=L2 (m)	y=L3 (m)	z=L4 (m)	Ft (N)	x=L3` (m)	y=L4` (m)	z=L4` (m)	Block 1		Block 2		Block 3		Block 4	
										P_{N1}	P_{T2}	P_{N2}	P_{T2}	P_{N3}	P_{T3}	P_{N4}	P_{T4}
0.5	0.5	29.43	0	0.05	0.18	-50	1	0	0.385	-24	-50	24	50	-24	-50	24	50
0.3	0.3	29.43	0	0.05	0.18	-50	1	0	0.385	-41	-83	41	83	-41	-83	41	83
0.4	0.4	29.43	0	0.05	0.18	-50	1	0	0.385	-31	-63	31	63	-31	-63	31	63
0.2	0.2	29.43	0	0.05	0.18	-50	1	0	0.385	-61	-125	61	125	-61	-125	61	125

The result shows that transverse forces are precisely half of RC_x & RD_x; this is because these values are for individual runner blocks. Also, it could be seen that the reaction forces increase as the distance between the runner blocks (L_w & L_s) decreases. If the distance between the runner block is increased to reduce the reaction force, the system becomes bulky, and the overall dimension of the system increases.

Also, there is a significant issue with reducing the distance L_w between two consecutive blocks on a rail. The sizing of the overall system is affected if the distance is smaller in comparison to the stroke length. Reducing the distance L_w means the runner block size must be smaller, and smaller runner blocks come with reduced load bearing capacity. And for larger blocks are not suitable for short stroke operations.

In operations with a short stroke, the same set of elements would always be loaded. This leads to a displacement of lubrication between the rails and rolling elements, leading to metal-to-metal contact causing higher temperature and structural transformation. Thus, the possibility of premature failure of the system increases. Hence, a decision had to be made on what type of linear system (profiled rail linear guide system or linear modules) must be used for the Z-translation unit. However, the system was evaluated with a simplified model; a detailed

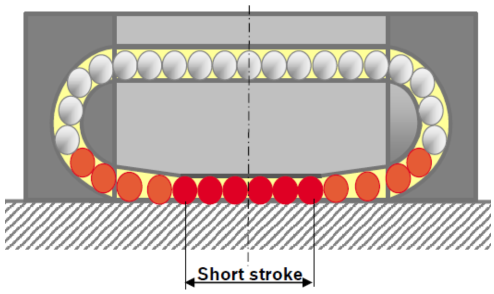


Figure 5-22: A short stroke of the guide blocks causes repetitive loading of a fixed set of rolling elements, thus leading to premature failure [33]

calculation and analysis were performed. This led to the detailed design on the linear stage along the z-axis.

As per the coordinate system (Figure 5-6) defined earlier, the z-translation unit positions the nutrunner along the z-axis. The height of the threaded hole for the largest body (EVFL DN350) is 146.5 mm and for the smallest body (EVS DN 40) it lies at 22.5mm above the surface of the product carrier (illustrated in Figure 3-8). Thus, the required stroke length is 124mm, which is rounded up to 130mm (to provide some translational freedom). As the stroke length is quite small, it is appropriate to use a compact module than a linear guide rail system. However, choosing an appropriate compact module is also necessary. The compact modules are available in 5 variants. To choose a suitable module calculation were performed on a profiled rail system with block dimensions equal to that of a compact module. The detailed explanation on calculations is given in the appendix. H).

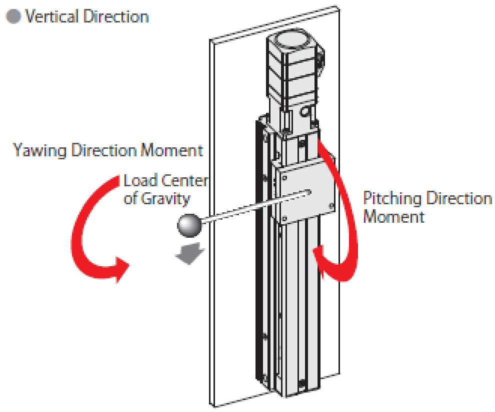


Figure 5-23: Pitching and Yawing moment experienced by a linear module when installed in vertical orientation [36].

When installed in a vertical orientation, a compact module experiences pitching and yawing moment. These are caused by the weight of the load to be translated by the module and the inertia forces. For this particular application of tightening the plug, apart from the weight and inertia force, the tightening torque is also responsible for exerting a force on the module. These moments are calculated and evaluated to determine the size of the module to be used.

Each module has different dimensions and therefore the y-coordinate for force, and mass load would vary. As the translation motion is divided into 7 phases, where phase 1-3 is forward stroke & 5-7 are a reverse stroke. In the 4^{th} phase, the tightening operation is performed. For simplified calculations, the stroke of 130mm is divided in 15mm of acceleration phase, 100 mm of uniform motion phase and 15mm of deceleration phase. Thus, for all these phase accelerations are calculated using kinematic equations. Based on the acceleration, inertia forces, yawing (M_Y), and pitching moments (M_P) are calculated. The yawing moment values would be the same for all the modules, whereas the pitching moment values vary because of variation in the height of each module. The maximum pitching occurs during the tightening phase. And, every module has a limit on maximum permissible moment along each direction. These permissible values for each module are defined and calculated by the manufacturer. Hence, the module is selected based on a comparison of actual moment acting with the maximum permissible value and the combined load condition. The calculated values are summarized in Table 5-2.

Table 5-2: Pitching moment & yawing moment values for different size variants of CCK modules

	CCK-070	**CCK-090**	**CCK-110**	**CCK-145**	**CCK-200**
Pitching moment	23.84 Nm	23.64 Nm	24.85 Nm	25.78 Nm	27.77 Nm
Yawing moment	50Nm				

After comparison, it was clear that CCK-070 & CCK-090 (with connection plate of 60mm) modules were not a viable solution. Therefore, the next suited module CCK-090 with connection plate of 125mm was selected. However, this module also had three variants based on the screw assembly. The selection amongst the variants is made based on the drive (motor). The deciding parameter is the ratio of mass moments of inertia of drive train and motor (denoted by 'V') which is the ratio of the mass moment of inertia of mechanical system to the summation of mass moment of inertia of motor & mass moment of inertia of motor brake. This ratio should be lesser than 1.5 if the module is used for processing operations. CCK-090 module comes with two possibilities of the motor, MSK030C, and MSM031C. However, the MSM031C motor is suitable for usage at voltage <= 230V. Hence it is not preferred for this application. Therefore, considering MSK-030C motor drive, the ratio for the first variants (12x2-screw assembly) is 1.39 which is close to 1.5 and for the 2nd variant (12x5 screw assembly) of the module is 0.52. Thus, CCK-090 with screw assembly of 12x5 screw assembly and MSK-030C motor was selected to translate the tool & fixture along the z-axis.

5.2.4.4 Stage S3: X-Translation Unit

The third stage of the Cartesian system, assigned for translation along the x-axis for picking the plug & ring from the fixture. The forces experienced by stage 1 are transferred to stage 3 inform of reactions of stage 2. The forces exerted are the weight of the Z-module, the weight of the tightening tool & the fixture and the tightening force. The stroke length of the body is the distance along the x-axis from the center of the body to the center of the plug & ring in the fixture (farthest from the body). This distance is 300mm and for this purpose, either a guide rail system could be used or a compact module. As stated earlier a guide rail system is slightly heavier than compact modules and takes up more space. And the same task could be done by a compact module in compact space.

Moreover, mounting Z-module on a linear guide would require a support fixture which has to be designed separately. Apart from being compact, there are connection brackets readily available for compact modules. Therefore, it is sensible to use a compact module for x-translation as well.

The detailing of z-unit showed that a further selection on a variant of the module must be made. For x-translation the orientation of the module is horizontal and therefore along with pitching and yawing, the unit experiences rolling moment (M_R) (illustrated by Figure 5-24). In this orientation, the yawing & pitching moment varies for all modules because of the variation in width & height of the modules. Based on the tightening torque and load carried by the module M_Y, M_P and M_R are calculated (summarised inTable 5-3).

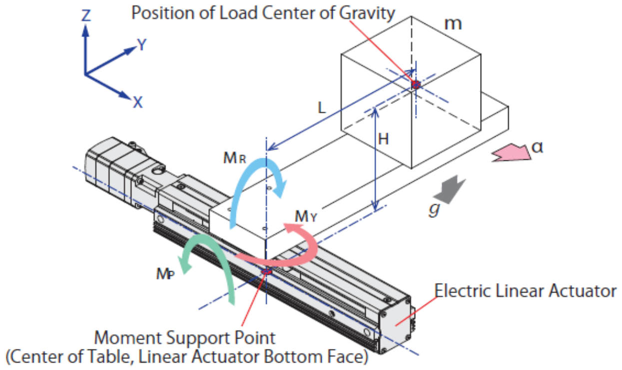


Figure 5-24: Pitching, Yawing and Rolling moment experienced by a linear module when installed in horizontal orientation [36]

Table 5-3: Pitching and yawing moment values for different variants of the CCK module

	CCK-070	CCK-090	CCK-110	CCK-145	CCK-200
Pitching moment	68.42 Nm	68.06 Nm	69.04 Nm	69.85 Nm	70.84 Nm
Yawing moment	19.42 Nm	20.55 Nm	22.22 Nm	24.58 Nm	28.90 Nm
Rolling moment	14.37 Nm				

All the three-moment values are compared with the maximum permissible moment values. And the comparison resulted in CKK-070 (BASA 8x2.5) module being a suitable option. But, this module has a connection plate of 95mm width, which cannot be attached to Z-module with the available set of mountings. Moreover, the drive for this module resulted in inertia ratio (V) higher than 1.5 and the next variant, CCK-090 module had these values close to 1.5. Thus, CCK-110 module was selected which was available in 3 variants with four possible motors (MSK-030C, MSM-031C, MSK-040C & MSK-050C). The MSK-030C motor could not be used because the inertia ratio is higher than 1.5 for all variants, and MSM-031C was ruled out due to voltage (<=230V). Motor MSK-040C was safe to use and was hence selected.

5.2.4.5 Stage S4: Y-Translation Unit

This unit moves the entire system along Y-axis such that the nutrunner could pick and fasten the plug and ring into the valve bodies. This stage is acted upon by loads from all the other stages. Assuming, at the start of operation the nutrunner and edge of product carrier would be 50 mm apart, the stroke length turns out to be approximately 320mm (The farthest hole position is 266.5mm). For a 320mm stroke, a compact module could be used. However, when all the other stages move along x, there would be high cantilever loads leading to higher rolling moments. Hence, a guide rail system was considered as a good option.

Literature research on guide rail showed that there was a wide range of runner blocks to choose from. However, choosing the most desirable one is necessary. To decide on the size & type of runner block the reaction forces on the runner blocks were calculated. The guide rail system experiences normal & transverse load. To support the X-module the guide rails had to be placed 450mm wide along the x-direction, and the runner blocks were placed 125mm wide on the guide rail. These values were determined after checking for the reaction forces on the runner blocks by placing them at different possible distances. The reaction forces for the selected orientation are 411N in the normal direction. Based on this reaction forces the runner blocks were selected.

The runner blocks are mounted on guide rail with slight pre-load. For this system, normal preload class is selected (C1- For precise guide systems with low external loads and high demands on overall rigidity). Different pre-load classes are described inTable. H-2 of the appendix. H. For C1 class pre-load, the runner blocks are mounted with certain pre-load force (defined & calculated by the manufacturer). For the smooth and precise operation of the runner blocks, the reaction forces acting on the runner blocks should be lower than the pre-load force. If the reaction forces exceed the pre-load force, then the runner block becomes pre-load free which leads to the clearance between the guide rail & runner blocks which ultimately hampers the positioning accuracy. Thus, each type of runner block of size 15, 20, 25, 30 & 35 was checked for the fulfillment of the condition.

From the calculations, it was determined that FNS, SNS & SNH of 25mm size were safer to use for 411N of reaction as their preload force was 480N. The SNS runner block was lighter than the other two types and hence was selected for the final design.

The runner blocks and guide rails together make up the guide system, but a separate drive system is needed to move the component over the guide. The drive unit discussed in literature research section has 3 variants with different variants in drive screw dimensions. The selection of the drive system and the selection of the compact modules are alike. It is selected by calculating the 3 moments acting on the system and then comparing it with the permissible values.

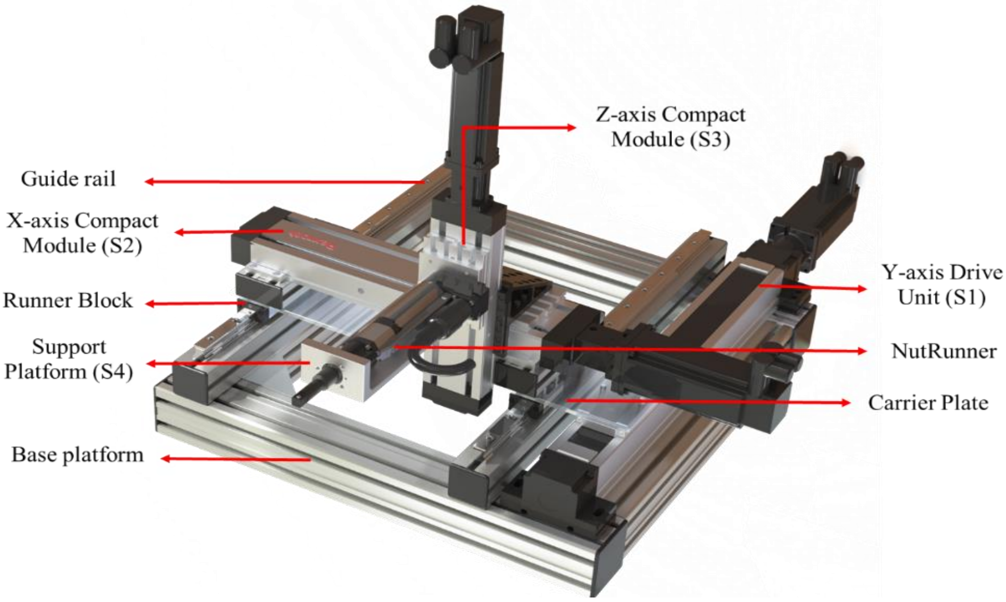


Figure 5-25: The Cartesian system for the assembly station

5.2.5 2D Profile sensor

The initial research conveyed that the operator places the component on the product carrier. Moreover, there would be some necessary sensors installed at the pick and place station to guide the operator to maintain the orientation and centering accuracy. It is evident that it is difficult for an operator to get consistent positioning accuracy in repetitive tasks, also adjusting the position is a time-consuming task. Moreover, there is a possibility of variation in positioning during the operations at disc & bottom shaft placement station. Thus, there is a checking requirement to ensure that the bottom hole position of the body coming to the station is at the expected position.

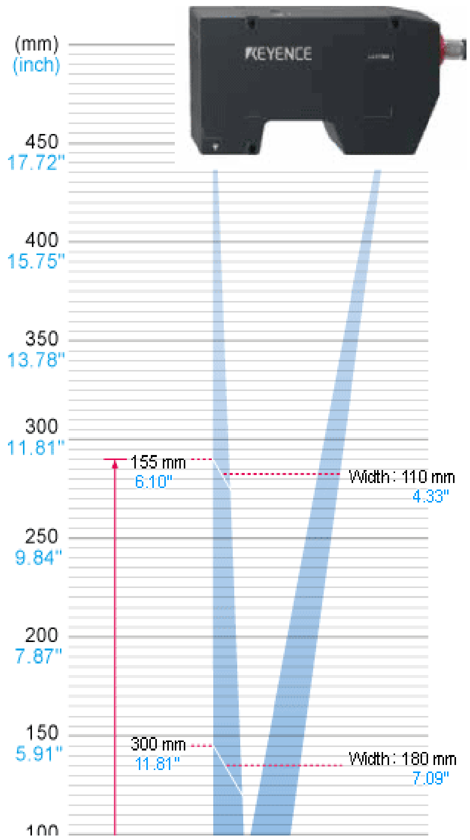


Figure 5-26: LV-J7300 sensor from KEYANCE with different field of view depending on installation height [31]

Therefore, a 2D profile detection sensor is considered. The advantage of these sensors is their accuracy in determining different profiles under their wide field of view and unaltered performance in low light conditions. The intention is to determine the position of the hole when the PC moves past the sensor. The sensor would continuously monitor the body, thus determining the profile and position of the bottom hole. This information could then be used to position the cartesian system accurately. The bottom hole position of all the bodies had to be measured using a single sensor. The variation in the position of the bottom hole along z-axis & y-axis is approximately 150mm & 270mm respectively (as shown in Figure 3-8). Products from different manufacturers were researched, and some of them lagged the required field of view. But, sensors from KEYANCE were promising and met the requirement. Thus, the LV-J7300 sensor was selected based on its wide field of view, which could be attained by adjusting its operational height. As seen in Figure 5-26, installing the fixture at 300mm, a field view of 180mm could be attained and is in accordance with the size of target objects to be detected.

5.2.6 Proximity sensors

The requirement for checking the replacement of tool bit was fore stated in chapter 2. The PR is picked along with the tool bit which is an integral part of the fixture. Picking of correct tool bit assures correct PR, and the information on its location is retrieved from the system. The importance of check comes into picture when assurance is needed that the nutrunner is fitted inside the tool bit and the PR is picked. Moreover, once the tightening operation is completed, it is essential to know that the tool bit is placed back in the fixture. For this, a height measuring sensor could have been used. However, such sensors have a small field of view (mostly a straight line or point), and this meant installing multiple sensors over the PR fixture.

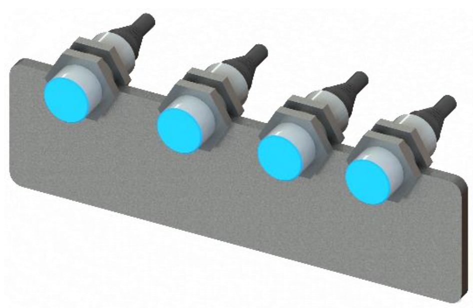


Figure 5-27: Set of proximity sensors positioned accurately as per the position of the tool bit in the PR fixture.

Moreover, the price of these sensors makes them uneconomical. Instead, a proximity sensor best serves the purpose. As discussed, based on the operation principle there are different types of proximity sensors. As the tool bits are made of stainless steel, inductive proximity sensors (IPS) are used. The IPS are available in shielded and non-shielded variants. As the name suggests, the sensing end of the shielded version is enclosed in a casing and is more profound against external interference. Whereas, the unshielded version is influenced by other metallic components which are in close vicinity of it is sensing. Thus, a shielded version proximity sensor EV-118M from KEYANCE (size M18 and sensing range of 5mm) is selected. The smaller versions have a sensing range of 1.5mm to 2.5mm and the larger variant with a sensing range of 10mm was of size M30 (this was difficult to mount because of space restrictions). The purpose of the sensor was to detect the placement of tool bit back into the fixture. The sensor would change state when the extended end of the tool bit is in its sensing range.

Thus, if there is some abnormality in placement, the sensor would give a no-go signal, and the condition must be checked and corrected. Since each tool bit had a distinct position in the fixture, there was a requirement for multiple sensors. These sensors were mounted on a plate which could then be attached to the conveyor to maintain the sensing distance (as seen in Figure 5-27).

5.3 Process flow diagram (PFD)

The following section gives a detailed description of a process flow for the entire system. The PFD outlines the entire assembly operation of the components graphically. It illustrates the flow between incoming components, the assembly operation, testing/sensing, and shipping of the assembled product. The PC moves to the assembly station with the body, the plug, and the sealing ring. The details of these components are served as inputs to the station, and these govern the sequence of operation. The inputs are processed by the system, and a sequential set of operations is carried out with simultaneous checking and sensing of necessary parameters. With the successful completion of the assembly, the valve is shipped to the next station, and the station prepares for the next product. The detailed process flow diagram is illustrated in Figure 5-28.

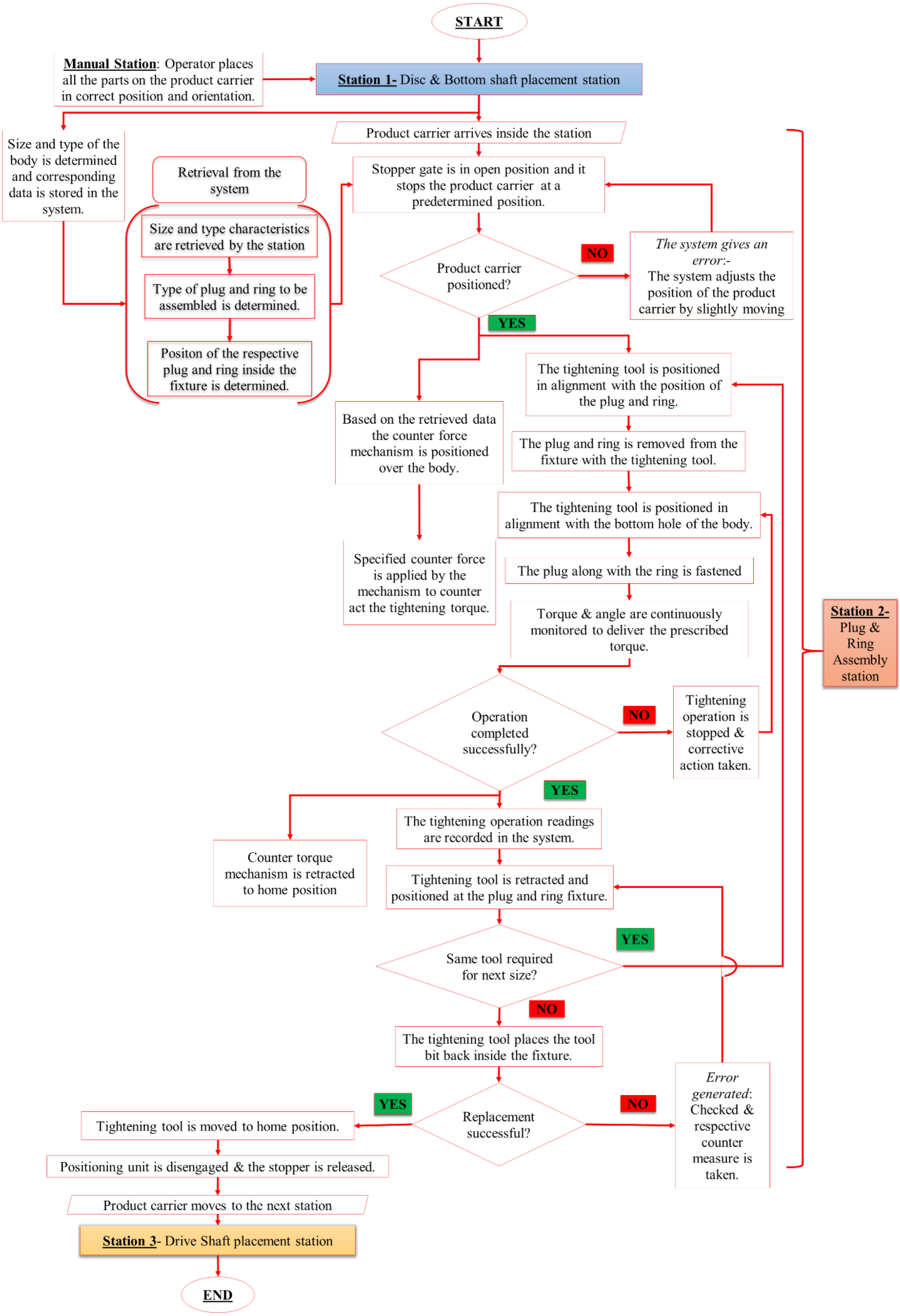


Figure 5-28: Process Flow Diagram is describing the overall operation of the assembly station.

5.4 Design-Failure Mode and Effect Analysis (D-FMEA)

An FMEA is a stepwise approach to identify possible failures in a design, manufacturing, assembly process, etc. FMEA is performed for a concept, system, design, process, service, and software. In addition, the type of FMEA to be performed is determined by the status of the project. The design & process FMEA play a crucial role in the development phase of a research project. The D-FMEA is a methodical approach for identifying potential risks in a new or changed design of a product/ system. Whereas the P-FMEA is used for identifying risks arising from changes in the process [2] The current assembly station is a new design, and at its detailed design phase, thus a D-FMEA would be performed. Failures are defined as errors or defects that affect the end customer or the system. The failure of a system can never be caused by one specific reason; it is an outcome of a series of events. Thus, for assuring the effective and efficient operation of the system, a detailed study of the designed system is done to generate an FMEA. This is explained in the next two sub-sections.

5.4.1 Possibilities of Error

This section highlights the possible modes and sectors of problem generation. The entire system is semi-automated, and every system at certain level interacts with the sub-system. Thus errors generated at a point are multiplied with the continued operation of the system. Therefore, it was necessary to evaluate all the factors and components which build up the system and point out the interaction method, which helped in pre-determining and tackling possible failures that could occur in the system.

A widely used cause and effect method (Root-Cause analysis process) is opted to identify underlying factors/causes of an adverse effect or near miss. Understanding and controlling the causes of failure help develop countermeasures and corrective actions. The fish-bone diagram (Ishikawa Diagram) is a widely used tool for root cause analysis. This tool categorizes the possible problem generation factors under man (operator), machine, material, method, measurement, and environment [44]. Based on the subcategories general compromising factors were listed, as could be seen in Figure 5-29 and based on these factors as reference a detailed D-FMEA was prepared.

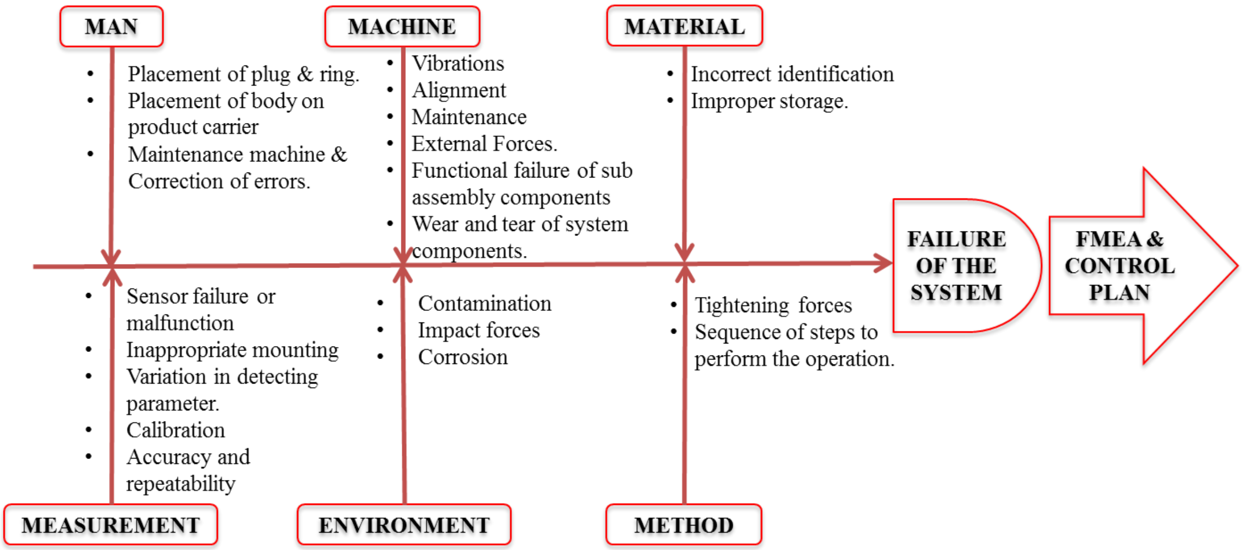


Figure 5-29: Possible modes of problem/ fault generation which could lead to minor and eventually major failure of the system. This fishbone diagram is used for generating FMEA & control plan.

5.4.2 Initial D-FMEA

In FMEA, the failures are prioritized according to their consequences (severity), their occurrence, and their ease of detection. These three parameters are graded from 1-10 (The explanation of rating a problem for its severity, occurrence and detection is given in the appendix. J) for each parameter that could have been a possible cause of failure. The graded values for each cause were then multiplied to obtain a risk priority number (RPN). The number with highest RPN no. is given the first preference and the purpose is to eliminate or reduce the failures with the highest RPN. A list of possible causes was made with reference to the Ishikawa diagram and these were graded to determine the RPN. The detailed FMEA is given in the appendix. J. The parameters with highest RPN (ranging from 60-80) were:

- False signal generation by the sensory system (RPN 80)
- Damaged sealing ring (RPN- 80),
- Wrong type (different material for rubber) of sealing ring (RPN 80)
- Misaligned/off-centred placement of the body over the product carrier (RPN 60).
- Wearing, contamination or damage of tightening tools (RPN 60)

These parameters affect the end customer and the operation on current & consecutive assembly station. The countermeasure to contain the failure would be discussed by generating a control plan.

5.5 Control Plan (CP)

A control plan is a quality document describing the necessary measurements, inspections, quality checks, or process monitoring parameters required throughout the process to assure the process outputs conform to predetermined requirements [40]. Importantly it has the necessary information for accurately controlling the process and instructions concerning actions to be taken in case of non-conformance. Advantages of using a control plan include waste reduction and product quality improvement. It helps to focus on parameters critical to quality, thus reducing scrap; maintenance issues, elimination of costly reworks, and most importantly prevent defective product delivery to the customer. This results in an inherent improvement in throughput of the process. The CP is developed by a cross-functional team (CFT). Moreover, it is implemented in three phases, namely prototype, pre-launch, and production [40]. However, RECap is the first automation project at WW; also, the detailed design of other station is scheduled in later phases, and without the detailed overview of other stations, the CP would lag many important parameters which remain unknown at the current stage. Thus, for this research project, a prototype CP is developed based on research and personal experience without the involvement of a multidisciplinary team.

The CP comprises information originating from PFD and DFMEA (there are few other sources of information, but not considered under the scope of this project). The PFD shows that the system primarily relies on component characteristics (size, type of the body and PR) as input parameters. Secondly, the effective operation of the electromechanical system assures the desired output. And, the D-FMEA provided with critical parameters that need have to be addressed to minimize the possibilities of failure.

Apart from these parameters, where are secondary parameters that need to be standardized to assure long-term functionality of the system. Some parameters included in the CP are described henceforth. However, the preliminary version of the CP could be in the appendix. K

1. <u>Monitoring the assembly operation</u>: The feedback parameters like applied torque and angle of rotation could be monitored. This monitoring process is included in the CP as an important parameter because this would provide information on process characteristic and variations. This will help understand if the plugs are being fastened at prescribed torque and this information could then be used to determine the quality of the product being manufactured.
2. <u>Calibration of tool and sensors</u>: The sensors are subjected to various operational and environmental conditions. Thus, their response could degrade over a period. The output signal generated might contain greater traces of noise. This affects the accuracy, precision, linearity, and other important characteristics. Thus, to reduce the errors and failure of the system the sensors must be periodically calibrated as per standards and manufacturers guidelines.
3. <u>Maintenance of system components</u>: All the mechanical components wear out during their life cycle, and this degrades their functionality. Thus, these systems must be periodically checked and maintained to get the maximum functionality with a prolonged life cycle. Therefore, maintenance is considered a critical control parameter. Maintenance in this

context refers to checking the ball screw assemblies for wear, noisy operations, lack of lubrication, etc.

4. Damaged sealing ring: With D-FMEA it was determined that a damaged (cracked or torn) sealing ring would not provide effective sealing in a leakage scenario. This is undesirable from a customer point of view. Thus, it must be assured that a damaged sealing ring is not used in the process. The sealing ring is ordered from an external supplier, and hence, quality check and confirmation parameters should be made stringent. And a batch inspection could also be incorporated.
5. Positioning error: Inaccurate positioning of the body on the product carrier could cause errors in determining the bottom hole position. Thus, affecting the assembling operation. This could be overcome by either making the process error proof or enhancing the check system.

Likewise, important process parameters of the system are listed, and their corresponding control and measurement criteria have been stated in the control plan.

5.6 Final design proposal

The result of the detailed design phase is an assembly station purely dedicated for assembling 5 different sizes of threaded plugs with sealing ring inside butterfly valves of size ranging from DN40-DN350. The designed station comprises of a Cartesian system with three translational degrees of freedom, a tightening tool, and a counter-torque mechanism. The visualized overview of the assembly station is shown in Figure 5-30.

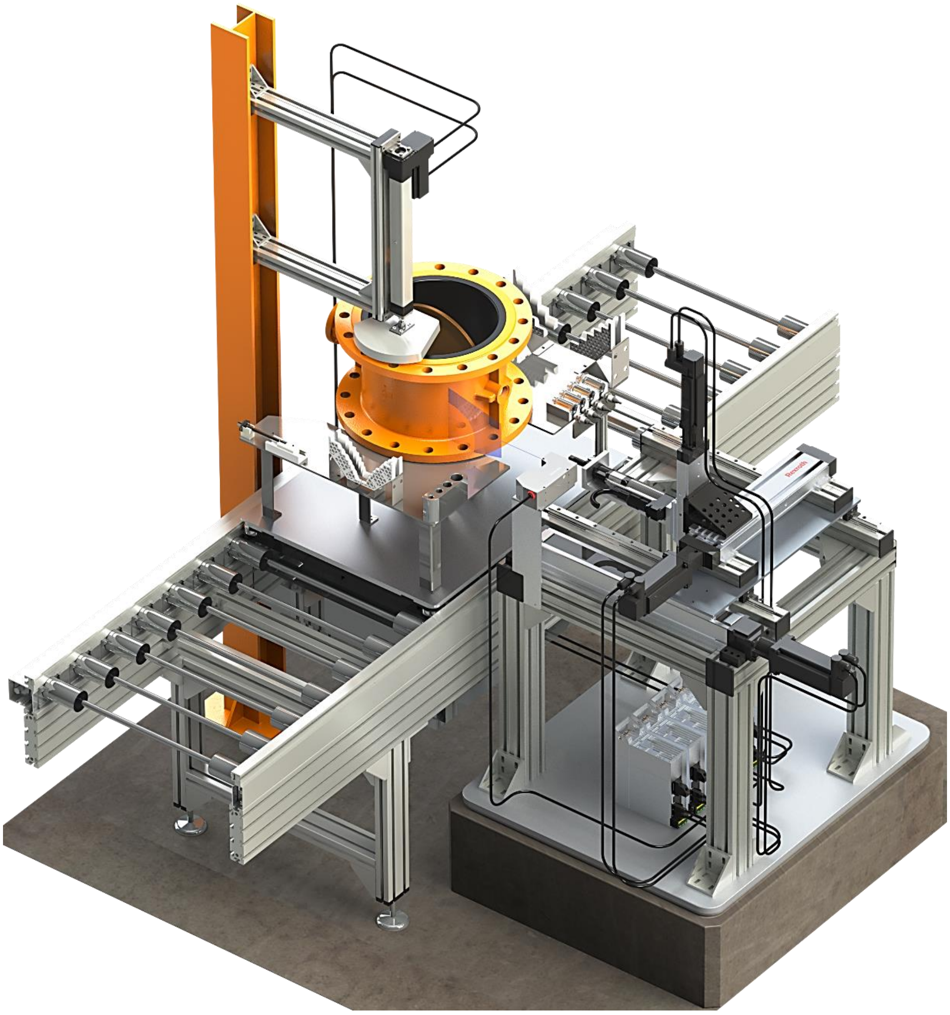


Figure 5-30: Visual representation of the designed assembly station for fastening different sizes of the threaded plug with sealing ring.

6 System Validation

With the design of the complete station to meet the initial phase requirements, the next step was to validate the design of the assembly station. Thus, this section would be providing the test and analysis performed to validate the operational feasibility. The first analysis performed confirms the cycle time of the assembly operation and the second part describes the testing.

6.1 Cycle Time Analysis (CTA)

With the detailed design of the Cartesian system and fixture, it was essential to determine the time required to assemble the components into the body. Thus, this section elaborates the cycle time analysis in detail. The system will be considered efficient and effective if the cycle time of the system is in accordance with the proposed cycle time of 2min. It is not necessary that the system should take 2 min to tighten the plug, but it should carry out the operation in the minimum possible time. The path with 11 steps as described in section. 5.2.2 (detailed tightening operation) is used to illustrate the cycle time analysis. The operation could be carried out by following a different path, and an optimum path had to be determined. The cycle time is majorly governed by the stroke length and operating speed of the linear systems. Thus, the cycle time was calculated using kinematic equations for different drive velocities for each possible path.

For instance, consider an 11-step process for tightening an M36 plug in EVFL DN 350 as illustrated in section 5.2.2 (Figure 5-7 to Figure 5-12). The position of the threaded hole with respect to coordinate system -1 is [x: 0, y: 94, and z: 146.5] and position of the plug is [x-300, y-0, and z-30] and position of tightening tool with a respective coordinate system is [x: 0, y: -50, z: 30]. The operation is carried out as follows:

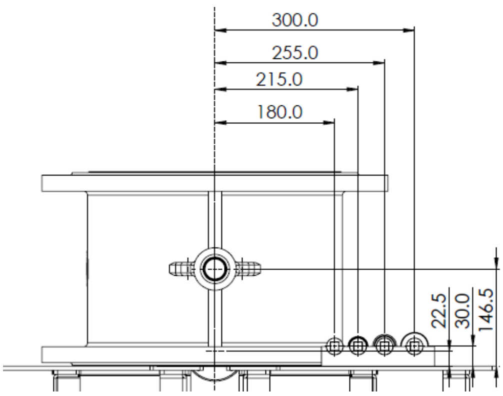


Figure 6-1: Position of the bottom hole for EVFL DN350 and the PR in the fixture, with respect to the coordinate system-1.

1. Tightening tool positions itself coaxially with the plug by moving along the +x axis for 300mm.
2. The plug is picked up by the tool by moving along the +y axis for 50mm.
3. The picked plug and ring are moved along the +z axis for 120 to bring the plug in the same plane as thread hole
4. The linear system is moved along -x-axis for 300mm to coaxially align the plug with the threaded hole.
5. Later, the system moves along the +y axis for 95mm to insert the plug inside the threaded hole
6. The tightening operation is carried out

All the steps are repeated consecutively in a reverse manner to position the tightening tool back at its original position.

Figure 6-2 illustrates the 11step process in the form of a time analysis chart. As described in section 5.2.4.1 each stroke of consecutive steps from 1 to 11 along an axis is divided into 3 phases. The A, U, & D stands for acceleration, uniform motion, deceleration respectively. The V_{max} indicates the maximum velocity at which the system modules could be operated. And ‘s’ indicates the stroke length (in mm) for a phase of operation. Thus, time for each phase is calculated using kinematic equations and summation of individual times gives the cycle time for the tightening process. However, the time taken by the product carrier to arrive into the assembly station, to be positioned by the positioning unit and departure from the assembly station, should also be taken into consideration. The TS 5 conveyor system can be operated at either 2, 4, 6, 9, 12, 15 & 18 m/min velocities [14]. Assuming the conveyor is operated at 9m/min, the time required for the product carrier (845mm in length) to move over the positioning unit is 5.633 sec. Therefore, the time for arrival, positioning, and departure of the product carrier could be approximated to 15sec (indicated by the last column of the chart- '*Total + 15 sec for PC*'). This is also called the takt time of the assembly station, which is defined as the time taken between the production of two consecutive units.

Vmax (m/s) ↓ S(mm) →	1 (300mm)			2 (50mm)			3 (120mm)			4 (300mm)			5 (95mm)			6
	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	T
	25	250	25	10	30	10	10	100	10	25	250	25	10	75	10	
0.05	1.00	5.00	1.00	0.40	0.60	0.40	0.40	2.00	0.40	1.00	5.00	1.00	0.40	1.50	0.40	5.00
0.10	0.50	2.50	0.50	0.20	0.30	0.20	0.20	1.00	0.20	0.50	2.50	0.50	0.20	0.75	0.20	5.00
0.15	0.33	1.67	0.33	0.13	0.20	0.13	0.13	0.67	0.13	0.33	1.67	0.33	0.13	0.50	0.13	5.00
0.20	0.25	1.25	0.25	0.10	0.15	0.10	0.10	0.50	0.10	0.25	1.25	0.25	0.10	0.38	0.10	5.00
0.25	0.20	1.00	0.20	0.08	0.12	0.08	0.08	0.40	0.08	0.20	1.00	0.20	0.08	0.30	0.08	5.00
0.30	0.17	0.83	0.17	0.07	0.10	0.07	0.07	0.33	0.07	0.17	0.83	0.17	0.07	0.25	0.07	5.00

7 (95mm)			8 (300mm)			9 (120mm)			10 (50mm)			11 (300mm)			Total Time (secs)	Total + 15 sec for P.C
A	U	D	A	U	D	A	U	D	A	U	D	A	U	D		
10	75	10	25	250	25	10	100	10	10	30	10	25	250	25		
0.40	1.50	0.40	1.00	5.00	1.00	0.40	2.00	0.40	0.40	0.60	0.40	1.00	5.00	1.00	46.00	61.00
0.20	0.75	0.20	0.50	2.50	0.50	0.20	1.00	0.20	0.20	0.30	0.20	0.50	2.50	0.50	25.50	40.50
0.13	0.50	0.13	0.33	1.67	0.33	0.13	0.67	0.13	0.13	0.20	0.13	0.33	1.67	0.33	18.67	33.67
0.10	0.38	0.10	0.25	1.25	0.25	0.10	0.50	0.10	0.10	0.15	0.10	0.25	1.25	0.25	15.25	30.25
0.08	0.30	0.08	0.20	1.00	0.20	0.08	0.40	0.08	0.08	0.12	0.08	0.20	1.00	0.20	13.20	28.20
0.07	0.25	0.07	0.17	0.83	0.17	0.07	0.33	0.07	0.07	0.10	0.07	0.17	0.83	0.17	11.83	26.83

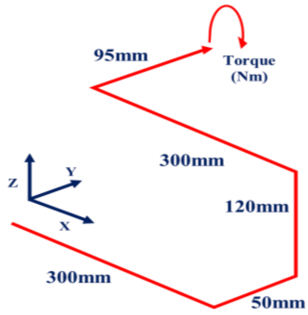


Figure 6-2: This chart shows the cycle time for 11 step tightening process (line diagram) for different velocities starting from 0.05m/s to 0.30m/s.

Likewise, the cycle time calculation has been done for different paths for M36 & M16 size plugs (Detailed explanation of path-based cycle time analysis could be studied in the appendix. I). Based on the evaluation it could be concluded that the most optimum path is when the tool is already positioned in front of the plug & ring fixture, and it moves in an x-z plane in one step rather than moving along each axis separately. Moreover, if the drive motors of the system are operated at a speed of 0.1m/s the entire operation of assembling the plug and ring could be carried out within 15 to 25.5 for all the sizes of the plug. Thus, the takt time for the assembly station would be 30 to 40.5 seconds. The choice of operational speed could be made based upon the cycle time of other assembly stations. This decision could only be made after the detailed design of other station and is not in the scope of this research project.

6.2 Position testing with LV-J2000

The following description illustrates the testing performed to check the feasibility of performing the tightening operation by determining the position of the bottom hole using a 2D sensor. The test was performed with an LJ-V2000 series 2D sensor from KEYANCE. As described in the functionality of the sensor, the unit was positioned at a distance from the test body (As shown in Figure 6-3). The test was performed to determine the position of the bottom hole of the body by with respect to the position of the sensor. Initially, the body was positioned at a certain distance and scanned to realize the profile of the bottom hole and a profile was captured to mark as a reference image (Figure 6-4 shows the captured image). Later the distance was determined in two scenarios:

1. By altering the distance between the body and the sensor: The body was placed further (at 225mm) from the sensor and distance was calculated. The change in position is visible in Figure 6-5 between the red outline profile and the yellow profile
2. By adjusting the height and distance of the body with respect to the sensor: The body was positioned lower and farther (at 175mm) than the original position, and the distance was calculated.

Figure 6-3: The test setup to determine the position of the bottom hole using the LVJ-2000 sensor.

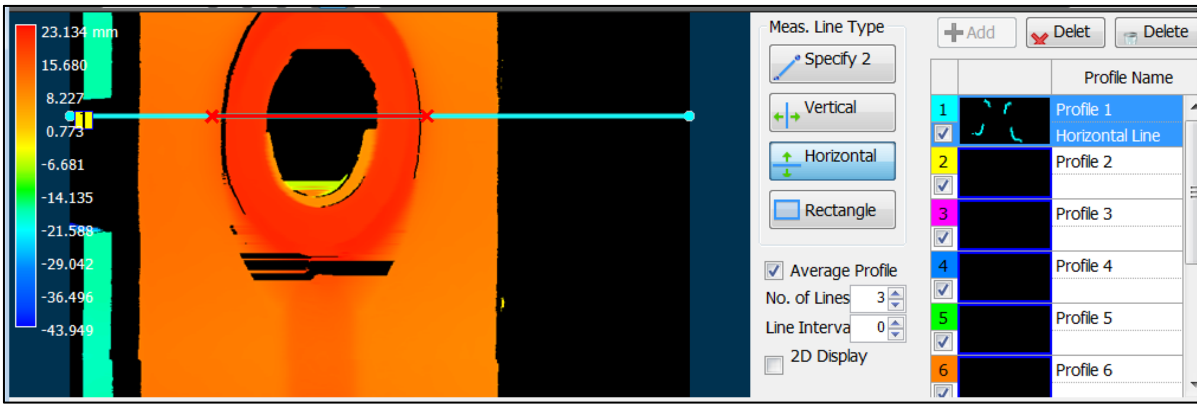


Figure 6-4: The scanned position of the bottom hole of the body, which was then translated in the form of a 3D graph. The red line in center markes the center of the bottom hole.

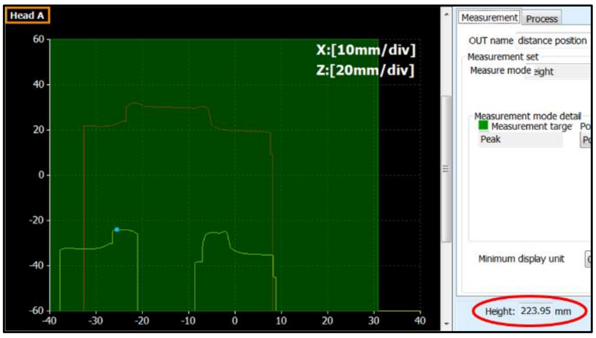


Figure 6-5: The yellow outline shows the position of the bottom hole of the body when compared with the standard outline of the body(determined at a fixed position as shown by the red colored profile. The straight line distance of the body from the sensor was determined to be 223.95mm.

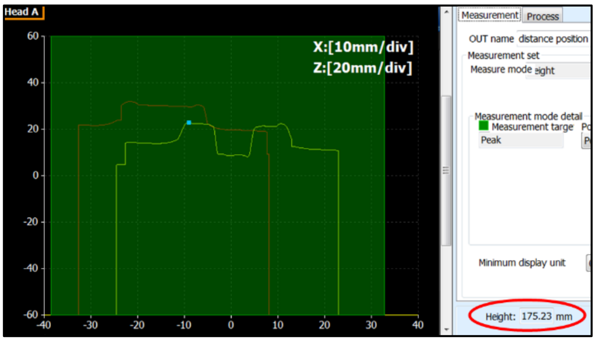


Figure 6-6: The yellow outline position of the body from the sensor, by comparing it with the standard profile (shown by the red profile). This was determined by placing the body at a different height. The straight line distance was determined to be 175.23mm.

The test showed, with the sensor at a fixed position the distance of the bottom hole from the sensor could be calculated accurately. Thus, the variation in sizes which lead to a different position of the bottom hole in the Y-Z plane of coordinate system-1 could be determined for each type of body. The data from the sensor would then be used to accurately guide the Cartesian system and perform the operation more effectively.

7 Evaluation

After the detailed design of the system, it is essential to evaluate the working of the system. It is not feasible to buy and install the components to validate the actual operation of the system.

7.1 Costing

The price estimated in the SLD is compared with the pricing determined after the detailing stage. This comparison is beneficial in determining if detail designing was carried out effectively and if the selected components lie under the spectrum of budget determined for this assembly station. The costs of all the components are retrieved from diversified sources. The strut profiles and connectors are standard components; therefore, their prices are determined from online suppliers [34]. A quotation was requested for nutrunner, linear modules, motor, controllers, and other accessories. The pricing obtained is summarized in Table 7-1

Table 7-1: Cost estimation of the designed assembly line

COST ESTIMATION				
System	**Components**	**Per unit Price**	**Required Unit**	**Total Price**
Cartesian System, Tightening tool, Fixture & sensor	Y-Module Drive	€ 5,483.00	1	€ 5,483.00
	Runner Blocks (pack of 5 units)	€ 146.77	1	€ 146.77
	Profile rails	€ 274.45	2	€ 548.90
	X-Compact Module	€ 4,750.00	1	€ 4,750.00
	Z-Compact module	€ 4,500.00	1	€ 4,500.00
	Connecting bracket	€ 250.00	1	€ 250.00
	NutRunner with controller	€ 8,000.00	1	€ 8,000.00
	EMC Cylinder (Counter torque mechanism)	€ 3,372.00	1	€ 3,372.00
	Control Unit	€ 1,015.00	5	€ 5,075.00
	Drive Motor	€ 300.00	4	€ 1,200.00
	Power Cables (1 meter)	€ 170.00	5	€ 850.00
	Encoder Cable (1 meter)	€ 94.50	5	€ 472.50
	Fixture	€ 63.01	1	€ 63.01
	Tool tip	€ 25.00	4	€ 100.00
	2D sensor with controller & software	€ 17,590.00	1	€ 17,590.00
	Proximity sensors	€ 20.00	4	€ 80.00
Components for machine frame & attachments	Strut profile- 90x90	€ 56.56	2500mm	€ 197.12
	Strut profile-30x90	€ 16.80	500mm	€ 16.80
	Strut profile-60x60	€ 17.92	1500mm	€ 41.44
	Strut profile-40x80	€ 20.25	500mm	€ 20.25
	Strut profile-20x20	€ 5.60	1000mm	€ 8.40
	Gusset	€ 12.04	26	€ 313.04
	Other accessories (Base platform, Base plate, mountings & fasteners)	€ 1,000.00	-	€ 1,000.00
	Total Price			**€ 54,078.23**

Total cost as derived from Table 7-1 is € 54,078.23, and the costing estimated during the SLD was €39,500. Thus, the comparison shows that the actual cost is approximately €14,600 more than the estimation. The detailed design gave an accurate overview of components that would be needed for the system, which helped in deriving pricing close to the real value of the products. Moreover, the added cost is because of the expensive 2D sensor.

8 Discussion, Conclusion, and Recommendations

The purpose of the master thesis was to carry out a detailed design of an assembly system to assemble a threaded plug and sealing ring. An adaptation of a proposed assembly line and operational overview during the system level design was used as a base for the research and development. Thus, the following chapter includes discussion and answers to the research questions of the thesis, and are followed by recommendations.

8.1 Discussion and Conclusion

1. The first research question was: What is the purpose of the assembly station and how are such systems designed?
   - The goal and scope of the research question was fulfilled by understanding the manual assembly process operation. The conclusions were: the system needs appropriate tightening tool, fixture units to place the plug and the ring, a counter torque mechanism, a set of tools in tool change station, and lastly a linear translational system.
2. The second question focused on: What are the requirements for designing the station?
   - The required tightening torque for assuring leak-proof sealing was determined by performing some tests. The test resulted in tightening torque values of 15Nm for M16, M18, and M22 plug, 20Nm & 25Nm for M27 & M36 plugs respectively. Thus, it could be concluded that if the plug & ring are fastened at a torque higher than the determined values, a leak-proof sealing could be attained. As a result, with a factor of safety of 2, a tightening tool with a maximum torque value of 50Nm is selected.
   - The second requirement was to determine the different components of a mechatronic system which collectively defines the assembly station. This led to studying different types of linear systems, actuators, and sensors. The conclusion was that the linear motion systems could be developed from scratch or by assembling together, off the shelf linear modules. Both the processes have certain advantages and disadvantages. However, developing the entire system from scratch is not desirable. Hence, it was concluded that selecting an off the shelf component that meets the system requirements is a suitable option.
3. Third research question: What components should be designed to build and evaluate the assembly station?
   - The research requirement was to design a fixture that could be used for placing the plug & ring. The initial design of the fixture could not fulfill the functional requirement and hence, was redesigned. In the new design, the plug & ring were mounted on the tooltip, which was an integral part of the fixture. The combination of tool bit with the fixture prohibits the rotation of the plug and ring, its orientation would not be changed during transportation, and uniquely & well-identified position makes it convenient for usage for the operator. Thus, a conclusion could be drawn that the fixture theoretically fulfills the design requirements & would turn out to be an error-proof design. Additionally, the placing of tool bits on the fixture eliminates the requirement for an auxiliary tool change station. The simulation result indicated that the fixture design could be robust, however, due to the lack of data on the material properties an assuring conclusion could not be made. Thus, the robustness testing and validity remains unanswered, and could only be confirmed with prototype testing.
   - An iterative approach has been used to determine the configuration of the system. The detailed calculations illustrate that the tightening operation exerts maximum forces on the system, which causes different moment loads on the linear systems (depending upon their orientation). Thus, only the modules suitable for the operation have been selected, and hence, theoretically, the configuration is robust against the forces acting on the system. The assembled CAD model facilitated in determining that there was no interference of the components and was dimensionally within the required limits. The

system design shows that no complex or undesired steps/ paths are followed by the system to complete the assembly operation.

- A detailed analysis had been performed to determine the sequence of operation. The analysis provides four possible sequences (path followed by the system). The assembly operation could be completed in minimum 7steps or maximum of 13 steps. A corresponding cycle time analysis (at an operational speed of 0.1m/s) for the sequence of operation shows that the assembly operation could be completed within 30-45.5 seconds. Thus, it could be concluded that the system can complete the assembly operation under 2 minutes (cycle time envisioned during system-level design).
- The last query about the possibility of system failure is addressed with developing a process flow diagram (PFD). And, the PFD was then used to develop a D-FMEA. The critical parameters with the highest RPN were-use of damaged or incorrect sealing rings, and incorrect positioning of the body on the product carrier. It can be concluded that these critical parameters must be controlled and the control method must be specified. The other possible cause of failure was not very critical because of their lower rating in detection and occurrence. The countermeasures, control methods, and guidelines for the critical causes of failure and secondary parameters necessary for the functionality of the system are included in the control plan. This gives a primary idea on parameters to be controlled and monitored. Thus, a basic platform for improvisation of the system has been laid.

The project lagged a prototype design which could have been utilized for validation of the detailed design. However, due to change in the course of events for RECap the prototyping phase was postponed. The anticipated cost based on system level design and the cost determined after detailed design were compared. This comparison demonstrated that detailed design estimates the primary implementation of the assembly station would cost € 54,078.23 and is € 14,600 more than the cost estimated during the system level design. And. the excess cost is undoubtedly because of the expensive 2D sensor.

Thus, it could be stated that the project was carried out in detail and covered most of the envisioned aspects.

8.2 Recommendations

The following section illustrates the future prospectus for the modification and successful implementation of the designed assembly station. These recommendations are the result of learnings derived during the detailed design phase.

1. During the SLD a proposal was made to have a Cartesian system for all assembly stations [39]. In this detailed design phase, a wholesome document has been prepared which would assist in the selection of components for the Cartesian system. It comprises formulation to filter different products based on their performance against the forces they could experience. Thus, it is recommended to carry out the detailed design of other assembly stations based on the methodology used for the design of this assembly station.
2. Moreover, component selection software like LMD and LIN SELECT from Bosch Rexroth could be used to speed up the design process. But this software has limitations on the input parameters and provide a wide list of suitable components, and this can affect the decision process.
3. The implementation cost for the system is comparatively high because of the proposed requirement of the 2D vision system. The sensor will not be required if the pick & place station, the disc & the drive shaft assembly station are carefully designed and equipped with necessary sensors. Also, it requires a definite process plan which ensures that the position of the body is readily known to the system.
4. The PR fixture could be modified into a modular fixture. The modules could then be used to incorporate smaller contact-based proximity switches and a microcontroller unit.

This combination could then be used to determine the replacement of the tool bit into the fixture. Thus, it eliminates the requirement of proximity sensors whose output is easily influenced by the presence of another metallic object.

5. The tool bit extensions used for fastening the plugs have not been designed in detail. It has a complex shape and is to be manufactured by assembling different components. Thus, a detailed design of the tools must be carried out.
6. During the optimization phase, there is a great possibility of eliminating the x-axis linear module from the current design if some provisions could be made to automate the plug & ring fixture, or it could be modified into a single position fixture.
7. The proposed D-FMEA and Control plan is quite preliminary; these must be evaluated and revised as per the installation and real-time operating conditions. Moreover, a Process FMEA must also be made.
8. The maximum permissible speed for the mechanical system must not be exceeded. And the choice of operational sequence governs the cycle times. Thus it should be selected & balanced based upon the cycle time of the other assembly station.
9. Assistance should be taken from experienced professionals prior to the implementation of the system.

References

[1] Advanced Micro Controls Inc. (2018, July). *Stepper vs Servo*. Retrieved from https://www.amci.com/industrial-automation-resources/plc-automation-tutorials/stepper-vs-servo/

[2] ASQ. (n.d.). Retrieved September 2018, from Failure Mode and Effect Analysis: http://asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html

[3] Assoc. Prof. Tomáš Březina, P., & Assoc. Prof. Vladislav Singule, P. (2006). *Design of Mechatronic Systems.*

[4] Atlas Copco. (n.d.). *Tensor ST Electric Nutrunner.* Retrieved June 2018, from https://www.atlascopco.com/en-uk/itba/products/assembly-solutions/electric-assembly-tools/corded-electric-nutrunners/tensor-ST?index=0&filter=model-type-dropdown-Straight

[5] B2B METAL EU, Online Metal Marketplace. (n.d.). *UPN (UNP) EUROPEAN STANDARD U CHANNELS, UPN STEEL PROFILE SPECIFICATIONS, DIMENSIONS, PROPERTIES.* Retrieved from http://www.b2bmetal.eu/u-sections-unp-specification

[6] Bart Schreurs. (March 2018). *Analyzing the current assembly process of butterfly valves at Wouter Witzel for automation to reduce costs and absenteeism.* Losser: Wouter Witzel.

[7] Betech A / S. (n.d.). *Bonded seals; Catalog*. Retrieved from https://betech.dk/produkt/taetning/statisk-taetning/bonded-seals

[8] Bonded/Dowty Seals. (n.d.). Retrieved June 15, 2018, from http://www.revataengineering.com/bonded-dowty-seals.htm

[9] Bosch Rexroth AG. (2008, April). *Ball Rail Tables TKK; R310EN 2501; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/ball-rail-tables

[10] Bosch Rexroth AG. (2014, december). *Ball rail systems;R999000485; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/profiled-rail-systems/ball-rail-systems

[11] Bosch Rexroth AG. (2015, December). *Precision Modules PSK; R999000500; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/precision-modules

[12] Bosch Rexroth AG. (2016, May). *Omega Modules OBB; R999001179 ; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/omega-modules

[13] Bosch Rexroth AG. (2017, May). *Closed-type drive units with ball screw drive AGK; R999001326 ; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/drive-units/agk-with-ball-screw-assemblies

[14] Bosch Rexroth AG. (2017, July). *TS 5 Transfer System [Catalouge], pg.no. 8-3, 9-3.* Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/assembly-technology/transfer-systems/ts-5-transfer-system

[15] Bosch Rexroth AG. (2018, March). *Compact Modules CKK/CKR; R999000499; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/compact-modules

[16] Bosch Rexroth AG. (2018, April). *Electromechanical Cylinder EMC; R999000493; [Catalog]*. Retrieved Sep 20, 2018, from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/actuators/emc

[17] Bosch Rexroth AG. (2018, April). *Linear Modules MKK, MKR, MLR; R999000496; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/linear-modules

[18] Bosch Rexroth AG. (n.d.). *Calculation program Linear Motion Designer*. Retrieved August 25, 2018, from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/topics/calculation-tool/index

[19] Bosch Rexroth AG, . (2018, August). *Function Modules FMS, FMB;R999001418; [Catalog]*. Retrieved from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes/function-modules

[20] Bosch Rexroth. (n.d.). *Linear Axes*. (Bosch Rexroth) Retrieved July 30, 2018, from https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/linear-axes

[21] Brokaw, J., & Martins, K. (2018, April 19). *Profitable design of linear motion: Choosing between DIY or turnkey builds.* Retrieved from Linear Motion Tips: https://www.linearmotiontips.com/profitable-design-of-linear-motion-choosing-between-diy-or-turnkey-builds/

[22] CORETEC. (n.d.). *AC SERVO NUTRUNNER.* Retrieved June 2018, from http://www.coretec.co.jp/en/products/acs/a200/#8

[23] Desoutter Industrial Tools. (n.d.). *ECD50 TECHNICAL DESCRIPTION.* Retrieved August 2018, from https://www.desouttertools.com/tools/2/electric-assembly-systems/25/cvic-ii-range/255/ecd-nutrunners/p/6151650950/ecd50

[24] *DIN 7603 Sealing Washers.* (n.d.). Retrieved June 10, 2018, from https://www.jwwinco.com/en-us/products/3.5-Controlling-venting-sealing-of-liquids-and-gases/Threaded-plugs-Sealing-plugs/DIN-7603-Gaskets

[25] ELESA. (2016, December). Retrieved from https://www.elesa.com/siteassets/PDF/PDF_EN/DIN%20908.pdf

[26] ESTIC CORPORATION. (2017, April). *TRANSDUCERIZED FIXTURED NUTRUNNER.* Retrieved from http://www.estic.co.jp/products/product_en.php?ac_id=detail&id=5&targ=tool

[27] FEC Automation Systems. (n.d.). Retrieved August 2018, from AFC3000 STRAIGHT NUTRUNNER: https://fec-usa.com/afc3000_tools_straight.htm

[28] Hansen, M. J. (2011). *FMEA Scales for Severity, Occurrence & Detection.* Retrieved from https://statstuff.com/ssfiles/tools/FMEAScalesGuide.pdf

[29] Ingersoll Rand. (n.d.). *QA6 Series - Fixtured Inline Remote Adjustable Shutoff.* Retrieved June 2018, from https://www.ingersollrandproducts.com/en-eu/power-tools/products/air-nutrunners/qa6-series-inline-remote-shutoff.html

[30] J.H.L.Hermsen. (March 2016). *Bachelor Thesis Introducing automation to a small assembly line with a high variety of products and series.* Losser: Wouter Witzel.

[31] KEYENCE. (n.d.). *INLINE PROFILE MEASUREMENT [Brochure]*. Retrieved September 25, 2018, from LJ-V7000Series: https://www.keyence.eu/landing/lpc/1703ljven.jsp

[32] L. Bos, Q. O. (n.d.). Retrieved July 2018, from http://portal.wouterwitzel.nl/kam/11%20KAM%20Handboek/K-010%20Valve%20testing%20%202018-07-16.pdf#search=leakage

[33] Linear Motion Technology Handbook. (n.d.). Retrieved August 28, 2018, from https://esa-uk.co.uk/wp-content/uploads/2016/04/LMT_handbook_071.pdf

[34] ltd, R. C. (n.d.). (B. Rexroth, Producer) Retrieved October 20, 2018, from https://nl.rs-online.com/web/c/enclosures-storage-material-handling/structural-systems-handrails/tubing-struts/

[35] M. Faes, Y. W. (2015). *VARIABILITY IN THE MECHANICAL PROPERTIES OF LASER SINTERED PA-12.* Austin, Texas, USA: The University of Texas; Austin.

[36] *Method for Calculating Moment Loads on Linear Actuators.* (n.d.). Retrieved August 30, 2018, from Oriental Motor: https://www.orientalmotor.com/linear-actuators/technology/calculating-moment-load-linear-actuators.html

[37] Mustafa W.Abdullaha, H. M. (2015). An Approach for Peg-in-Hole Assembling using Intuitive Search Algorithm based on Human Behavior and Carried by Sensors Guided Industrial Robot. *IFAC-PapersOnLine*, 1477-1479.

[38] *NewDealSeals*. (n.d.). (NewDealSeals) Retrieved June 20, 2018, from https://newdealseals.com/en/metallic-seals/bonded-seals-dowty-washers/

[39] Nijensteen, G. (September 2017 – July 2018). *Design and validation for automated assembly of EuroValve butterfly valves.* Losser: Wouter Witzel.

[40] Quality-One. (n.d.). *Control Plan Development*. Retrieved from https://quality-one.com/control-plan/

[41] S B Reddy. (2016, December 4). *Insrtumention Tools*. Retrieved from https://instrumentationtools.com/limit-switch-works/

[42] Shetty, D., & A.Kolk, R. (2011). *Mechatronics System Design.* Global Engineering: Christopher M. Shortt.

[43] STUART. (2018, February 6). *Ball Hex vs. Straight Hex Tools*. Retrieved from https://toolguyd.com/ball-hex-vs-straight-hex-tools/

[44] Tague’s, N. R. (2005). *The Quality Toolbox.* ASQ Quality Press. Retrieved from http://asq.org/learn-about-quality/cause-analysis-tools/overview/fishbone.html

[45] *The Dowty 'Bonded Seals'.* (n.d.). Retrieved June 28, 2018, from http://www.potterassoc.com/pdf/bonded_seal_information_and_sizing_chart.pdf

[46] UK SEALS. (n.d.). *Bonded Seals German Metric Size Guide.* Retrieved June 5, 2018, from http://www.ukseals.com/sealing-products/bonded-seals/

[47] WARREN C. YOUNG, R. G. (2002). Roark’s Formulas. In *Roark’s Formulas* (p. 401). Chapter 10.

[48] WON ST CO., LTD. (n.d.). *LINEAR MOTION GUIDE*. Retrieved from http://www.kellenberg.ch/fileadmin/user_upload/PDF/WON_ST_-_CATALOG_EN_.pdf.

[49] Wouter Witzel EuroValve B.V. (n.d.). *Wouter Witzel Valve Technology*. Retrieved Oct 10, 2018, from https://www.wouterwitzel.nl/products/rubberlined-butterfly-valves/

[50] Wouter Witzel EuroValve B.V. (n.d.). *Wouter Witzel Valve Technology*. Retrieved Oct 10, 2018, from https://www.wouterwitzel.nl/about-us/

APPENDICES

A. INFORMATION ON RLBV.

As mentioned in section 1.2 the size of RLBV ranges from DN40-DN2200 with availability in 9 types. The difference is their shapes is shown in Figure. A-1 to Figure. A-9 [49]

Figure. A-1: EVS (Short pattern, from DN50 with centering lug.

Figure. A-2: EVCS (Short pattern from DN50 with centering lugs)

Figure. A-3: EVBS (Short pattern, alignment holes for the end of line duty)

Figure. A-4: EVBLS (Short pattern, alignment holes for the end of line duty and long neck)

Figure. A-5: EVTLS (Short pattern, alignment holes for the end of line duty)

Figure. A-6: EVTLLS (Short pattern, tapped or drilled through holes)

Figure. A-7: EVML (Long pattern)

Figure. A-8: EVFS (Double flanged short pattern)

Figure. A-9: EVFL (Double flanged long pattern)

B. MANUAL ASSEMBLY PROCESS

The manual assembly process was studied and analyzed to identify the design and operational requirements of the system. The sequence stated henceforth illustrates the sequence of operations performed by an operator to fully assemble the valve.

The parts to be assembled are present on the workstation and remaining are made available (body & sub-assembly of disc, pin, and shaft) as per the production order.

1. The operator picks the body from the pallet and places it on the work table, and the drive shaft hole in the body is deburred.
2. Then he places the disc, shaft and pin subassembly on the table. The Sub assembled components are separated by hammering out the pin.
3. Next, he applies grease on the vulcanized rubber lining of the body and inserts the disc inside the body in open position (Open Position-Flat faces of the body and disc are perpendicular to

each other). Later he checks and adjusts the alignment of the driveshaft and bottom shaft hole of the body& disc.

4. The Bottom shaft is greased and inserted into the bottom hole.
5. This is followed by tightening a copper sealing ring and threaded plug together in the threaded hole with an impact gun.
6. Later, the drive shaft subassembly is made by inserting an O-ring bush onto the shaft. This sub-assembly is hammered into the drive shaft hole of the body, and the shaft orientation is adjusted to align the pinhole with the pinhole of the disc.
7. Lastly, the conical pin is inserted and secured.
8. Next, using the drive shaft, the disc is rotated to its closed position (Position in which the flat faces of the body and disc are in one plane), and the assembled valve is placed in leak testing machine to perform leak testing.

C. PRODUCT STUDY

This section addresses the study and analysis performed during the research phase to understand the components that would be assembled during the assembly. The most crucial components of the system are the plug & the sealing ring. Thus, it was essential to study the variation in dimensions of different size of these components.

C.1 DIMENSIONAL SUMMARY OF PLUG

Five different sizes of plug and rings are used in the process depending on the size of the body. The variation in size governs the size of tool extension/adaptor and the tightening torque. All the dimension of the plug is summarised in the Table. C-1

Table. C-1: Detailed dimensions of DIN-908 plugs [25]

PLUG DIMENSION (in mm)										
PLUG SIZE	Diameter of thread		Pitch	Plug length	Flange diameter	Flange thickness	Hexagon width	Hexagon depth	Total length	Total weight
	d1	d1`	P	l1±0.2	d2	l2±0.5	SW	T	L	W
M16x1.5	16	14.5	1.5	12	21	3	8	7.5	15	20
M18X1.5	18	18.5	1.5	12	23	4	8	7.5	16	38
M22X1.5	22	20.5	1.5	14	27	4	10	7.5	18	53
M27x2	27	25	2	16	32	4	12	9	20	75
M36x2	36	34	2	16	42	5	19	10.5	21	145

C.2 DIMENSIONAL SUMMARY OF SEALING RING

In the section. 3.1.2, two types of sealing rings were discussed that could have been possibly used. A dimensional comparison of BS ring & ScBS ring with the copper ring is made, as shown in Table. C-2

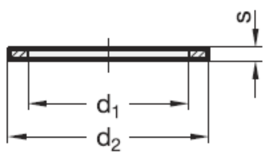


Figure. C-1: Copper sealing ring [24]

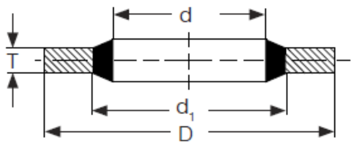


Figure. C-2: Bonded sealing ring [7]

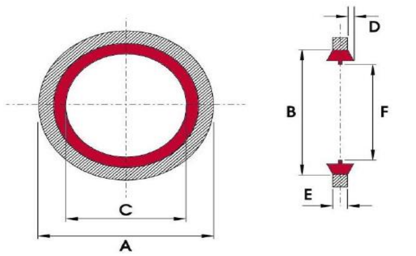


Figure. C-3: Self-centering Bonded Sealing (ScBS) ring [46]

Table. C-2: Detailed dimensions of the different type of sealing rings

PLUG SIZE	**Copper ring**	**Bonded Sealing Rings**	**Self-centring Bonded seals (ScBS)**	**The difference in outer diameter**	**Copper ring**	**Bonded Sealing Rings**	**Self-centring Bonded seals (ScBS)**
	Outer Diameter				**Inside Diameter**		
	$(d_2)^{+0}_{-0.2}$ **(mm)**	$(D)^{+0.13}_{-0}$ **(mm)**	$(A)^{+0.13}_{-0}$ **(mm)**	Δ (mm)	$(d_1)^{+0.3}_{-0}$ **(mm)**	$d^{\pm 0.1}$ **(mm)**	$d^{\pm 0.2}$ **(mm)**
M16x1.5	20	24	24	4	16.2	16.7	13.41
M18x1.5	22	26	26	4	18.2	18.7	14.76
M22x1.5	27	30	30	3	22.2	22.7	18.74
M27x2	32	36	36	4	27.3	27.2	23.3
M36x2	42	46	46	4	36.3	36.7	31.1

In comparison to the copper ring, the bonded sealing rings and self-centering sealing rings have a larger outer diameter. It is evident that the change in the sealing ring would lead to change in spot face diameter of the body (Figure. C-5). Thus, the required spot face diameter to rest these sealing rings is determined from [45] Accordingly, the required change in diameter was determined.

Table. C-3: Change in spot face diameter of the body

Figure. C-4: Spot face diameter for bonded seals [45]

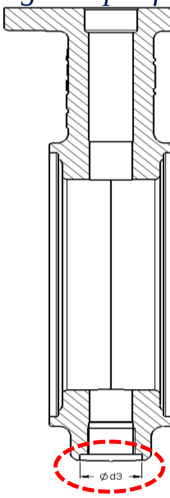


Figure. C-5: Spot face diameter of the body

Plug size	**Current Machined body Spot face diameter (d3 (mm))**	**Required Spot face diameter (d3 (mm))**
M16	22±0.2	24.15
M18	-	26.15
M22	-	30.15
M27	33±0.2	36.15
M36	44±0.1	46.15

C.3 DIMENSIONAL SUMMARY OF THE VALVE BODY

There is enormous variation in dimensions of the body depending on their size, and it becomes more evident with different types. However, only two dimensions govern the overall design of the system, these are summarized in Table. C-4 and

Table. C-5.

Table. C-4: Centre to bottom hole dimensions of the body. All dimensions are in mm.

DN40	DN50	DN65	DN80	DN100	DN125	DN150	DN200	DN250	DN300	DN350
56	61	68	76	94	105	129	154	189	214	234

Table. C-5: Face to face dimension of all the different type of bodies according to their sizes

Type→ / ***Size↓***	**EVS, EVCS, EVBS, EVTLS**	**EVBLS, EVTLLS**	**EVML**	**EVFS**	**EVFL**
DN40	-	-	-	108	-
DN50	45	45	45	110	152
DN65	48	48		114	172
DN80	48	48	66	116	182
DN100	54	54	66	129	192
DN125	58	58	72	142	202
DN150	58	58	78	142	212
DN200	62	62	91	154	232
DN250	70	70	116	167	252
DN300	80	80	116	180	272
DN350	83	-	132	193	293

Using the dimension from the tables above a graph is plotted to show the different position of the bottom hole with respect to the support frame of the product carrier. The x-axis of the plot is the position of the hole when measured from the edge of the support frame, and the y-axis depicts the height from the face of the support frame. The points marked in the graph correspond to Figure 3-8.

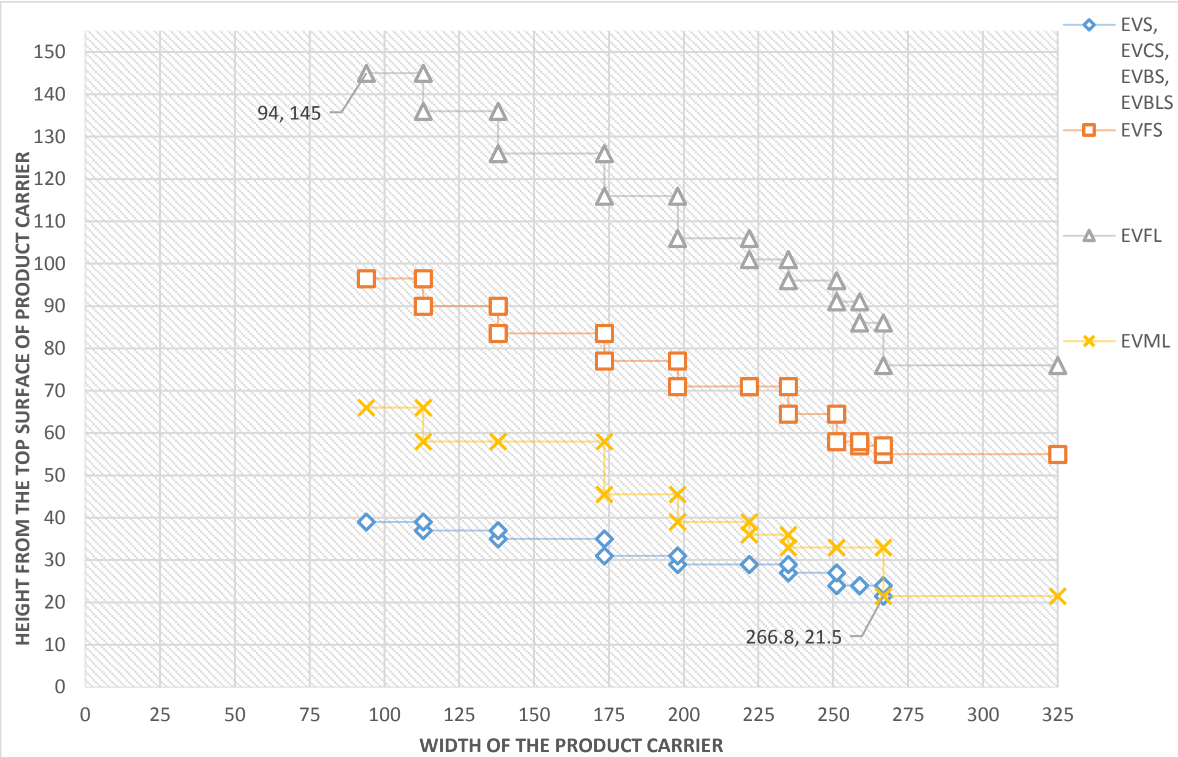


Figure. C-6: Position of bottom hole of different type of bodies based on the size variation.

D.COMPONENTS OF CARTESIAN SYSTEM.

The Cartesian system can be made up of linear guide rail systems of from linear modules. And it is essential to determine what type of linear system is appropriate for the application. The research study showed that a fixed guideline (shown in Figure. D-1) must be followed for accurate selection of components. The guideline would be followed for component selection during the detailed design phase.

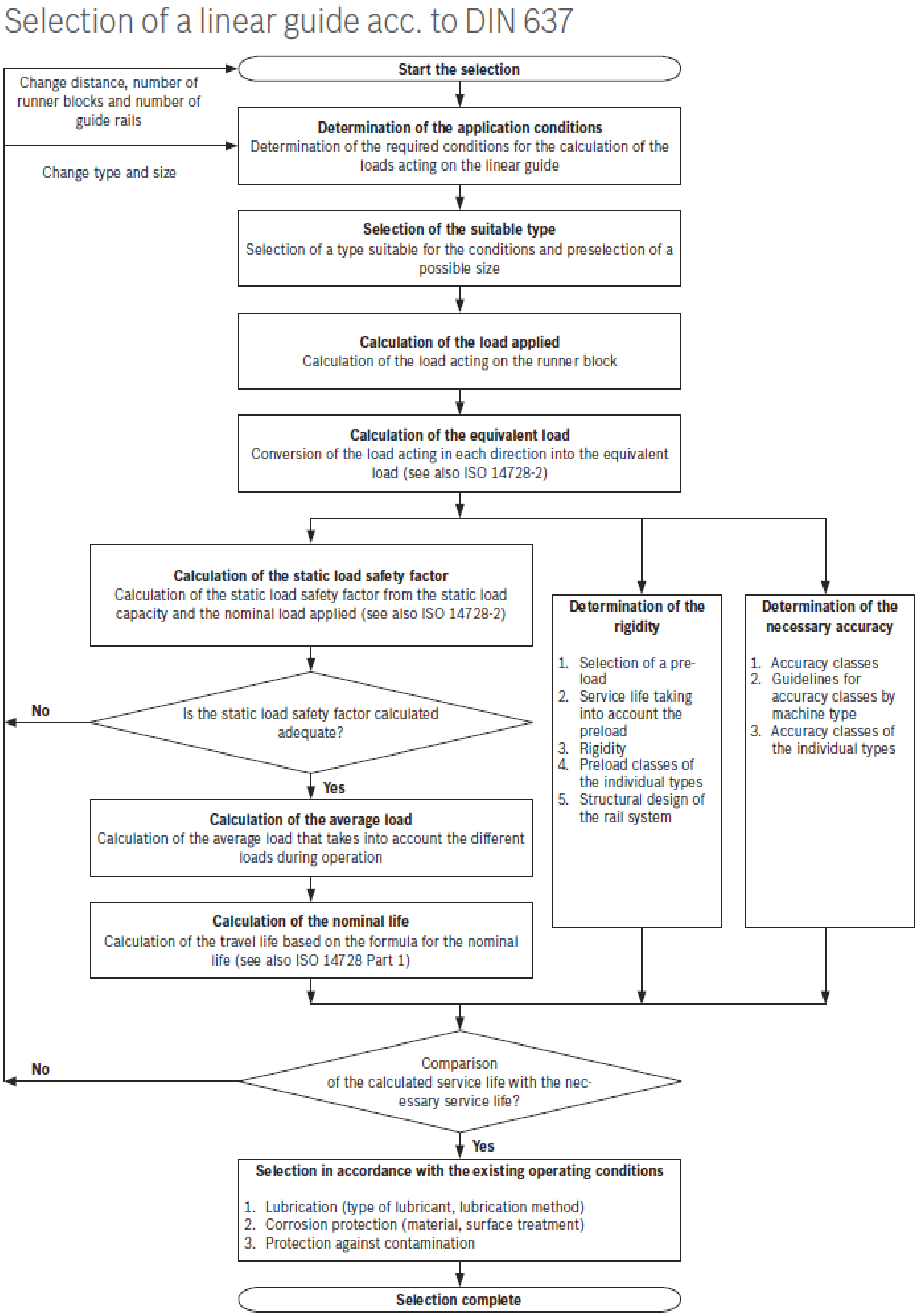


Figure. D-1: Guideline to be followed for the selection of a linear guide unit [10].

As per the discussion in section 3.2.4.2 Bosch Rexroth provides six different variants of linear modules. Every module has a different characteristic and is equally efficient. The core requirements for the design of the linear system are its performance under applied loads. Additionally, size is also an important factor to consider. Thus, the modules are compared based on their dynamic load carrying capacity, and overall dimensions. Based on the detailed requirements of the system, a suitable module would be selected during the detailed design phase. The comparison parameters are summarized in Table. D-1.

Table. D-1: Comparison of dimension, dynamic load-bearing capacity, and repeatability of all the different types of linear guide modules.

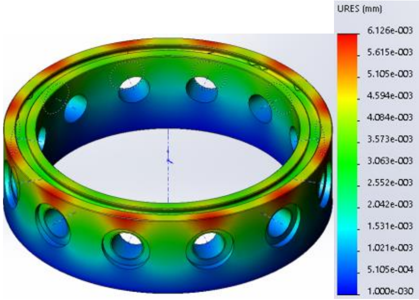
Variant		Width A (mm)	Height H (mm)	Dynamic load Capacity C (N)	Repeatability
Precision Modules	**PSK-040**	40	20	4980	Up to ±0.005mm
	PSK-050	50	26	11850	
	PSK-060	60	33	14620	
	PSK-090	86	46	34600	
Function Modules	**FMS, FMB-80**	80	107	23700	FMS up to ± 0.015mm
	FMS, FMB -110	110	89	24000	FMB up to ± 0.05mm
Linear Modules	**MKK, MKR-40**	40	52	3750	MKK up to ± 0.005mm MKR up to ± 0.05mm
	MKK, MKR-65	65	85	16000	
	MKK, MKR-80	80	110	38000	
	MKK, MKR-110	110	129	46500	
	MKK, MKR-165	165	195	84100	
Omega Modules	**OBB-055**	75	135	20790	N.A.
	OBB-085	107	222	60600	
	OBB-120	135	285	96200	
Ball Rail Tables	**TKK 15-155**	155	60	25300	Up to ±0.005mm
	TKK 20-225	225	75	79200	
	TKK 30 325	325	90	129960	
	TKK 35 455	455	120	180600	
Compact Modules	**CKK, CKR-070**	70	44.5	3830	CKK up to ± 0.005mm CKR up to ± 0.05mm
	CKK, CKR-090	90	56	7505	
	CKK, CKR-110	110	66	32035	
	CKK, CKR-145	145	85	76025	
	CKK, CKR-200	200	127	121185	

E. TEST SETUP & TESTING

The test rings were designed and manufactured (Figure. E-1 shows the test ring of M27x2) for performing preliminary tests. The results of the test would govern the overall design of the system. Thus, a Solidworks simulation was performed to check if the design of the ring could withstand the testing conditions. The simulation result demonstrates minor stresses and little deformation (Figure. E-2). The test ring was used to determine the following.

- The required torque to tighten the plug and sealing ring to assure a leak-tight seal.
- The chamfer provided should aid in centering the bonded sealing ring about the plug thus assuring accurate centering.
- The chamfer was to be tested to check if the bonded sealing ring is still an option or the self-centering rings must be used.

Figure. E-1: Leak test ring for plug size M27x2.



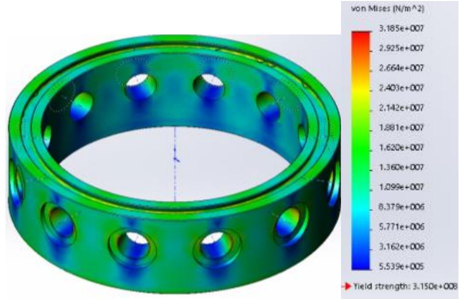


Figure. E-2: The simulation results show the maximum stress of $3.185e^{+007}$ N/m^2 and a maximum deformation of $6.126e^{-003}$mm.

The test parameters and guidelines (Figure. E-3) defined by WW were used to test the rings. All rings were tested at 37.5bar pressure, for 15 mins.

Work instruction Nr: K-010 Rev: G Date: 2018-10-18 Pag: 4 | 29	**Valve testing** Testen van afsluiters	WOUTER WITZEL VALVE TECHNOLOGY

Annex A: Works standard testing of concentric butterfly valves (EV series)

Table A1: Test programme

Closure test 1) 2)	Shell test	Functional test
- High pressure closure test with water: Test 4, or - High pressure closure test with air: Test 5.	Test 16	Valve: Test 8 Valve with actuator: Test 9

Notes:
1) The selection of the test fluid (water or air) depends on the production line equipment, valve size and test pressure. EV valves are tested with the shaft in horizontal position, the internal lining and external coating in place.
2) The closure test may be performed in one flow direction only, as EV valves have equal closure capability in both flow directions and are able to pass the test in both flow directions satisfactorily.
3) For compliance of the test programme with API 598 the following pressure tests are required: Test 1, Test 6.

Table A2: Test pressure (bar)

Cold Working Pressure 1) (CWP)	Closure test (1,1 x CWP)	Shell test (≥1,5 x CWP)
2,5	2,8	3,8
5	5,5	7,5
6	6,6	9
10	11	15
16	17,6	24
19,7	22	30
20	22	30
21	23,2	32
25	27,5	37,5

Notes:
1) The cold working pressure is the minimum of the pressures as indicated on the routing card. Closure test pressures of intermediate CWP's can be calculated with factor 1,1x CWP and the shell test pressure with factor 1,5x CWP.

TABLE A3 – TEST DURATION (SECONDS) 2)

DN	NPS	Closure test	Shell test
≤ 50	≤ 2	15	15
65 - 150	2 ½ - 6	60	60
200 - 300	8 - 12	120	120
350 - 700	14 - 28	120	300
750 - 2200	30 - 84	120 1)	300 1)

NOTES:
1) Minimum test durations for valves DN 750-2000 acc. Australian Standards are: closure test 300 s and shell test 600 s.
2) Minimum test duration for a type test is 15 minutes (all sizes)

Table A4 - Seat leakage rates

DN	NPS	Allowable leakage rate
≤ 50-2200	≤ 2-88	No visually detectable leakage for the duration of the test

Notes:
1) The allowable leakage rate is in compliance with table 5 of API 598:2016, with ISO 5208 table 4, Rate A and with EN 12266-1.

Prepared by: L. Bos, QHSE Officer | Reviewed by QHSE: L. Bos, QHSE Officer | Approved by: N. Runia, QHSE Manager

Figure. E-3: Testing pressure, Time and allowable leakage as per testing standard for EV series valves [32]

E.1 TEST PROCEDURE

There are 5 different hydraulic leak test machines (test fluid –water) at WW which could be used for performing the test. A suitable test machine was chosen based on the test pressure. The sealing was to be checked for the worst-case scenario, and the highest-pressure class of body under the automation project is of PN25. And as per the WW guidelines, the bodies are tested at 1.5 times the pressure class. Therefore the rings are tested at 37.5bar hydraulic pressure. Based on the test pressure, leak test machine no. 3309, 3308, & 3307 could be used, and these had a base plate of 300mm, 450mm, & 600mm respectively. Also, the maximum DN size that could be tested on 3309 was DN200, 3308-DN400, and 3307-DN500. The inner diameter of the test ring is 200mm, and the outer diameter is 250mm. Hence machine 3309 was suitable for testing the rings with ease.

The testing procedure to be followed is

1. The threaded holes with loose fit were marked from 1-6, and the other hole with chamfered edge were marked from 7-12.
2. The plugs with ScBS ring were placed in holes 1-6, and plugs with BS ring were placed in holes 7-12.
3. Initially, all plug and rings were tightened with a torque of 10 Nm using a digital torque wrench.
4. The assembled ring was then placed on the leak test machine and filled with water to make sure no air is trapped inside.
5. The press is safely locked using lock pins at a certain height from the test ring. Later an aluminum cover plate is placed in the slots of the press.
6. The hydraulic cylinder of the press is actuated to lift the base platform till the point where the test ring experiences compressive load between the top & base platform. The actuation is turned off when the pressure has reached 110bar.
7. Use compressed air to remove any drops of water that might be present on the ring or the platform.
8. Next, actuate the pressurizing unit to pressurize the water inside the ring. Turn off the unit when the dial indicates a pressure reading of 37.5bar.
9. If there is a leakage, the internal pressure would gradually drop. Note the hole number where the leak was detected.
10. Release the internal pressure and then open the hydraulic pressure valve to lower the press.
11. Remove the ring from the press. Unfasten the plugs and retighten them with an increment of 5Nm torque. Repeat the procedure from step 4.
12. If the internal pressure does not drop immediately, then leave the setup in the current state for 15min. If the leak is detected after 15minutes, go back to step 9.
13. If no leak is detected then follow step 10 and note the value for the tested torque.
    Remove the ring from the setup and disassemble it.

The same procedure was followed for testing all the other test rings.

Figure. E-4: The completely assembled ring is kept on the leak test machine and filled with water up to its brim

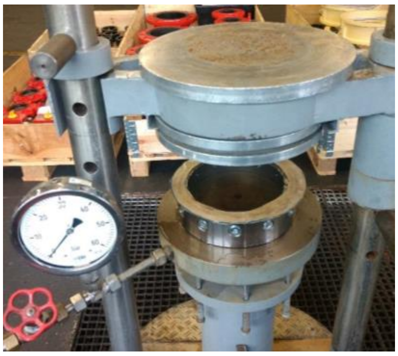


Figure. E-5: An extra gasket kept on the circumference of the ring to avoid any leakage past the o-ring inside the test ring.

Figure. E-6: The press is closed, and the water is pressurized to 37.5 bar and left in this condition for 15min. After 15mins each plug is checked for visible leakage and results are noted.

E.1.1 Test results:

All the plug sizes were tested with both bonded sealing rings and self-centering sealing rings for leak tightness. As stated in the test procedure the test was carried out until no visible leakage was observed. The test results are shown in Table. E-1, the numbers in the cell corresponding to the applied tightening torque. The numbers from 1 to 12 denote the identification given to the holes. In addition, the cells marked with red indicate, the PR at the corresponding hole was leaking at that tightened torque.

Table. E-1: Tested torque values and corresponding leak tightness for different plug and ring sizes.

Plug Size	Self-Centering Sealing Ring												Bonded Sealing Ring											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
M16x1.5	10.2	10.2	10.2	10.3	10.4	10	10.2	10.2	9.8	9.8	10.3	10.1	10	10.2	10.1	10.1	10.1	10.2	10.1	10.1	10.2	10.2	10.2	10.2
	15.1	15.2	15	15	15	14.9	15.4	15.3	15.2	15.2	15.1	15.2	15.1	15.2	15.3	15.2	15.2	15.2	15.3	15.2	15.2	15.2	15.2	15.1
M18x1.5	10.3	10.3	10.4	10.2	10.2	10.2	10.3	10.2	10.2	10.1	10.1	10.2	10.2	10.2	10.2	10.1	10.2	10	10.1	10	10	10	10.2	10.3
	15.2	15.2	15.1	15.2	15.2	15.1	15.2	15.2	15.1	15.3	15.1	15.2	15.3	15.2	15.2	15.4	15.2	15.1	15.1	15	15	15.1	15.3	15.4
M22x1.5	10	10	10.2	10.2	10.1	10.1	10.3	10.2	10.1	10.1	10.1	10	10.1	10.2	10.1	10.2	10.2	10.2	10.3	10	10.1	10.3	10.2	10
	15.2	15.3	15.3	15.3	15.3	15	15.2	15.2	15.2	15.2	15.2	15.3	15.2	14.8	15.2	15.2	15.5	15.2	15	15.2	15.2	15.1	15	15
M27x2	10.1	10.2	10.1	10.2	10.4	10.2	10.3	10.2	10.2	10.1	10.2	10.2	10.2	10.1	10.1	10.3	10.3	10.3	10	10.1	10.1	10.2	10.2	10.2
	15.3	15.1	15.2	15.4	15.1	15	15.1	15.1	15.3	15.2	15.2	15.1	15.1	15.1	15.2	14.9	15.2	15.2	15	15.2	15.4	15.4	15	15
	20.1	20.1	20.2	20.1	20.1	20.2	20.1	20.2	20	20	20.2	20	20.1	20.2	20.1	20.2	20.3	20.4	20.2	20.4	20.1	20.1	20.1	20.2
M36x2	-	-	-	-	-	-	-	-	-	-	-	-	20.1	20.2	19.8	20.2	20.2	20.3	20.1	20.2	20.1	20	20.2	20.2
	-	-	-	-	-	-	-	-	-	-	-	-	25.4	25.3	25.4	24.8	25.2	25.1	25.2	25.1	25.2	25.2	25.2	25.3

Figure. E-7: BS ring eccentric to the threaded hole and the lower edge of the vulcanized rubber does not cover the threaded hole. Thus, compromised sealing.

Figure. E-8: BS ring completely covers the threaded hole because of its close fit inside the counterbored hole.

Figure. E-9: ScBS ring inside the counterbore hole with larger clearance around the circumference. Though the Ring is eccentric, the inner centering projection of the ring covers the threaded hole and thus assures leak proofing.

Figure. E-10: BS ring eccentric to the plug and hanging loose.

Figure. E-11: BS ring outer edge in contact with the chamfered edge of the hole.

Figure. E-12: BS ring guided by the chamfer and the ring is being centered around the neck of the plug.

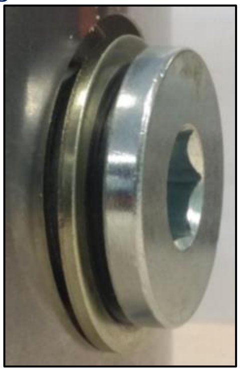


Figure. E-13: BS ring eccentric to the plug and hanging loose beyond the edge of the hole without a chamfer.

F. REDESIGN OF PLUG & RING FIXTURE.

There were a few significant challenges that were affecting the overall design of the system. One such major problem was the orientation of the plug. Though the fixture provided stability and positional accuracy, it lacked to provide accurate positioning. There is no surety on how would be the orientation of the plug when it reaches the station, as it could be placed randomly by the operator or assembling forces from the prior station could change the orientation.\

Hence, few approaches were suggested and analyzed to see which would help overcome the problem or completely solve it.

F.1 APPROACH 1: USING SENSORS GUIDED ROBOT TO CORRECT THE POSITION AND TRAJECTORY DURING THE PROCESS [37]

The human operator uses two main senses: vision sense to estimate and locate the parts and roughly mate them, and kinesthetic sense to insert the peg into the hole. For a robot, a vision and Force/Torque sensors can simulate these senses. Therefore, most of the researchers tend to use either one of these sensors or their combination [37]. A few possible approaches to guide a robot to perform such assembly tasks are briefly described below:

1. *Static Contact Forces Analysis* (Figure. F-1): Attempts are made to carry-out the assembling using contact force information focused on statically analysis for possible contact forces, including the friction force, to calculate the angle (θ) between the peg axis and hole axis [37].
2. *Force/ Torque Map* (Figure. F-2): The location of the hole is determined using a guiding map based on interpretation of force and torque data retrieved from each contact point between the peg and the hole. This approach is quite effective for rounded holes [37].
3. *Vision System*: Incorporating a vision system to accurately guide the robotic system towards the location of the hole. In this approach, the robot arm spins the peg around the hole with specified force until the mating is successful, similar to human approach [37].

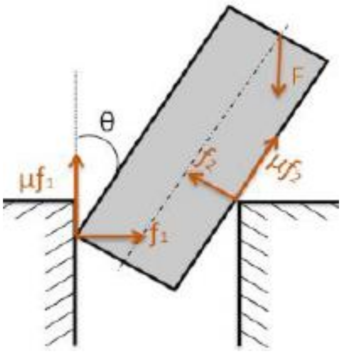


Figure. F-1: Attempts to insert the peg into the hole using contact force information to calculate the angle (θ) [37].

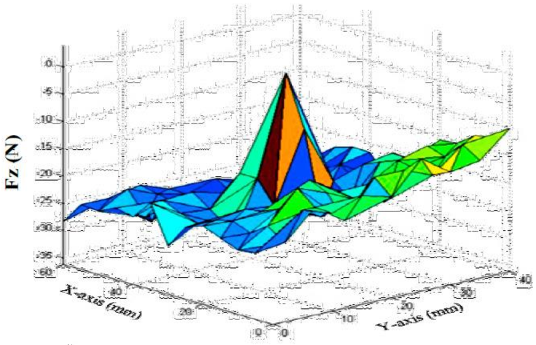


Figure. F-2: A map illustrating the location of the hole in the X-Y plane by plotting the data (force) retrieved from the force-torque sensor [37].

In the considered approaches either an external Force/Torque sensor is used, or by computing, the internal robot's joints torque to estimate the force at the end-effector. However, the possible approaches have some limitations such as:

- "Statically analysis of forces is not feasible due to the dynamic behavior of assembling task."
- "Changes in parts locations and orientation in the working area or repeatability error of the robot can affect the distribution of forces in the pre-calculated force/torque map."
- "Contact state estimation models need the accurate and sufficient amount of data to predict the correct state. These data usually are collected in a lab environment which differs from the industrial work environment."

In addition, the arbitrary mating of peg-in-hole might consume some time resulting in increased takt time.

Thus, a possible solution is proposed by combining the vision-based servoing approach and force torque based guiding. Where the vision system provides a rough estimation of the location of the hole. Then, assembling is carried out using the contact force information from the force-torque sensor. The first step in the proposed approach is to locate the closest edge of the hole to the robot end-effector. The robot end-effector grips the peg and reaches the roughly estimated edge of the hole. Next, the operation is carried out in 6 phases as described below.

- *Phase-I*: Peg approaches the hole's edge vertically until a contact force is sensed.
- *Phase-II*: The robot rotates the peg, while keeping the contact with work area, in four directions, i.e., on the ± x-axis and ± y-axis, thus monitoring the torque on each rotation to

determine the center of the hole. With the known location, the peg is tilted toward the center to ensure that the lower edge of the peg is inside the hole.

- *Phase-III*: Peg will be moved in the center until a contact force (generated from an encounter with the side of the hole) is sensed. Thus, the procedure would give an assurance that the peg is entirely inside the hole.
- *Phase-IV*: The misalignment of the peg caused due to tolerances between the peg diameter and hole diameter is corrected.
- *Phase-V*: Displacement is corrected by spinning the peg inside the hole and ensuring that it touches all the inside wall of the hole.
- *Phase VI*: The assembly is completed by pushing the peg into the hole until the measured force on this axis exceeds the configured limit.

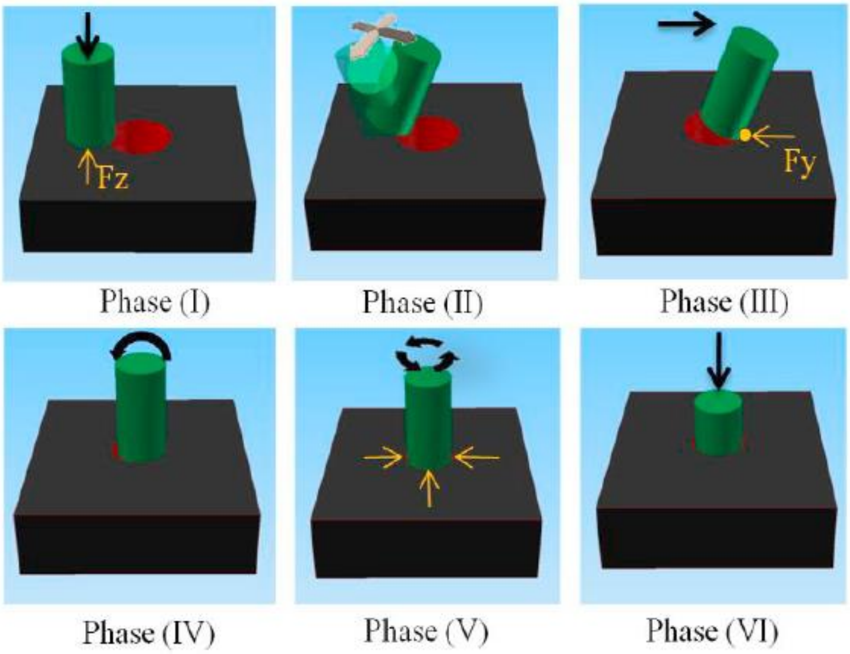


Figure. F-3: Steps (phases) followed by a robotic system to insert a peg inside the hole using guidance from the feedback the of a force-torque sensor.

F.2 APPROACH 2: USING AN OFFLINE GUIDING, PRE-PROGRAMMED ROBOT [37].

With the second approach, the task becomes a bit simpler. As per this method, the robot will be pre-programmed in a manner that the position and orientation of the plug inside the fixture would not be of major concern. This is because the plug and ring would be placed at a unique position in the fixture. All the plugs are of standard sizes, and their dimensions are known, and so is the dimensions of the fixture. This information is sufficient to determine the position of the plug in 3D space with reference to the position of the product carrier. For instance, the distance of the Center of the plug could be determined by considering the edge of the product carrier as the datum.

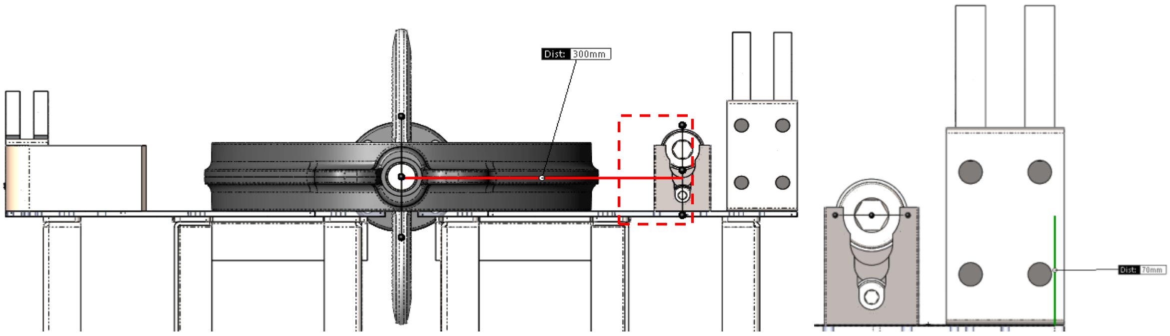


Figure. F-4: Fixed distance of components on the product carries aid in determining the center of the plug, ring and the body.

The exact position of the plug and ring inside the fixture would enable the alignment & centering of the tightening tool and hence eliminates the requirement of a vision system. The second step is to hold the plug inside the hexagon to aid the picking from the fixture. For this, the orientation of the plug inside the fixture comes into play. The orientation is defined as the position of the hexagon with respect to the central axis (as shown in Figure. F-5(.

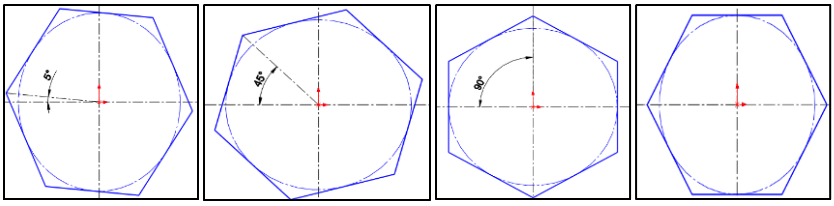


Figure. F-5: A possible orientation of the hexagon of the plug.

To hold the plug, the tip of the tightening tool has to be in the same orientation as that of the plug. To ensure proper fit a trial and error method has to be used and unlike the sensory feedback as in the peg and hole method. The Center position of the plug inside the fixture is known as per the size; hence, the tool positions itself accurately. For the tool to fit inside the hexagon of the plug, the orientation of the hexagon must be known. For this, a vision system could be a reliable solution or a trial and error method could be used. In trial and error approach the tool would advance towards the plug until it experiences a counter force (i.e., makes contact with the plug). If the tool and plug have the same orientation, the tool would fit-in directly. If the plug has a different orientation, when contact is established, the tool experiences a counterforce. Now, it could be rotated and advanced simultaneously. The rotation should be incremental and slow — this way the tool gets in the same orientation as that of the plug and snaps inside. The drawback with this approach is a possible simultaneous rotation of the plug with the tool. Thus, it would be difficult to attain the desired orientation. Also, this approach might contribute towards the wear of the plug and the fixture.

F.3 APPROACH 3: WRENCHES WITH BALL END

There is a quite simple and cheaper method of solving the problem. A wrench with ball end is just another Allen key where the hexagonal end shape is machined to form a drop/ball shape. This shape gives a significant advantage, as the rounded end can easily be guided into the hole and it can be inserted at an angle (Figure. F-6). If this kind of tool bit is mounted on the tightening tool, then it completely resolves the problem of unknown orientation of the plug. But its strength is also its weakness, as the neck is narrow and small, it has higher possibilities of snapping off during operation. The rounded surface of the tool has a lesser area of contact with the fastener and

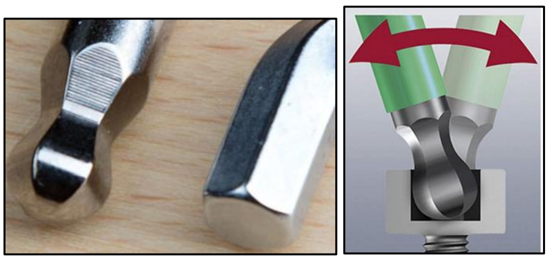


Figure. F-6: Ball end Allen key tool. It could be inserted at an angle [43] thus, increases the wear of the tool. With prolonged usage, the tool would rotate freely inside the hexagonal hole and would not carry out the tightening operation. In addition, their availability in limited sizes is another disadvantage.

F.4 TOOL TIP DETACHMENT TESTING

The new design of the fixture includes a tool bit for holding the plug and ring. The same tool bit is used for tightening operation and placed back into the fixture after the completion of the operation. While placing the tool-bit back into the fixture, the nutrunner exerts a pull force to detach itself. The pull force is translated to the fixture, and it is essential that the fixture is not damaged during this operation. Therefore, a test was performed to determine the pull force required to detach half inch drive socket from a tool bit (with half inch drive) used for tightening an M36 size plug. Figure. F-7 shows the test setup for the testing. The drive socket is clamped inside a vice, and used for disc insertion testing during system-level design). The gripper is fastened to the force sensor which has been clamped inside the chuck of a drill machine. The clockwise rotation of the machine spindle would lower the gripper, and the tool bit would be attached with the drive socket. Rotating the spindle in the counterclockwise direction would detach the tool bit off the drive socket. Thus, the pull force would be recorded. The same procedure has been repeated multiple times, and the results show a maximum pull force of 0.091kN.

Figure. F-7: Test setup for determining the pull force required to detach a tool bit used for the M36 plug.

G. SELECTION OF THE NUTRUNNER

The nutrunner from different manufacturers were compared based on the torque range, the weight of the tool, and the total length of the tool. These parameters greatly influence the overall design of the system. The comparison chart is shown in Table. G-1.

Table. G-1: Comparison of nutrunners from different manufacturers.

Manufacturer	Part no.	Tool	Torque Range (Nm)	Weight (kg)	Total length (mm)
Ingersoll Rand. [29]	QA6ASRS 055BF41S 08		25-55	2	454
Desoutter Industrial Tools [23]	615165095 0		16-50	2.6	456
Atlas Copco [4]	ETD ST81-50-13 (84332153 34)		Max 50	2.1	493

Estic [26]	ENRZ-TU004R-S		4-40	3.8	337.5
FEC Automation System [27]	CFT-401RS1-S		Max 40	1.44	315
Coretec [22]	2505S		19-56	5.5	430

H. CALCULATIONS FOR DETAILED DESIGN

H.1 DESIGN OF FIXTURE ARM FOR NUTRUNNER

The detailed design of stage 1 is carried out to assure that the tightening tool remains in a fixed position over the operational cycle. To determine the size for the support, it is treated as a cantilever beam, and corresponding torsional stress, shear stress, angular and linear displacement/deformation were calculated. The results were compared to decide on suitable dimensions. The length of the fixture is considered in accordance to support the length of the nutrunner, and the torque application point is assumed 100 mm further from the end face of the fixture (because of tool extension and tool bit for the nutrunner). Other parameters of the plate and material properties are listed in Figure. H-1.

Constant Parameter	
Fixture Length (L1)	275
Forced application point from tip of fixture	50
Length (mm)	325
Density (kg/m3)	2700
Modulus of Rigidity [G (N/mm2)]	27000
Modulus of Elasticity [E (N/mm2)]	70000
Applied Torque [T (Nm)]	50
Weight of the tool [mg(N)]	19.62
Distributed load [w (N/mm)]	0.071

Figure. H-1: Constant parameters for the fixture support (stage 1). These are used for determining the required dimensions for the fixture.

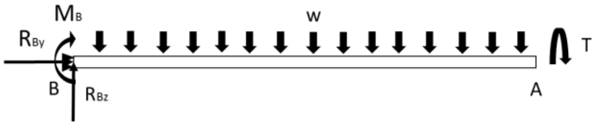


Figure. H-2: FBD of support structure simplified as a cantilever beam and acted upon by distributed mass load of the tightening tool and tightening torque

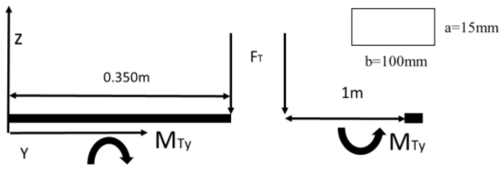


Figure. H-3: Illustration of FBD to show the moment load acting on the support structure.

Using equilibrium equations for 2D bodies the reaction forces are calculated.
RB_y= 0N
RB_z= 19.635 N
MB = 1.89 Nm.
The torque of 50 Nm is denoted as a 50N force (F_T) applied at 1m from the tip of the tool. The torsional moment at the tip has an equal, and opposite reaction at the fixed end of the beam. It is necessary to assure that the plate is not twisted because of torsion, as this would affect the accuracy of the system. Angular deflection is calculated using $\theta = \frac{TL}{GJ}$. The support structure was tested for different dimensions and results are shown in Figure. H-4.

Plate Characteristics				Tosion			Bending		
Width of the beam	**Thickness of the**	**Polar moment of**	**Moment of Inertia**	**Angular Deflection**		**Max shear Stress**	**Deflection**		**Total Weight**
a (mm)	**b (mm)**	**J/K (mm4)**	**I (mm4)**	**θ(°)**	**(rad)**	**τmax (N/mm2)**	**δ (mm)**	**θ(°)**	**(kg)**
80	5	3.20E+03	8.33E+02	10.77	0.181	7.81E+01	8.935E+00	0.0070	0.35
80	10	2.46E+04	6.67E+03	1.40	0.023	2.04E+01	1.117E+00	0.0009	0.70
80	15	7.94E+04	2.25E+04	0.43	0.007	9.46E+00	3.309E-01	0.0003	1.05
90	5	3.62E+03	9.38E+02	9.53	0.161	6.91E+01	8.746E+00	0.0062	0.39
90	10	2.79E+04	7.50E+03	1.24	0.020	1.79E+01	1.093E+00	0.0008	0.79
90	15	9.06E+04	2.53E+04	0.38	0.006	8.29E+00	3.239E-01	0.0002	1.18
100	5	4.04E+03	1.04E+03	8.55	0.145	6.19E+01	8.594E+00	0.0056	0.44
100	10	3.12E+04	8.33E+03	1.10	0.018	1.60E+01	1.074E+00	0.0007	0.88
100	15	1.02E+05	2.81E+04	0.34	0.005	7.37E+00	3.183E-01	0.0002	1.32

Figure. H-4: Result of torsional stress and deformation for different sizes of the reaction plate.

The analytical calculations demonstrate (for instance plate with 5mm thickness), there is a variation of approximately 0.2mm in deformation/deflection values for a plate with the same thickness, but 10mm increased width. Similarly, the variation for stress and weight is under 1N/mm^2 and 0.05 kg. Thus, it could be concluded that the slight variation in plate dimensions would not affect the overall design. Moreover, the analytical results were cross-checked by performing simulation on the preliminary model, with a plate width of 90mm & thickness of 15mm. The analytical results (highlighted in Figure. H-4) shows a deformation of 3.239e^{-1} mm and torsional shear stress of 8.294e^{+00} N/mm^2, which is comparable to the results of the simulation, with maximum deformation of 3.674e^{-1} mm and stress at the end face of the plate equivalent to 8.282e^{+06} N/m^2,) (Figure. H-5)

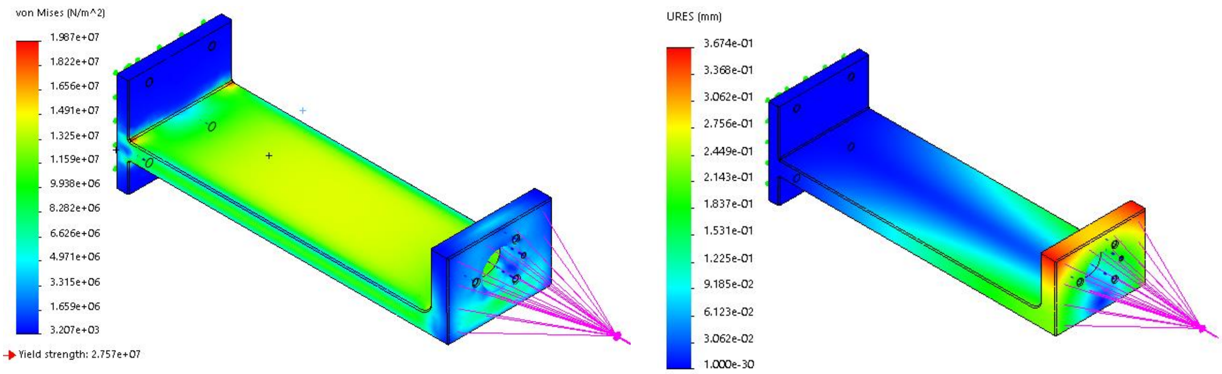


Figure. H-5: Deformation of the reaction support plate with a width of 90mm & thickness, acted upon by a tightening torque of 50Nm and distributed the load of the nutrunner. The simulation results show the maximum stress of 1.987 e^{+7} N/m^2, with a yield strength of 2.757 e^{+7} N/m^2 and deformation of 3.674e^{-1}mm.

However, the simulation result shows higher stress along the length of the plate. Thus, the fixture design was modified to avoid premature failure and enhance torsional rigidity. The central flat rectangular plate is replaced with a C-profile bar and would be welded together with the front and rear support plate. Due to the smaller cross-sectional area and to keep the design simple for manufacturing, a C-profile is selected over the other available profiles. The C-profiles are available in width ranging from 30mm to 400mm. However, considering the 60mm diameter of the nutrunner plus the width of its drive motor, a 100mm wide profile is suitable for the application.

The modified fixture is checked for deformation and stresses. The result shows the maximum stress of 1.107e^{+008} N/m^2 and maximum deformation of 3.146e^{-001} mm (Figure. H-5). Thus, the stress distribution is uniform in the structure and is profoundly rigid against torsion.

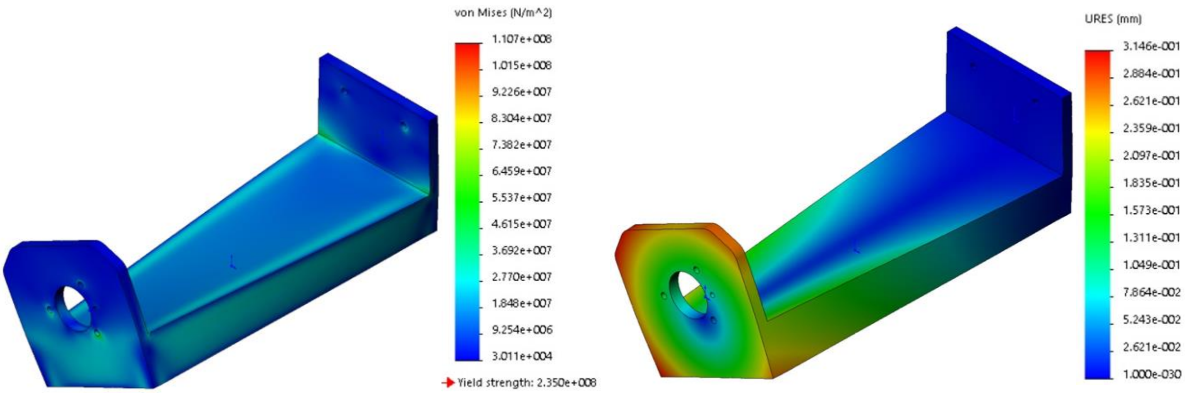


Figure. H-6: Optimized design of the support fixture for mounting the nutrunner. The simulation results show the maximum stress of $1.107e^{+08}N/m^2$ and deformation of 0.3146mm at the welded joints.

H.2 DESIGNING OF Z-AXIS LINEAR SYSTEM

Initially, the design process was started by considering a linear profiled guide system for translation along the z-axis. A 4 block and 2 rail, linear system were considered. The intention was to determine the reaction forces on the system and then to determine if a guide rail system should be used or a linear module.

As per the overview provided in the section. 3.2.4.1, a different type of guide blocks and their selection procedure are explained in this section. The different variants of runner block available in the catalog [10] were considered for selection. The designation of different variants of runner blocks is given in Figure. H-7. The selection of the runner blocks is made based on their height, width, length and the load-bearing capacity (with respect to the current requirement). The guide blocks with long length are eliminated because these are not suitable for this particular application with short stroke lengths. The selected runner blocks are summarised in the Figure. H-8. The runner blocks are available in sizes up to 90mm. However, size 15mm to 35 mm is considered for confining the calculations and simplifying the selection.

Criterion	Designation	Abbreviation (example)		
		F	N	S
Width	Flange	F		
	Slim line	S		
	Wide	B		
	Compact	C		
Length	Normal		N	
	Long		L	
	Short		K	
Height	Standard height			S
	High			H
	Low			N

Figure. H-7: Definition of ball runner block format & Abbreviation of the formats of all available ball runner blocks.

STEEL	Block Size		Load bearing capacity
	Type	Varient	
Std Ball runner blocks made of steel	FNS	R1651/R2001	High
	FKS	R1665 / R2000	Medium
	SNS	R1622 / R2011	High
	SKS	R1666 / R2010	medium
	SNH	R1621	High
Std Ball runner blocks made of steel	FNN/ SNN	R1693 / R1694	High
	FKN / SKN	R1663 / R1664	Medium
Aluminum ball runner	FNS	R1631	High
	SNS	R1632	High

Figure. H-8: Sorting of the runner blocks based on the load-bearing capacity and length of the blocks [10]

Now that varieties of runner blocks were available, a specific selection had to be done. The driving parameters were the load to be carried, the orientation of the guide system and the stroke length.

Table. H-1: Runner block characteristic notification and their respective units [10]

Parameter		Unit
C	Dynamic load capacity:	N
C0	Static load capacity	N
Mt	Dynamic torsional moment load capacity	Nm
Mt0	Static torsional moment load capacity	Nm
ML	Dynamic longitudinal moment load capacity	Nm
ML0	Static longitudinal moment load capacity	Nm
Xpr	Preload of the guide	-
Fpr	Preload force (Xpr *C)	N

Table. H-2: Preload class of the runner blocks and their particular application [10]

Code	**Preload**	**Preload factor Xpr**	**Application Area**
C0	Without preload (Clearance)	0	For particularly smooth-running guide systems with the lowest possible friction for applications with large installation tolerances. Clearance versions are available only in accuracy classes N and H.
C1	Moderate preload	0.02	For precise guide systems with low external loads and high demands on overall rigidity.
C2	Average preload	0.08	For precise guide systems with both high external loading and high demands on overall rigidity; also recommended for single-rail systems. Above average moment, loads can be absorbed without significant elastic deflection.
C3	High preload	0.13	For high-rigidity, guide systems like precision machine tools, etc. Above average loads and moments can be absorbed with the least possible elastic deflection.

Based on Table. H-2, a moderate preload (C1) is considered for all further calculations. Moreover, accordingly, the preload force applied to the runner blocks is calculated. The dynamic load capacity (C) & pre-load force for the selected sizes is shown in Table. H-3. The runner blocks are preloaded to increase the rigidity of the system and block with no preload could have clearance between the ball runner block and the rail of 1 to 10µm.

Table. H-3: Dynamic load capacity (C) and preload force (F_{pr}) for different variants of runner blocks.

STEEL	**Block Size**		**15**		**20**		**25**		**30**		**35**	
	Type	**Varient**	C	Fpr	C	Fpr	C	Fpr	C	Fpr	C	Fpr
Std Ball runner blocks made of steel	FNS	R1651/R2001	9860	160	23400	380	28600	460	36500	630	51800	840
	FKS	R1665 / R2000	6720	110	15400	250	19800	320	25600	440	36600	590
	SNS	R1622 / R2011	9860	160	23400	380	28600	460	36500	630	51800	840
	SKS	R1666 / R2010	6720	110	15400	250	19800	320	25600	440	36600	590
	SNH	R1621	9860	160	23400	380	28600	460	36500	630	51800	840
Std Ball runner blocks made of steel	FNN/ SNN	R1693 / R1694			14500	290	28600	460				
	FKN / SKN	R1663 / R1664			9600	190	19800	320				
Aluminum ball runner	FNS	R1631										
	SNS	R1632										

For Z-translation, the entire system had to be mounted in a vertical direction as shown in Figure. H-9. For the detailed calculation, an elaborated formulation was formed as could be referred from Table. H-4, the formulation from Figure. H-10 was used as a base, and the changes were made according to the actual operating condition, nomenclature, and coordinate system of the assembly station.

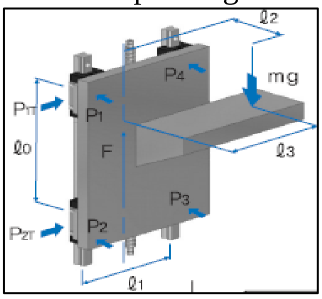


Figure. H-9: Vertical orientation of a linear guide system [48]

$$P_1=P_4=-\frac{m(g-\alpha_1)\ell_2}{2\cdot\ell_0}$$
$$P_2=P_3=\frac{m(g-\alpha_1)\ell_2}{2\cdot\ell_0}$$
$$P_{1T}=P_{4T}=\frac{m(g-\alpha_1)\ell_3}{2\cdot\ell_0}$$
$$P_{2T}=P_{3T}=-\frac{m(g-\alpha_1)\ell_3}{2\cdot\ell_0}$$

Acceleration phase

$$P_1=P_4=-\frac{mg\cdot\ell_2}{2\cdot\ell_0}$$
$$P_2=P_3=\frac{mg\cdot\ell_2}{2\cdot\ell_0}$$
$$P_{1T}=P_{4T}=\frac{mg\cdot\ell_3}{2\cdot\ell_0}$$
$$P_{2T}=P_{3T}=-\frac{mg\cdot\ell_3}{2\cdot\ell_0}$$

Uniform motion phase

$$P_1=P_4=-\frac{m(g-\alpha_3)\ell_2}{2\cdot\ell_0}$$
$$P_2=P_3=\frac{m(g-\alpha_3)\ell_2}{2\cdot\ell_0}$$
$$P_{1T}=P_{4T}=\frac{m(g-\alpha_3)\ell_3}{2\cdot\ell_0}$$
$$P_{2T}=P_{3T}=-\frac{m(g-\alpha_3)\ell_3}{2\cdot\ell_0}$$

Deceleration phase

Figure. H-10: Forces acting on the individual runner blocks in different phases of motion during the stroke [48]

Table. H-4: Formulation of forces acting on the runner block as per the nomenclature used in the calculation.

	Acceleration & Deceleration Phase	
	(Runner Blocks 1 & 4)	**(Runner Blocks 2 & 3)**
Normal Forces	$F_{N1} = F_{N4} = -\sum_{i,t=1}^{n} \frac{(m_i(g - a_{i,t})z_i + (F * z_i))}{(2l_w)}$	$F_{N2} = F_{N3} = \sum_{i=1}^{n} \frac{(m_i(g - a_{i,t})z_i + +(F * z_i))}{(2l_w)}$
Transverse Forces	$F_{T1} = F_{T4} = \sum_{i,t=1}^{n} \frac{(m_i(g - a_{i,t})y_i + (F * y_i))}{(2l_W)}$	$F_{T2} = F_{T3} = -\sum_{i,t=1}^{n} \frac{(m_i(g - a_{i,t})y_i + (F * y_i))}{(2l_W)}$
	Uniform Motion	
Normal Forces	$F_{N1} = F_{N4} = -\sum_{i,t=1}^{n} \frac{(m_i(g)z_i + (F * z_i))}{(2l_W)}$	$F_{N2} = F_{N3} = \sum_{i=1}^{n} \frac{(m_i(g)z_i + +(F * z_i))}{(2l_W)}$
Transverse Forces	$F_{T1} = F_{T4} = \sum_{i,t=1}^{n} \frac{(m_i(g)y_i + (F * y_i))}{(2l_W)}$	$F_{T2} = F_{T3} = -\sum_{i,t=1}^{n} \frac{(m_i(g)y_i + (F * y_i))}{(2l_W)}$

The stroke length along z is 130mm which is sub-divided as 15mm of acceleration phase, 100mm of uniform motion & 15mm of deceleration phase during the forward stroke. This is followed by dwell phase and then the reverse stroke. Acceleration is calculated for each phase based on the distance traveled. In this case, the nutrunner & the fixture are translated along the z-axis. Therefore their weight, inertia force and the tightening torque acts on the system. Weight & inertia force is acting at the center of gravity (CoG) of the respective component, and torque is acting at the tip of the tool. Thus, the location of CoG with respect to CoG of Z is estimated. The corresponding normal and transverse reaction forces on the runner blocks are calculated using the derived formulation (shown in Figure. H-11). The distance Lw & Ls respectively denotes the distance between two guide rails, and between two guide blocks on the same rail. These values are considered equivalent to the distance between guide rails and blocks of a CCK 90 compact module. This is done for understanding the possibilities of using a compact module or a linear guide rails system.

Distance between the rails along "Y"	Distance between the rails along "X"	Weight (m1-1.5kg)	Acc Force (N)	Coordinates of application of "m1g"			Weight (m2-1.5kg)	Acc Force (N)	Coordinates of application of "mg 2"			Torque Force	Coordinates of application of "F"			Reaction forces (N)								Max F_N & F_T on the runner blocks	
Lw	Ls	m1g	m1a	x	y	z	m2g	m2a	x	y	z	F	x	y	z	Block 1		Block 2		Block 3		Block 4			
mm	mm	N	1.5	mm	mm	mm	N	3.5	mm	mm	mm	N	mm	mm	mm	F_{N1}	F_{T1}	F_{N2}	F_{T2}	F_{N3}	F_{T3}	F_{N4}	F_{T4}	N	
65	54	-15	-0.5	0	0	130	-34	-1.2	0	0	150					56	0	-56	0	56	0	-56	0		
65	54	-15	0.0	0	0	130	-34	0.0	0	0	150					54	0	-54	0	54	0	-54	0	$F_{N\,max}$	189
65	54	-15	0.5	0	0	130	-34	1.2	0	0	150					52	0	-52	0	52	0	-52	0		
65	54	-15	0.0	0	0	130	-34	0.0	0	0	150	-50	0	1000	350	189	385	-189	-385	189	385	-189	-385		
65	54	-15	0.5	0	0	130	-34	1.2	0	0	150					52	0	-52	0	52	0	-52	0		
65	54	-15	0.0	0	0	130	-34	0.0	0	0	150					54	0	-54	0	54	0	-54	0	$F_{T\,max}$	385
65	54	-15	-0.5	0	0	130	-34	-1.2	0	0	150					56	0	-56	0	56	0	-56	0		

Figure. H-11: Normal and Transverse forces acting on the 4 runner blocks during the 7 different phases of operation. The weight force is applicable in all 7 cases, whereas acceleration forces occur during 1st, 3rd, 5th & 7th phase. Lastly, the force due to tightening torque is experienced only during the 4th phase.

Ball Runner Block		Pre Load force on Runner Blocks				
		15	20	25	30	35
Type	Varient					
FNS	R1651/R2001	~~160~~	380	460	630	840
FKS	R1665 / R2000	~~110~~	250	320	440	590
SNS	R1622 / R2011	~~160~~	380	460	630	840
SKS	R1666 / R2010	~~110~~	250	320	440	590
SNH	R1621	~~160~~	380	460	630	840
FNN/ SNN	R1693 / R1694	~~0~~	290	460	~~0~~	~~0~~
FKN / SKN	R1663 / R1664	~~0~~	190	320	~~0~~	~~0~~

Figure. H-12: Preload forces on the runner blocks based on pre-load class C1. And the Lift-off force for different sized runner blocks of different type.

Figure. H-11 shows the forces acting on the runner block during the operating phases. From the forces, the maximum force on the blocks is determined, and a check is performed to see if the reaction forces are higher than the preload force of the runner block. For the above case, the maximum load in the normal direction is 189N, the preload force for different size blocks below 189 are marked orange and canceled out. This signifies those blocks cannot be used for this application because the operating conditions make the guide blocks preload free and which is not desirable. The calculations show that all the available guide blocks for 20mm sized rail are suitable for the Z-translational unit (with a 54mm gap between the guide rails and 65 mm gap between the two guide blocks on the same rail). Using a 20mm sized rail would not have enough room for mounting the drive mechanism, and ultimately the size of the guide rail system would increase.

Moreover, the maximum operating stroke along the Z-axis is 130mm (short stroke), and there is no need for a bulky & wide linear system. Thus, in contrast, to guide rail mechanism a compact module is considered. It is like a linear guide rail system with similar components which are embodied as a compact unit. The compact design of the module saves on space and cost. Also, no extra mountings must be designed.

Z-Translation.

Each phase of the stroke is denoted as load case "j."

Mass of the tightening Tool + fixture+ Cable + Other accessories (m1 - kg)	6
Mass of support plate (m2 - kg)	2
Stroke/Travel Length (mm)	130
velocity (m/s)	0.10

In campa-rison	Load case	Distance traveled in each phase	Discrete travel step	Acce during the phases
	j	si	qsn	a
		mm		m/s2
CCK-90	1	15	0.06	0.33
	2	100	0.38	0.00
	3	-15	-0.06	-0.33
	4	0	0.00	0.00
	5	-15	-0.06	-0.33
	6	-100	-0.38	0.00
	7	15	0.06	0.33

H.3 LINEAR MODULE CALCULATIONS

The selection of a linear module is carried out in two major steps. Initial step identifies the sizes of compact modules that could be used for the application. The second is a multistep procedure for dimensioning the module and selecting an appropriate motor drive.

H.3.1 Step I: Filtering the modules based on load conditions

The compact modules are available in five variants. Mechanical characteristics of each variant were checked to determine the suitable variant. Unlike the guide rail system, in a vertical orientation, a module experiences yawing & pitching moments. And these should be lower than the maximum permissible values specified by the manufacturer. Due to variation in dimensions, the position of the center of gravity (CoG) is different for each variant. This indicates the pitching & yawing moments would be different as well. A linear module should satisfy the condition for combined loading as shown in Figure. H-13. The F_y, F_z, M_x ,M_y, and M_z are the forces and moments acting on the modules and compared with the maximum limit of the modules.

$$\frac{|F_y|}{F_{y\,max}} + \frac{|F_z|}{F_{z\,max}} + \frac{|M_x|}{M_{x\,max}} + \frac{|M_y|}{M_{y\,max}} + \frac{|M_z|}{M_{z\,max}} \leq 1$$

Figure. H-13: Condition for combined loading

Respective moments for each module are calculated, and a check is performed to determine if they meet the combined loading criteria.

H.3.2 Step II: Selection bade on drive unit characteristics

This section illustrates the next procedure followed to define the dimensions of the module and select a suitable drive motor. The procedure is explained for only for Z-module. The selection of the module is distributed in nine steps.

Step 1: Defining the requirements: Initially the following governing parameters of the system are defined:

1. The load to be translated= Weight of the tool, fixture, torque, and the inertia forces
2. The effective travel length (s_{eff}) = *130mm*
3. The operational speed of the system = *assumed 0.1 m/s*
4. The orientation of the module =*Vertical*
5. Size of the ball screw assembly used= *12mm x2mm*
6. Size and characteristics of the motor= *MSK 030C*

Step 2: Selection of ball screw drive: The type of ball screw drive governs the length of the module. It is advised to choose the screw with the lowest lead as it is favorable in terms of resolution, braking distance & length.

Step 3: Estimation of length L (mm)-The length of the module is calculated based on the effective travel length. This length is equivalent to the threaded length of the drive screw and does not include the length of end bearings.

$$L = S_{eff} + 2S_e + L_{ca} + L_{ad} = 288mm$$

Where excess travel $(S_e) = 2.\,Pitch\ of\ the\ lead\ screw\ (P)$

L_{ca}= Length of the carriage connection plate on which the load is carried= *125mm*

L_{ad}=Additional length of the connection plate= *25mm*

Step 4: Frictional torque M_R (Nm): Next, the frictional torque of the motor is calculated. This is essential to determine if the selected motor is capable of translating the load over the desired length. For a motor attached to the module with a coupling, the M_R is equivalent to the frictional torque of the ball screw drive (denoted as M_{RS}) and is provided by the manufacturer. *“This turned out to be 0.14Nm for the selected motor”.*

Step 5: Mass moment of inertia J_{ex} (kgm^2): The J_{ex} is calculated for the mechanical system and is summation of mass moment of inertia of the coupling (J_c), mass moment of inertia of the linear motion system (J_S), and translational mass moment of inertia of external load based on the linear system screw journal (J_t). *“The value was 5.1e^{-05}kgm^{2}.”*

Step 6: Maximum permissible speed v_{mech} (m/s): The lowest of all the values for the maximum permissible speed of all mechanical components of the drive train determines the maximum permissible speed of the mechanical system (n_{mech}). This is treated as the upper limit for the drive when sizing the motor. It is calculated using: *"This was 0.225m/s."*

$$V_{mech} = \frac{n_{mech}.P}{60000}$$

Step 7: Maximum permissible drive torque M_{mech}(Nm): The lowest (minimum) of all the values for permissible drive torque of all mechanical components of the drive train determines the maximum permissible drive torque of the mechanical system. And similar to v_{mech} this value is considered as the upper limit for the drive when sizing the motor. For a module attached to the motor with a coupling, it is the minimum of rated torque of coupling (M_{cN}) and maximum permissible drive torque of the linear system (M_p). *"The values were M_{cN} = 0.8Nm and M_p =13N. Therefore M_{mech} was selected as 0.8Nm."*

Step 8: Confirmation of the selected motor: The next step in the sequence is to confirm that the selected motor fulfills the above state condition. The confirmation is governed by the fulfillment of the following three conditions:

Condition 1: The maximum speed (n_{max}) of the motor must be greater than or equal to the required maximum permissible speed of the mechanical system (n_{mech}). "*The* n_{max} *= 9000rpm which was greater than* n_{mech} *=6750rpm."*

Condition 2: The control performance of the motor-controller combination is governed by the ratio of the mass moment of inertias (V). It is the ratio of the mass moment of inertia of mechanical system (J_{ex}) to the summation of mass moment of inertia of motor brake (J_{br}) & motor (J_m). The value of V should be lesser or equal to 6.0 for handling applications, whereas it should be lesser or equal to 1.5 for applications dedicated to processing. *"The values for J_{br} 7.0e^{-6} kgm^2, J_m 3.0e^{-6} kgm^2, and J_{ex} was found to be 5.1e^{-05}kgm^2. Thus the ratio was 1.39".*

Condition 3: Lastly, a check is performed to determine if the ratio of static load moment (M_{stat}) to the continuous torque of the motor (M_0) is lesser or equal to 0.6. *"The values were, M_{stat} = 0.15Nm and M_0 =0.8Nm, this resulted in a ratio of 0.19".*

Thus, following all the steps a CCK compact module of size 90 turned out to meet all the requirement. But, the ratio of the mass moment of inertia(V=1.39) is close to the required value of 1.5. Therefore, to be well assured the second variant of 12x5 ball screw assembly with V=0.55 was selected for the final design.

The entire procedure was repeated for selecting X-axis linear system. And it turned out that it was convenient to use a compact module (size CCK-110) than the guide rail system.

H.4FORCE CALCULATION FOR LINEAR GUIDE RAIL UNIT ALONG Y-AXIS.

Lastly, the linear guide rail system was selected as a linear system for motion along Y-axis. The details of the calculations have not been described; however Figure. H-14 shows the matrix used for performing the calculations and selecting appropriate components. The maximum stroke length along Y axis is 310, which has been distributed in seven phases of the motion and corresponding accelerations are determined (highlighted with blue in Figure. H-14). Next, all the forces and their approximate point of application is considered (highlighted with yellow shade Figure. H-14) for calculating the reaction forces on the runner blocks (highlighted with red shade Figure. H-14).

Load case	Distance Traveled	Discrete travel step	Acceleration	Distance of drive unit along Z	Distance of drive unit along Y	Distance between the rails along "Y"	Distance between the rails along "X"	Weight (6kg)	Acceleartion Force	Coordinates of application of "mg"			Weight (12kg)	Acceleartion Force	Coordinates of application of "mg 2"			Weight (1.5kg)	Acceleartion Force	Coordinates of application of "mg 2"			Weight (2.5kg)	Acceleartion Force	Coordinates of application of "mg 2"			Torque Force	Coordinates of application of "F"			Reaction forces							
j	si	qsn	a	Lz	Ly	Lw	Ls	m1g	m1a (N)	x	y	z	m2g	m2a (N)	x	y	z	m3g	m3a (N)	x	y	z	m4g	m4a (N)	x	y	z	F	x	y	z	Block 1		Block 2		Block 3		Block 4	
	mm	%	m/s2	mm	mm	mm	mm	N	6	mm	mm	mm	N	12	mm	mm	mm	N	1.5	mm	mm	mm	N	3.5	mm	mm	mm	N	mm	mm	mm	Fz1	FT1	Fz2	FT2	Fz3	FT3	Fz4	FT4
1	25	0.05	0.20	50	320	125	450	-58.9	-1.2	210	188	400	-117.7	-2.4	100	188	135	-14.7	-0.3	350	188	270	-14.7	-0.7	350	188	245					-229	5	40	-2.2	-229	5	40	-2.2
2	260	0.48	0.00	50	320	125	450	-58.9	0.0	210	188	400	-117.7	0.0	100	188	135	-14.7	0.0	350	188	270	-14.7	0.0	350	188	245					-232	0	43	0.0	-232	0	43	0.0
3	-25	-0.05	-0.20	50	320	125	450	-58.9	1.2	210	188	400	-117.7	2.4	100	188	135	-14.7	0.3	350	188	270	-14.7	0.7	350	188	245					-235	-5	47	2.2	-235	-5	47	2.2
4	0	0.00	0.00	50	320	125	450	-58.9	0.0	210	188	400	-117.7	0.0	100	188	135	-14.7	0.0	350	188	270	-14.7	0.0	350	188	245	-50	500	1188	270	-411	0	65	0.0	-411	0	65	0.0
5	-25	-0.05	-0.20	50	320	125	450	-58.9	1.2	210	188	400	-117.7	2.4	100	188	135	-14.7	0.3	350	188	270	-14.7	0.7	350	188	245					-235	-5	47	2.2	-235	-5	47	2.2
6	-260	-0.48	0.00	50	320	125	450	-58.9	0.0	210	188	400	-117.7	0.0	100	188	135	-14.7	0.0	350	188	270	-14.7	0.0	350	188	245					-232	0	43	0.0	-232	0	43	0.0
7	25	0.05	0.20	50	320	125	450	-58.9	-1.2	210	188	400	-117.7	-2.4	100	188	135	-14.7	-0.3	350	188	270	-14.7	-0.7	350	188	245					-229	5	40	-2.2	-229	5	40	-2.2

Figure. H-14:A part of the calculation matrix showing the normal and transverse reaction force on each runner block based on the forces acting during different phases of translation.

Based upon the reaction forces the runner block sizes are selected by ruling out the sizes which become preload force free (shown with cancelled out mark and red colour values in Figure. H-15).

Preload Class		Pre Load force on Runner Blocks				
		15	20	25	30	35
FNS	R1651/R2001	~~160~~	~~380~~	460	630	840
FKS	R1665 / R2000	~~110~~	~~250~~	~~320~~	440	590
SNS	R1622 / R2011	~~160~~	~~380~~	460	630	840
SKS	R1666 / R2010	~~110~~	~~250~~	~~320~~	440	590
SNH	R1621	~~160~~	~~380~~	460	630	840
FNN/ SNN	R1693 / R1694	~~0~~	~~290~~	460	~~0~~	~~0~~
FKN / SKN	R1663 / R1664	~~0~~	~~190~~	~~320~~	~~0~~	~~0~~

Figure. H-15: Matrix with suitable runner block sizes which have preload force below the normal force acting on the system.

I. PATH BASED CYCLE TIME ANALYSIS (CTA)

The cycle time analysis was performed to evaluate the functionality of the system with respect to the cycle time of the SAAL. The M16 plug is used for size DN40 which is placed farthest from the coordinate system-1; similarly, the M36 plug is used in size DN350 which has the bottom hole position at the highest and nearest with respect to the coordinate system-1. Moreover, M16 & M36 plugs are placed closest & farthest from the coordinate system. Thus, these sizes are considered for the CTA. The analysis is carried out by considering different paths that the system can follow to complete the assembly operation. In section 6.1 (CTA) it was described how 11 steps are traversed by the systems to fasten an M36 plug in EVFL DN350 body. But, in the 11-step path, there are some paths which could be overlapped, and the steps could be reduced to 9. At the start of 11 step tightening process the tightening tool has coordinates {x= 0, y=-50, z=30} and then it initially moves to pick the align itself with the position of the M36 plug which is at {x= 300, y=0, z=30}, and this travel is accounted as a 1st step. Instead, if the tool starts at the position when it is aligned with the plug & ring position, then the 1st step of 300mm stroke along x-axis could be eliminated. And thus, the total no of steps would reduce to 9. Similarly, after step 3 in step 4 & 5 the PR are positioned coaxially with the bottom hole of the body; since two different linear modules perform these steps, they could be operated simultaneously. Thus, the PR could be positioned in the x-y plane in a single step, and the total no. of steps could be reduced to 9. Likewise, if the tightening tool starts at the aligned position and positions itself in the x-y plane in a single step then total no. of steps could be reduced to 7. The cycle time is checked for all the possible paths, and the corresponding summary is prepared, as shown in the Figure. I-1 The line drawing demonstrates the path followed by the tool. From this analysis, it could be seen that at 0.1m/s operational velocity an 11-step process cost 35.50 sec. Whereas, the same operation could be done in 26.50sec if 7 steps path is followed.

Likewise, the analysis is performed to determine the cycle time for M16 size plug for EVBLS DN40. Since the bottom hole position for this type is at 21.5mm w.r.t coordinate system-1, the operation could per performed in maximum 13 steps and minimum 9 step. This is illustrated by the line diagram in the Figure. I-2.

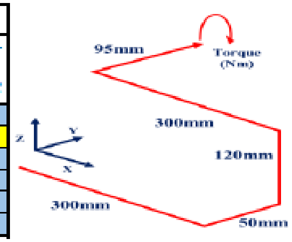
Vmax (m/s) - Maximum operating velocity
S (mm) - Distance travelled during the stroke
A (sec) - Travel time during Acceleration
U (sec) - Travel time during Uniform Motion
D (sec) - Travel time during Deceleration
T (sec) - Time for Fastening the plug & ring
Total time (sec) - A+U+D+T for all steps
Total + 15 sec for P.c (sec) - Assumed that the arrival and departure of product carrier to and from the station + Positioning takes approximately 10 secs

$$A = D = \frac{0^2 + 2(Vmax - 0) * S}{1000 * Vmax^2}$$

$$U = \frac{S}{1000 * Vmax}$$

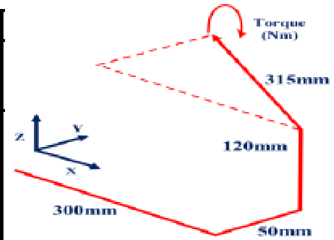
11 Step Tightening Process

Vmax (m/s) ↓	1 (300mm)			2 (50mm)			3 (120mm)			4 (300mm)			5 (95mm)			6	7 (95mm)			8 (300mm)			9 (120mm)			10 (50mm)			11 (300mm)			Total Time (secs)	Total + 15 sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	25	250	25	10	30	10	10	100	10	25	250	25	10	75	10		10	75	10	25	250	25	10	100	10	10	30	10	25	250	25		
0.05	1.00	5.00	1.00	0.40	0.60	0.40	0.40	2.00	0.40	1.00	5.00	1.00	0.40	1.50	0.40	5.00	0.40	1.50	0.40	1.00	5.00	1.00	0.40	2.00	0.40	0.40	0.60	0.40	1.00	5.00	1.00	46.00	61.00
0.10	0.50	2.50	0.50	0.20	0.30	0.20	0.20	1.00	0.20	0.50	2.50	0.50	0.20	0.75	0.20	5.00	0.20	0.75	0.20	0.50	2.50	0.50	0.20	1.00	0.20	0.20	0.30	0.20	0.50	2.50	0.50	25.50	40.50
0.15	0.33	1.67	0.33	0.13	0.20	0.13	0.13	0.67	0.13	0.33	1.67	0.33	0.13	0.50	0.13	5.00	0.13	0.50	0.13	0.33	1.67	0.33	0.13	0.67	0.13	0.13	0.20	0.13	0.33	1.67	0.33	18.67	33.67
0.20	0.25	1.25	0.25	0.10	0.15	0.10	0.10	0.50	0.10	0.25	1.25	0.25	0.10	0.38	0.10	5.00	0.10	0.38	0.10	0.25	1.25	0.25	0.10	0.50	0.10	0.10	0.15	0.10	0.25	1.25	0.25	15.25	30.25
0.25	0.20	1.00	0.20	0.08	0.12	0.08	0.08	0.40	0.08	0.20	1.00	0.20	0.08	0.30	0.08	5.00	0.08	0.30	0.08	0.20	1.00	0.20	0.08	0.40	0.08	0.08	0.12	0.08	0.20	1.00	0.20	13.20	28.20
0.30	0.17	0.83	0.17	0.07	0.10	0.07	0.07	0.33	0.07	0.17	0.83	0.17	0.07	0.25	0.07	5.00	0.07	0.25	0.07	0.17	0.83	0.17	0.07	0.33	0.07	0.07	0.10	0.07	0.17	0.83	0.17	11.83	26.83



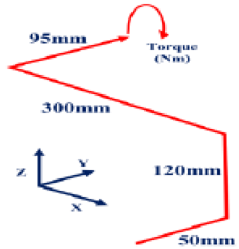
9 Step Tightening Process

Vmax (m/s) ↓	1 (300mm)			2 (50mm)			3 (120mm)			4 (315 mm)			5	6 (315 mm)			7 (120mm)			8 (50mm)			9 (300mm)			Total Time (secs)	Total + 15 sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	25	250	25	10	30	10	10	100	10	25	265	25		25	265	25	10	100	10	10	30	10	25	250	25		
0.05	1.00	5.00	1.00	0.40	0.60	0.40	0.40	2.00	0.40	1.00	5.30	1.00	5.00	1.00	5.30	1.00	0.40	2.00	0.40	0.40	0.60	0.40	1.00	5.00	1.00	42.00	57.00
0.10	0.50	2.50	0.50	0.20	0.30	0.20	0.20	1.00	0.20	0.50	2.65	0.50	5.00	0.50	2.65	0.50	0.20	1.00	0.20	0.20	0.30	0.20	0.50	2.50	0.50	23.50	38.50
0.15	0.33	1.67	0.33	0.13	0.20	0.13	0.13	0.67	0.13	0.33	1.77	0.33	5.00	0.33	1.77	0.33	0.13	0.67	0.13	0.13	0.20	0.13	0.33	1.67	0.33	17.33	32.33
0.20	0.25	1.25	0.25	0.10	0.15	0.10	0.10	0.50	0.10	0.25	1.33	0.25	5.00	0.25	1.33	0.25	0.10	0.50	0.10	0.10	0.15	0.10	0.25	1.25	0.25	14.25	29.25
0.25	0.20	1.00	0.20	0.08	0.12	0.08	0.08	0.40	0.08	0.20	1.06	0.20	5.00	0.20	1.06	0.20	0.08	0.40	0.08	0.08	0.12	0.08	0.20	1.00	0.20	12.40	27.40
0.30	0.17	0.83	0.17	0.07	0.10	0.07	0.07	0.33	0.07	0.17	0.88	0.17	5.00	0.17	0.88	0.17	0.07	0.33	0.07	0.07	0.10	0.07	0.17	0.83	0.17	11.17	26.17



9 Step Tightening Process

Vmax (m/s) ↓	1 (50 mm)			2 (120mm)			3 (300 mm)			4 (95 mm)			5	6 (95 mm)			7 (300mm)			8 (120mm)			9 (50mm)			Total Time (secs)	Total + 15 sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	10	30	10	10	100	10	25	250	25	10	75	10		10	7	10	25	250	25	10	100	10	10	30	10		
0.05	0.40	0.60	0.40	0.40	2.00	0.40	1.00	5.00	1.00	0.40	1.50	0.40	5.00	0.40	0.14	0.40	1.00	5.00	1.00	0.40	2.00	0.40	0.40	0.60	0.40	30.64	45.64
0.10	0.20	0.30	0.20	0.20	1.00	0.20	0.50	2.50	0.50	0.20	0.75	0.20	5.00	0.20	0.07	0.20	0.50	2.50	0.50	0.20	1.00	0.20	0.20	0.30	0.20	17.82	32.82
0.15	0.13	0.20	0.13	0.13	0.67	0.13	0.33	1.67	0.33	0.13	0.50	0.13	5.00	0.13	0.05	0.13	0.33	1.67	0.33	0.13	0.67	0.13	0.13	0.20	0.13	13.55	28.55
0.20	0.10	0.15	0.10	0.10	0.50	0.10	0.25	1.25	0.25	0.10	0.38	0.10	5.00	0.10	0.04	0.10	0.25	1.25	0.25	0.10	0.50	0.10	0.10	0.15	0.10	11.41	26.41
0.25	0.08	0.12	0.08	0.08	0.40	0.08	0.20	1.00	0.20	0.08	0.30	0.08	5.00	0.08	0.03	0.08	0.20	1.00	0.20	0.08	0.40	0.08	0.08	0.12	0.08	10.13	25.13
0.30	0.07	0.10	0.07	0.07	0.33	0.07	0.17	0.83	0.17	0.07	0.25	0.07	5.00	0.07	0.02	0.07	0.17	0.83	0.17	0.07	0.33	0.07	0.07	0.10	0.07	9.27	24.27



7 Step Tightening Process

Vmax (m/s) ↓	1 (50 mm)			2 (120mm)			3 (315 mm)			4	5 (315 mm)			6 (120 mm)			7 (50 mm)			Total Time (secs)	Total + 15 sec for P.C
	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D		
S(mm) →	10	30	10	10	100	10	25	265	25		25	265	25	10	100	10	10	30	10		
0.05	0.40	0.60	0.40	0.40	2.00	0.40	1.00	5.30	1.00	5.00	1.00	5.30	1.00	0.40	2.00	0.40	0.40	0.60	0.40	28.00	43.00
0.10	0.20	0.30	0.20	0.20	1.00	0.20	0.50	2.65	0.50	5.00	0.50	2.65	0.50	0.20	1.00	0.20	0.20	0.30	0.20	16.50	31.50
0.15	0.13	0.20	0.13	0.13	0.67	0.13	0.33	1.77	0.33	5.00	0.33	1.77	0.33	0.13	0.67	0.13	0.13	0.20	0.13	12.67	27.67
0.20	0.10	0.15	0.10	0.10	0.50	0.10	0.25	1.33	0.25	5.00	0.25	1.33	0.25	0.10	0.50	0.10	0.10	0.15	0.10	10.75	25.75
0.25	0.08	0.12	0.08	0.08	0.40	0.08	0.20	1.06	0.20	5.00	0.20	1.06	0.20	0.08	0.40	0.08	0.08	0.12	0.08	9.60	24.60
0.30	0.07	0.10	0.07	0.07	0.33	0.07	0.17	0.88	0.17	5.00	0.17	0.88	0.17	0.07	0.33	0.07	0.07	0.10	0.07	8.83	23.83

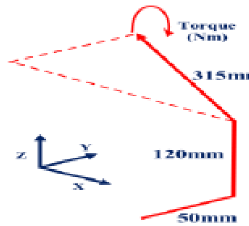
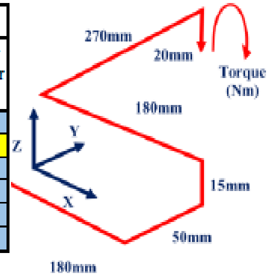


Figure. I-1: Cycle time analysis for fastening M36 size plug in EVFL DN350, following different paths (red line diagram) at different velocities.

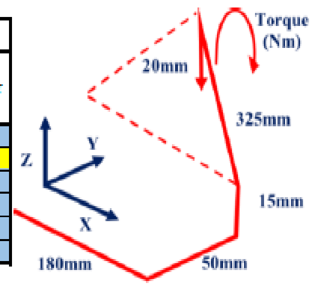
13 Step Tightening Process

Vmax (m/s) ↓	1 (180mm)			2 (50mm)			3 (15mm)			4 (180mm)			5 (270mm)			6 (20mm)			7	8 (20mm)			9 (270mm)			10 (180mm)			11 (15mm)			12 (50mm)			13 (180mm)			Total Time	Total + 15sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	15	150	15	10	30	10	5	5	5	15	150	15	10	250	10	5	10	5		5	10	5	10	250	10	15	150	15	5	5	5	10	30	10	15	150	15	(sec)	P.C
0.05	0.60	3.00	0.60	0.40	0.60	0.40	0.20	0.10	0.20	0.60	3.00	0.60	0.40	5.00	0.40	0.20	0.20	0.20	5.00	0.20	0.20	0.20	0.40	5.00	0.40	0.60	3.00	0.60	0.20	0.10	0.20	0.40	0.60	0.40	0.60	3.00	0.60	38.4	53.4
0.10	0.30	1.50	0.30	0.20	0.30	0.20	0.10	0.05	0.10	0.30	1.50	0.30	0.20	2.50	0.20	0.10	0.10	0.10	5.00	0.10	0.10	0.10	0.20	2.50	0.20	0.30	1.50	0.30	0.10	0.05	0.10	0.20	0.30	0.20	0.30	1.50	0.30	21.7	36.7
0.15	0.20	1.00	0.20	0.13	0.20	0.13	0.07	0.03	0.07	0.20	1.00	0.20	0.13	1.67	0.13	0.07	0.07	0.07	5.00	0.07	0.07	0.07	0.13	1.67	0.13	0.20	1.00	0.20	0.07	0.03	0.07	0.13	0.20	0.13	0.20	1.00	0.20	16.1	31.1
0.20	0.15	0.75	0.15	0.10	0.15	0.10	0.05	0.03	0.05	0.15	0.75	0.15	0.10	1.25	0.10	0.05	0.05	0.05	5.00	0.05	0.05	0.05	0.10	1.25	0.10	0.15	0.75	0.15	0.05	0.03	0.05	0.10	0.15	0.10	0.15	0.75	0.15	13.4	28.4
0.25	0.12	0.60	0.12	0.08	0.12	0.08	0.04	0.02	0.04	0.12	0.60	0.12	0.08	1.00	0.08	0.04	0.04	0.04	5.00	0.04	0.04	0.04	0.08	1.00	0.08	0.12	0.60	0.12	0.04	0.02	0.04	0.08	0.12	0.08	0.12	0.60	0.12	11.7	26.7
0.30	0.10	0.50	0.10	0.07	0.10	0.07	0.03	0.02	0.03	0.10	0.50	0.10	0.07	0.83	0.07	0.03	0.03	0.03	5.00	0.03	0.03	0.03	0.07	0.83	0.07	0.10	0.50	0.10	0.03	0.02	0.03	0.07	0.10	0.07	0.10	0.50	0.10	10.6	25.6



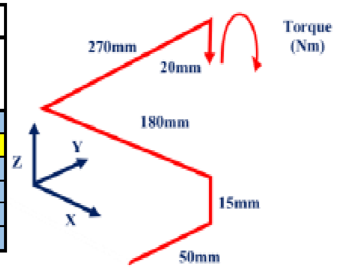
11 Step Tightening Process

Vmax (m/s) ↓	1 (180mm)			2 (50mm)			3 (15mm)			4 (325 mm)			5 (20mm)			6	7 (20mm)			8 (325 mm)			9 (15mm)			10 (50mm)			11 (180mm)			Total Time	Total + 15sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	15	150	15	10	30	10	5	5	5	25	275	25	5	10	5		5	10	5	25	275	25	5	5	5	10	30	10	15	150	15	(sec)	P.C
0.05	0.60	3.00	0.60	0.40	0.60	0.40	0.20	0.20	0.10	1.00	5.50	1.00	0.20	0.20	0.20	5.00	0.20	0.20	0.20	1.00	5.50	1.00	0.20	0.10	0.20	0.40	0.60	0.40	0.60	3.00	0.60	33.4	48.4
0.10	0.30	1.50	0.30	0.20	0.30	0.20	0.10	0.10	0.05	0.50	2.75	0.50	0.10	0.10	0.10	5.00	0.10	0.10	0.10	0.50	2.75	0.50	0.10	0.05	0.10	0.20	0.30	0.20	0.30	1.50	0.30	19.2	34.2
0.15	0.20	1.00	0.20	0.13	0.20	0.13	0.07	0.07	0.03	0.33	1.83	0.33	0.07	0.07	0.07	5.00	0.07	0.07	0.07	0.33	1.83	0.33	0.07	0.03	0.07	0.13	0.20	0.13	0.20	1.00	0.20	14.5	29.5
0.20	0.15	0.75	0.15	0.10	0.15	0.10	0.05	0.05	0.03	0.25	1.38	0.25	0.05	0.05	0.05	5.00	0.05	0.05	0.05	0.25	1.38	0.25	0.05	0.03	0.05	0.10	0.15	0.10	0.15	0.75	0.15	12.1	27.1
0.25	0.12	0.60	0.12	0.08	0.12	0.08	0.04	0.04	0.02	0.20	1.10	0.20	0.04	0.04	0.04	5.00	0.04	0.04	0.04	0.20	1.10	0.20	0.04	0.02	0.04	0.08	0.12	0.08	0.12	0.60	0.12	10.7	25.7
0.30	0.10	0.50	0.10	0.07	0.10	0.07	0.03	0.03	0.02	0.17	0.92	0.17	0.03	0.03	0.03	5.00	0.03	0.03	0.03	0.17	0.92	0.17	0.03	0.02	0.03	0.07	0.10	0.07	0.10	0.50	0.10	9.7	24.7



11 Step Tightening Process

Vmax (m/s) ↓	1 (50mm)			2 (15mm)			3 (180mm)			4 (270mm)			5 (20mm)			6	7 (20mm)			8 (270mm)			9 (180mm)			10 (15mm)			11 (50mm)			Total Time	Total + 15sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	10	30	10	5	5	5	15	150	15	10	250	10	5	10	5		5	10	5	10	250	10	15	150	15	5	5	5	10	30	10	(sec)	P.C
0.05	0.40	0.60	0.40	0.20	0.10	0.20	0.60	3.00	0.60	0.40	5.00	0.40	0.20	0.20	0.20	5.00	0.20	0.20	0.20	0.40	5.00	0.40	0.60	3.00	0.60	0.20	0.10	0.20	0.40	0.60	0.40	30.0	45.0
0.10	0.20	0.30	0.20	0.10	0.05	0.10	0.30	1.50	0.30	0.20	2.50	0.20	0.10	0.10	0.10	5.00	0.10	0.10	0.10	0.20	2.50	0.20	0.30	1.50	0.30	0.10	0.05	0.10	0.20	0.30	0.20	17.5	32.5
0.15	0.13	0.20	0.13	0.07	0.03	0.07	0.20	1.00	0.20	0.13	1.67	0.13	0.07	0.07	0.07	5.00	0.07	0.07	0.07	0.13	1.67	0.13	0.20	1.00	0.20	0.07	0.03	0.07	0.13	0.20	0.13	13.3	28.3
0.20	0.10	0.15	0.10	0.05	0.03	0.05	0.15	0.75	0.15	0.10	1.25	0.10	0.05	0.05	0.05	5.00	0.05	0.05	0.05	0.10	1.25	0.10	0.15	0.75	0.15	0.05	0.03	0.05	0.10	0.15	0.10	11.3	26.3
0.25	0.08	0.12	0.08	0.04	0.02	0.04	0.12	0.60	0.12	0.08	1.00	0.08	0.04	0.04	0.04	5.00	0.04	0.04	0.04	0.08	1.00	0.08	0.12	0.60	0.12	0.04	0.02	0.04	0.08	0.12	0.08	10.0	25.0
0.30	0.07	0.10	0.07	0.03	0.02	0.03	0.10	0.50	0.10	0.07	0.83	0.07	0.03	0.03	0.03	5.00	0.03	0.03	0.03	0.07	0.83	0.07	0.10	0.50	0.10	0.03	0.02	0.03	0.07	0.10	0.07	9.2	24.2



9 Step Tightening Process

Vmax (m/s) ↓	1 (50mm)			2 (15mm)			3 (325 mm)			4 (20mm)			5	6 (20mm)			7 (325 mm)			8 (15mm)			9 (50mm)			TotalTime	Total + 15sec for P.C
	A	U	D	A	U	D	A	U	D	A	U	D	T	A	U	D	A	U	D	A	U	D	A	U	D		
S(mm) →	10	30	10	5	5	5	25	275	25	5	10	5		5	10	5	25	275	25	5	5	5	10	30	10	(sec)	P.C
0.05	0.40	0.60	0.40	0.20	0.10	0.20	1.00	5.50	1.00	0.20	0.20	0.20	5.00	0.20	0.20	0.20	1.00	5.50	1.00	0.20	0.10	0.20	0.40	0.60	0.40	25.0	40.0
0.10	0.20	0.30	0.20	0.10	0.05	0.10	0.50	2.75	0.50	0.10	0.10	0.10	5.00	0.10	0.10	0.10	0.50	2.75	0.50	0.10	0.05	0.10	0.20	0.30	0.20	15.0	30.0
0.15	0.13	0.20	0.13	0.07	0.03	0.07	0.33	1.83	0.33	0.07	0.07	0.07	5.00	0.07	0.07	0.07	0.33	1.83	0.33	0.07	0.03	0.07	0.13	0.20	0.13	11.7	26.7
0.20	0.10	0.15	0.10	0.05	0.03	0.05	0.25	1.38	0.25	0.05	0.05	0.05	5.00	0.05	0.05	0.05	0.25	1.38	0.25	0.05	0.03	0.05	0.10	0.15	0.10	10.0	25.0
0.25	0.08	0.12	0.08	0.04	0.02	0.04	0.20	1.10	0.20	0.04	0.04	0.04	5.00	0.04	0.04	0.04	0.20	1.10	0.20	0.04	0.02	0.04	0.08	0.12	0.08	9.0	24.0
0.30	0.07	0.10	0.07	0.03	0.02	0.03	0.17	0.92	0.17	0.03	0.03	0.03	5.00	0.03	0.03	0.03	0.17	0.92	0.17	0.03	0.02	0.03	0.07	0.10	0.07	8.3	23.3

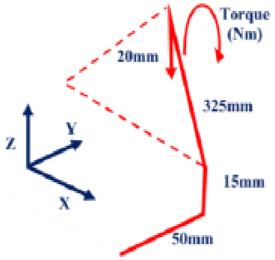


Figure. I-2: Cycle time analysis for fastening M16 size plug in EVBLS D40, following different paths(red line diagram) at different velocities.

J. EVALUATION CRITERIA FOR FMEA

For evaluating the failure parameter, it essential to define the grading criteria. Any factor which could lead to the failure of the system is evaluated by 3 parameters; Severity, Occurrence & Detection. An influencing factor is considered severe based on the degree of damage it could cause to a person, product or the entire system. Sometimes, the factor itself does not contribute directly to the failure. Instead, it acts as an initiator for some other sever event. Secondly, a check has to be done to know how often failure is occurring or is being initiated. Based on the frequency of occurrence corresponding corrective actions could be suggested. Lastly, detection is an essential factor, as it determines how efficiently the root cause of a problem is foreseen. All the three parameters are rated from 1 to 10 based on the characteristic of the problem (The detailed distribution of the ratings is explained in Table. G-1 [28]. The product of the rating gives a risk priority number (RPN), and this value determines the effect of a particular influencing factor on the failure of the system. The factor with the highest RPN is given 1st priority for correction, followed by descending RPN factors [2][2]

Table. G-1: Distribution of grades from 1-10 for Severity, Occurrence & Detection [28].

	Severity		Occurrence	Detection	
1-2	***Minor***	Unreasonable to expect that the minor nature of this failure will have any noticeable effect on item or system performance or subsequent process or assembly operation.	***Remotely***	***Very High***	Reliable detection controls are known with similar processes. The process automatically prevents further processing.
3-4	***low***	Slight deterioration of the item or system performance or a slight inconvenience with a subsequent process or assembly operation, i.e., minor rework.	***Very low***	***High***	Controls have a good chance of detecting failure mode; the process automatically detects failure mode.
5-6	***Moderate***	Requires maintenance: noticeable item or system performance deterioration. This may result in scheduled rework/repair and/or damage to equipment.	***Moderate***	***Moderate***	Detected with careful inspection. Controls may detect the existence of a failure mode.
7-8	***High***	Needs immediate attention. Inoperable item or system. May result in severe disruption to subsequent processing or assembly operations and/or require major rework.	***Frequently***	***Low***	Controls have a reduced chance of detecting the existence of failure mode
9-10	***Very High***	Permanent damage is demanding a replacement. Failure affects safety or involves noncompliance to government regulations. May endanger machine or assembly operator (9 with a warning, 10 without warning)	***Very High***	***Very low***	Controls probably will not detect the existence of failure mode

J.1 DESIGN-FAILURE MODE AND EFFECT ANALYSIS

FAILURE MODE AND EFFECT ANALYSIS

Sr.No	Process Item/ Function	Requirements	Potential Failure Mode	Potential Cause(s)/ Mechanism(s) of Failure	Potential Effect(s) of Failure	Severity (S)	Occurrence (O)	Detection (D)	RPN (S*O*D)
1	Proximity sensors of the positioning unit	The proximity sensors should precisely detect the presence of the product carrier and actuate the positioning unit	No detection	Circuit failure. (short circuit, damaged wiring, etc.)	The product carrier is not detected by the system and positioning unit will not be actuated. Next operations would not be carried out and the line would ultimately stop.	10	1	5	50
2				Incorrect mounting of the sensor		10	1	2	20
3			Disturbed positioning of the sensor	Prolonged exposure to vibration from system movements or impact forces.	Inaccurate position sensing of the product carrier causing prior or post actuation of the positioning unit leading	8	1	4	32
4			False detection	False signal generation	Unit actuated even though the Product carrier is not present. And when the product carriers arrives it could damage the positioning unit.	10	1	8	80
5				Presence of metal particles on the face of the sensor	Presence of metal particles will not let the switch change state. This could either falsely actuate the positioning unit or wouldn't actuate it. This could either stop the assembly process or cause	5	2	2	20
6			Change in detection distance (increased)	Wear and tear of the mechanical parts, either by rough usage or damage caused due to external impact forces.	Positioning inaccuracy of the system because of the tolerances. Gradual damage caused to the product carrier	8	1	5	40
7	Proximity sensor to detect the tools in plug & ring fixture.	To detect the presence of component in the fixture before and after the tightening operation.	No detection	Circuit failure. (short circuit, damaged wiring, etc.)	Subseqent operation is affected and the line might stop.	8	1	7	56
8	Tool Tip	● Appropriate tool change must be carried out to perform the tightening operation ● Robust tool tip to firmly hold the plug and carry out the tightening operation.	Tool not changed	No tool present in the tool fixture.	● Assembly cannot carried out. ● Valve without a plug.	5	1	1	5
9			Incorrect tool bit picked	Incorrect tool on the required position.	● Wrong plug or no plug could be assembled in the body ●Incorrect tightening torque delivered by the system causing damage to the body & tool.	6	1	2	12
10			Improper tool mounting/loose fit	Tool wear caused by poor handling.	● Inappropriate mounting / Loose fit of the tool can lead to insufficient tightening of the plug and thus compromising leak tightness. ● Worn out slots compromise the orientation accuracy and thus damage	10	1	6	60
11				Contamination inside the tool.		2	2	5	20
12				Inaccurate positioning of the tightening system w.r.t the	System causing damage to the fixture and tool	10	1	6	60
13				Nut Runner tool extension socket damaged.	The tool might remain in the plug after tightening and damage the components of next station.	10	1	1	10
14			Deformation of the tool bit	● Poor tool design ● Stresses generated due to prolonged usage.	Failure to deliver desired torque. Damage caused to Nut Runner	9	1	6	54
15	Plug	Correct size plug & ring should be installed in the valve to get a leak-proof sealing.	No Plug	Plug not kept in the fixture by the operator	● Body without a plug. ● No assembly carried out- Line stopped.	10	1	1	10
16				Placement at incorrect position in the fixture		8	1	1	8
17			Wrong plug	Different size plugs stored	No plug or wrong size plug assembled in the body.	10	2	2	40
18				Same size plug but of different material kept together.		5	2	2	20
19				Wrong identification by the operator.		6	5	1	30

20	Sealing ring		No sealing ring	Operator forgot to mount the sealing ring on the plug.	No leak-proof sealing.	10	1	1	10
21			Incorrect sealing ring is present on the bottom plug.	Wrong type of sealing rings (with different rubber type) placed by the operator.	Sealing ring with different type of rubber can cause quality issue.	4	2	10	80
22				Wrong size of sealing ring mounted on the plug.	Damage caused to the body and tool	10	1	1	10
23			Damaged sealing ring	● Damaged product from the supplier. ● Damage caused while mounting the sealing ring on the plug.	No leak-proof seal	5	2	8	80
24	Bottom hole alignment.	The body should be placed and should remain centered on the product carrier.	Incorrect alignment with the coordinate system of the product carrier	Incorrect and misaligned placement of the body by the operator.	Difficulty in tightening the plug or inappropriate tightening leading to damage to the body or the mechanism.	6	2	5	60
25				Disturbed centring of the body	Vibrations or assembly forces at previous stations.	6	2	5	60
26	Torque	Accurate tightening torque must be applied to tighten the plug.	The plug is not properly tightened inside the bottom hole.	Foreign material contamination inside the threaded hole causes frictional resistance.	Insufficient tightening of the plug might lead to leakage.	8	1	1	8
27				Mechanical or electrical failure of the Nut Runner.		8	1	7	56
28				Torque sensor failure.		8	1	8	64
29			Change in tightening torque	Wear of Nut Runner	No leak-proof sealing	8	1	2	16
30				Wrong tightening torque values specified.		10	1	1	10
31	Overhead counter torque mechanism.	The body must be restricted from rotating about its central axis under the action of tightening torque.	Incorrect positioning of the mechanism over the body.	Incorrect signal-Lowering the unit before the product carrier is at correct position.	● Damaged product. ● Damage / breakdown of entire station and its components.	10	1	1	10
32				Improper contact with the body.		10	1	1	10
33			Insufficient force application	Incorrect values fed/ calculated by the system.		10	1	1	10
34	Linear guide system	Guide system should have smooth movement to ensure accurate positioning of the system.	Misalignment of the guide blocks.	Incorrect assembly	Restricted or excessive motion leading to undesired stresses in the system. Also leading to inaccurate positioning.	10	1	1	10
35				External impact forces	Deformed guide rails cannot carry out the positioning operation	10	1	2	20
36				Non-uniform installation surface	Positional inaccuracy of the system will non-uniform restricting forces.	6	1	4	24
37			Permanent deformation on the raceway	Undue forces used during installation.	Loss of functionality in short period of time	8	1	4	32
38			Wear/Pitting/Dent/Corrosion.	Contamination of guide blocks and side rails	Smooth operation not possible and hence inaccuracy in positioning , which would result in operation not being	6	5	2	60
39				Insufficient lubrication		4	2	6	48
40	Drive system for linear guides (Motors)	Smooth operation to make sure the Cartesian system is positioned accurately	Insufficient torque delivered	Wear of the mechanical and electrical components	Inappropriate movement leading to inaccurately positioned system which could then damage the fixture / product.	10	1	5	50
41			Mechanical failure	Bearing failure, shaft or coupling failure due to excessive loading or lack of	Vibration, undesired operation leading to positioning inaccuracies.	8	1	5	40
42	Lead screw and nut	Smooth operation to make sure the cartesian system is positioned accurately	Deformation of the lead screw	Improper installation and assembly.	Inaccurate positioning of the units can damage the product and the tightening unit	8	1	1	8
43				Excessive loading		8	1	1	8
44				External impact forces		8	2	2	32
45			Wear	Contamination		8	2	1	16
46				Lack of lubrication		4	2	2	16

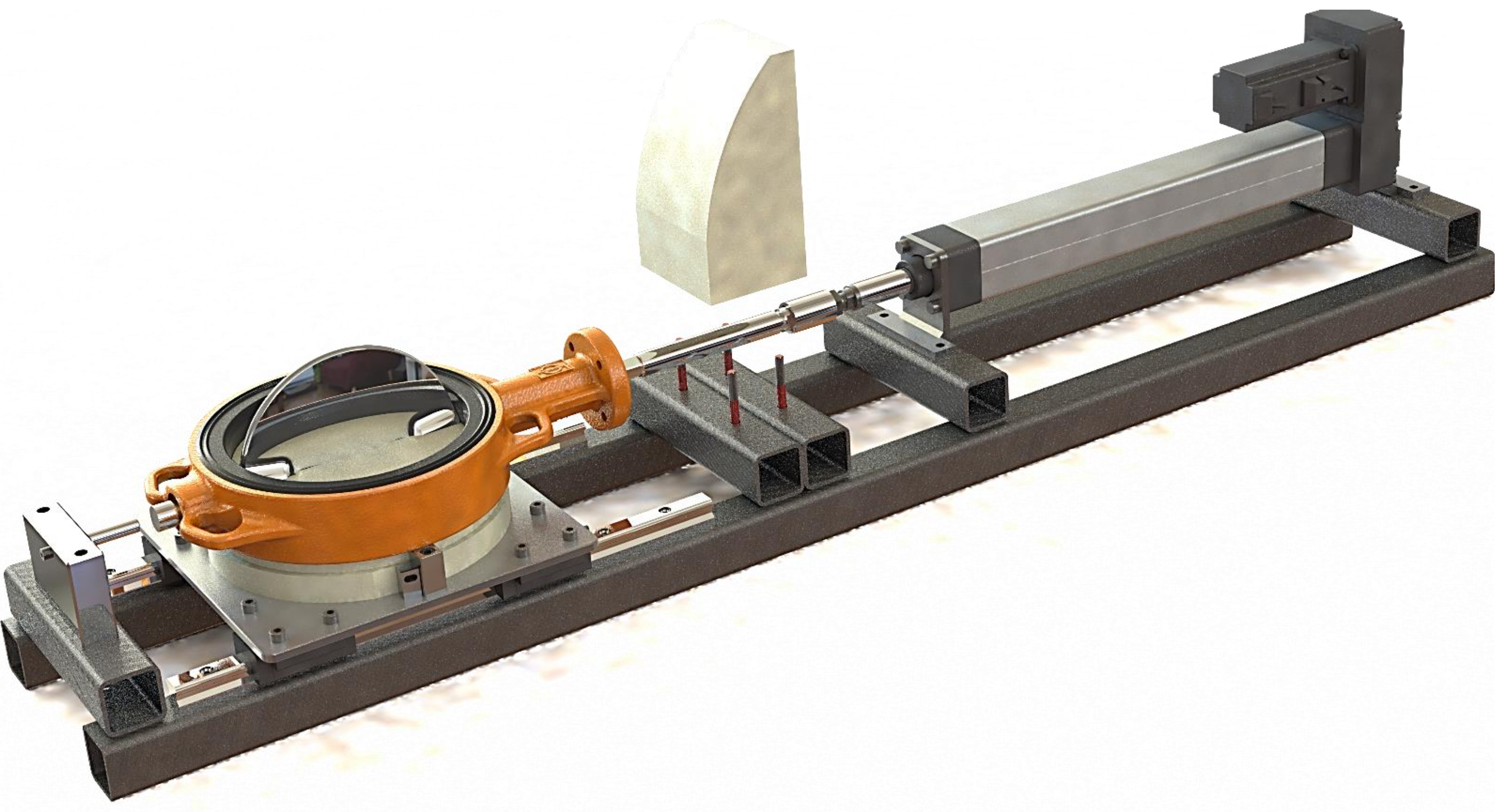
K.CONTROL PLAN

CONTROL PLAN

Part/ Process Number	Process Name/ Operation Description	Machine, Device, Jig, Tools, for Mfg.	Product	Process	Special Char. Class	Product/Process Specification/ Tolerance	Evaluation/ Measurement Technique	Size	Freq.	Control Method
1	Tightening the plug and ring inside the body	Electric Nut-Runner		tightening the plug & ring with specified amount of torque	Y	Applied torque should be as per the process as specified for a particular size and type of the body.	Torque and angle measurement sensor embedded inside the tightening tool monitor the process and provide feedback	All sizes	Every Assembly	100% Torque monitoring
2	Counter acting the tightening torque	Electro-Mechanical Drive	Electromechanical cylinder	Applying specific force at the outer edge of the body.	Y	Corresponding to size, type and the tightening torque.	Force measuring sensor.	All sizes	Every Assembly	100% Monitoring
3	Sensing operation of proximity sensor		Proximity Sensor	Sensing presence of tool bits inside the fixture	Y	Sense object within 5mm of its range	Calibration setup	All proximity sensors	As per standard guidelines/ define a period	Check sheet
4	Tool wear		Tool bits	Accurate mounting and demounting from tool extension and plug	Y	Minimum Wear	Visual inspection and comparison with standard sample	All sizes	Once per week	Check sheet
5	Linear movement		All components	All the ball screw assemblies and the runner blocks should have a smooth movement, without any noise or wear	Y	No wear / no noise	Inspection	All components	N/A	Check sheet
6	Position of bodies		All valve bodies	The bodies should be accurately positioned in the center of the product carrier	Y	0° angular misalignment	2D profile sensor	All sizes	Every Assembly	100% monitoring
7	Storage and usage of sealing rings		Sealing rings	The sealing rings should be as per the product order		N/A	Error proofed identification and storage	all sizes	N/A	Error proofed
8	Stopping the product carrier.	Stopper Gate		Stopper Gate is always in open condition, thus product carrier is stopped at the desired location	-	Contact with the stopper unit	Proximity sensor	All sizes	Every Product	100% Monitoring
9	Actuation of the positioning unit			The positioning unit is actuated after the stopper gate has stopped the product carrier		±0.3mm	Proximity sensor	All sizes	Every Product	100% Monitoring
10	Lifting the product carrier above the C/V system			After positioning the product carrier , it is lifted up by 5mm		5mm		All sizes	Every Product	100% Monitoring
11	Positioning the tightening tool along x-Axis.	Cartesian system as positioning unit	Control System logic for the drive unit	The size of the body determines the position of the plug and ring in the fixture and thus the tightening tool is positioned in alignment with the respective position in the fixture		Accurately aligned. 0mm deviation (expected)	Monitoring the positioning feedback.	1 piece	Every Product	Speed and rotation monitoring
12	Positioning the tightening tool along Y & Z axis	Cartesian system as positioning unit		The size and type of the body determines the position in Y-Z plane.		Accurately aligned. 0mm deviation (expected)	Positioning monitored by monitoring the no. of motor revolutions based on encoder feedback	Every size	Every operation	100% Monitoring
13	Check the presence and absence of the components in the fixture.	Tightening tool	Plug, Ring & Tool tip	Picking with positive mounting		Components should be present in the component	Proximity sensor	Every size	Every operation	100% Monitoring
14	Signal generation by the sensors	All sensors of the system		Sensor like proximity sensor provides go-no-go signal based on presence of the object to be detected.	Y	Providing correct signals to aid in effective operation of the system	Monitoring the sucessful feedback signals of the system	Every size	Every operation	100% Monitoring

PART- B

"MACHINE AIDED- ASSEMBLY SETUP DESIGN"



CONTENTS

1 Introduction

Wouter Witzel had invested its resources in investigating the feasibility of automating the butterfly valves assembly process under the RECap project. The feasibility study presented different possibilities of automating the assembly process. With the possibilities as a foundation, a system level design was carried out to develop a layout of the automated assembly line and propose an overview of the assembly process. The subsequent step was to carry out a detailed design of an assembly station (as developed in the previous section of this report). However, the following research project is an extension to RECap project, and the goal is to determine the possibilities of modifying the current assembly process with a semi-automated machine-aided assembly process. The size of bodies under RECap ranged from DN40-DN350; thus, the same sizes were considered for this extended part of the project. The details on the overall project are explained in brief in subsequent chapters of the report.

1.1 Background information

The results of the research and study conducted during the system level design led to the proposal of final layout of the semi-automated assembly line with the detailed design of the product carrier. The results were presented to the executive from AVK. Because of the high investment costs and the severity of the project, a decision was made to implement the project in gradual steps. Thus, the implementation of the semi-automated assembly line was postponed in the future. Moreover, it led to an agreement of investigating into how the current assembly process could be enhanced using automation technique as proposed for the fully automated assembly line. The purpose was to utilize the knowledge gained during the system level design and the detailed design phase to modify the current assembly process.

1.2 Goal description and research topic

This research and implementation project intends to implement automation in the current assembly process. The general topic of research is to design an assembly process and setup which could be used to assemble a butterfly valve. As a result of the research, a fully functional setup would be developed and tested. This research question has been further divided into sub-questions, as described below:

1. Which assembly steps would be performed by machines/mechanisms?
2. What size and type of bodies would be considered under the scope of prototyping?
3. What mechanism would be used to perform the assembly?
4. What parameters would be tested using the prototypes?
5. Could the designed assembly setup perform the assembly operation as per expectations?

1.3 Structure and Approach

The approach to realize the end goal is distributed amongst different chapters. Each chapter lays the foundation in the form of learnings and which would then be translated into requirements & goals for the subsequent chapter.

Chapter 1-Introduction: The current chapter provides information on the state of RECap, and an overview of the need for performing the following research and development project. This further defines the design requirements and the adopted approach.

Chapter 2-Research and brainstorming: The second stage of the research is focused on the research and development of an initial prototype for performing the assembly operation. This is concluded with conceptual design and evaluation.

Chapter 3-Prototype-I: This chapter is dedicated to the details of the development of the first prototype based on the test results and findings of the first prototype testing.

Chapter 4-Prototype-II: This addresses the design and development of the second prototype. The prototype is developed based on the results obtained & lesson learned from testing of a first prototype.
Chapter 5-Design validation: The chapter covers the results obtained from the testing of the second prototype. Thus, it validates the designed prototype.
Chapter 6-Discussion; Conclusion and Recommendation: In this final chapter, a summary and conclusion derived from the research project would be presented; and finally, value adding recommendations would be provided for the next phase of the project.

2 Research and brainstorming

This section illustrates the research conducted to lay the foundation for realizing the design of machine-aided assembly process. The conducted research would then be utilized to develop conceptual designs and based upon the evaluation; the concepts would be developed into a prototype.

2.1 Learnings derived from RECap

The process of manually assembling the valve is reconsidered. The procedure is stated in part-A of this report and hence, not repeated. The change in shaft design (inclusive of the anti-blowout plate (ABOP)) adds up an extra step in the entire process. Earlier the operator had to mount the O-ring bush on the drive shaft and then hammer it inside the shaft hole of the body all the way into the disc. However, with the changed design, the operator would prepare the drive shaft sub-assembly and then insert it as a single unit into the body. To secure the shaft in position two screws must be fastened in the ABOP.
The testing performed during the system level design for automated assembly of valves showed that each assembly step requires a certain amount of force. The value of applied force depends on the size of the body & its components. Those results were studied to determine how much force is required for each step of the assembly process. The intention was to determine which steps could be automated and how flexibility & intelligence of an operator could be utilized. It was found out that high assembly forces are required for:

1. Inserting the disc inside the body
2. Inserting the driveshaft sub-assembly
3. Inserting bottom shaft
4. Turning the disc to the closed position
5. Fastening the plug and ring
6. Fastening the anti-blow-out plate (ABOP) screws

Testing carried out during the system level design demonstrate, highest forces are needed for inserting the drive shaft, bottom shaft, followed by inserting and closing the disc. Moreover, detailed design of plug & ring station showed that orientation of plug is a critical parameter. Also, with the use of self-centering sealing rings the torque required to fasten the plug is considerably reduced. Thus, it could be concluded that the tightening of the plug & ring does not need high forces.

Moreover, at present, this operation is already done using impact guns. And likewise, tightening ABOP does not need high force and could be fastened using a small electric screwdriver. Thus, these two steps could be eliminated from the automation process, and only steps with a requirement for high forces should only be automated.

The undesired or incorrect alignment of components was one of the most common and yet critical problems faced during the previous phase of RECap. Thus, it was necessary to develop a setup which could minimize the alignment errors.

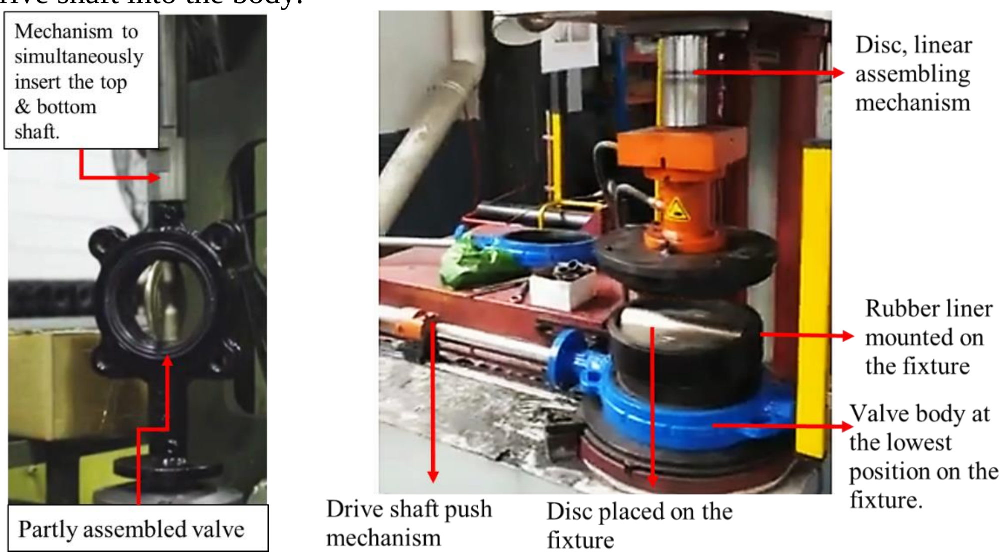
2.2 Machine-aided assembly process.

This research was focused on determining different valve assembly techniques in valve manufacturing companies. The intention was to gain insight into different processes. Similar to Wouter Witzel, many valve manufacturing companies manually assemble the valve. In some company's equipment and mechanisms like force, applicators are used to insert the disc, the drive shaft and the bottom shaft.

Unlike Wouter Witzel, most of the companies use rubber liner as a separate component and is assembled on the body as a part of the assembly process.

Some manufacturers like "*Milwaukee Valves*" use press machine set up (shown in Figure 2-1 (a) [2]) where the shaft is placed vertically upright into a fixture, and then the body mounted over the shaft, followed by inserting the disc. Next, the bottom shaft is placed, and this partly assembled valve is then moved under a press machine, where both the shafts are pushed into the body.

Likewise, at "*Tianjin Tanggu Water-Seal Valve Co., Ltd*." and "*Ho-Cun*" the valves assembly process is semi-automated (shown in Figure 2-1 (b)) [7][3]. The valves are assembled on a machine equipped with a spring-loaded fixture and two push mechanisms. The operator places the body on the fixture, then places a rubber liner over it, and the disc is placed on the top of the fixture. Lastly, the drive shaft is partly inserted in the drive shaft hole. Once, all the components are placed in the machine; the operator actuates the first force applicator unit. This unit pushes the disc along with the liner into the body. Once, all the three components are assembled, the second force applicator unit is actuated to insert the drive shaft into the body.



(a) *(b)*

Figure 2-1: Semi-automated valve assembly mechanism implemented at: (a) - Milwaukee Valves [2] and (b)- Ho-Cun valves [3]

2.3 Design requirements

The learnings of the research were translated into requirements for the design of the assembly setup. These would be used in the subsequent stage to define some preliminary concepts. And, a suitable concept would later be worked out in details. Thus, the basic requirements are:

1. The placement/ positioning of the body and the disc should assure accurate alignment of shaft holes. (Accurate positioning denotes the position of body or disc or both where the distance of the shaft holes could be determined or controlled with the proposed mechanism).
2. Assembly steps with high assembly forces must be carried out with the aid of machines.
3. Minimized handling of the components by the operator.
4. Modular: Suitable for all the sizes and type of bodies.
5. Easy & safe to operate and maintain.

2.4 Conceptual design-Brainstorming

The findings from the preliminary research are presented to the team involved in the project, and a brainstorming session was conducted. The purpose of the brainstorming session was to come up with different ideas. As a result of the session, three general ideas were presented. These are described in the following sub-sections

2.4.1 Concept #1: Assembly setup with three jaw mechanism.

Description: The concept uses an expandable three jaw mechanism which could be used to position and center the body. Next, the operator would have to insert the disc into the body, which could later be pushed further using a force applicator. Lastly, the shafts are pushed in using another push mechanism (Figure 2-2).

Pros:
- The body could be accurately held in position (such that the shaft holes are aligned, and their position is known) without any possibilities of changes in the orientation.
- Universal mechanism-Compatible with different sizes of the valves.

Cons
- Possibilities of causing indents on the rubber lining.
- Considering the variation in sizes of the body, the required size of the jaw mechanism would be enormous.

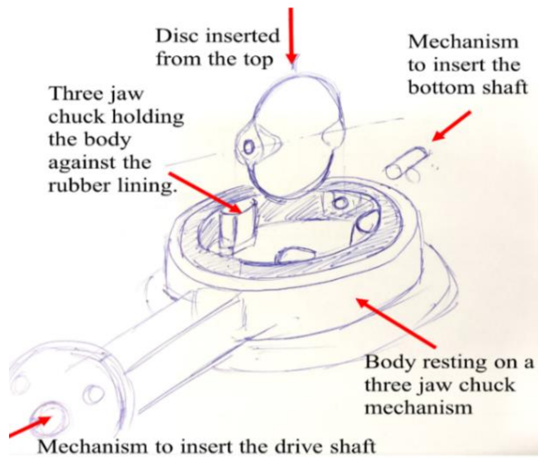


Figure 2-2: Assembling the body by mounting and centering it over a three jaw chuck mechanism.

2.4.2 Concept #2: Assembly setup with a rotating platform.

Description: The proposal was to assemble the valve over a rotating platform. The body would be placed on a centering fixture, mounted on the rotating platform. Next, the disc would be inserted in the well-positioned body. Subsequently, a push mechanism would insert the drive shaft, and the platform would turn by 180°. Thus, the same mechanism would insert the bottom shaft. Lastly, the platform would turn 90°, and the operator can fasten the plug& ring, and anti-blowout plate (Figure 2-3).

Pros:
- Minimized handling of the components.
- Single mechanism required to assemble both the shafts.
- The rotation platform could provide accurate positioning (known position of the shaft holes) of the valve bodies.

Cons
- Incorrect positioning of bodies could hamper the operational accuracy of the system.
- Multiple fixture required for different valve sizes.

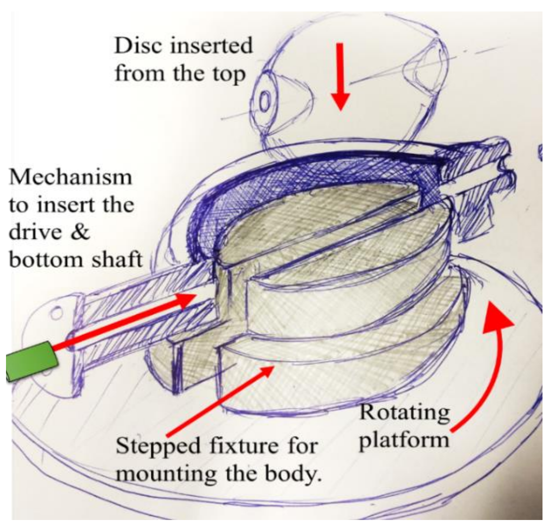


Figure 2-3: Assembling the body by mounting it over a centering fixture and performing the assembly on a rotating platform.

2.4.3 Concept #3: Assembly setup with a disc fixture.

Description: A fixture specially designed to hold the disc would be the most important component of the system. The disc would be positioned in the fixture, and the body would be mounted over the disc. This would be followed by pushing in the drive shaft and bottom shaft using a force applicator (Figure 2-4).

Pros:
- The push force required to mount the body over the disc would be reduced due to the weight of the body which aids in the assembly operation.
- Minimized handling of the body.
- Accurate alignment of the shaft holes

Cons
- Separate disc fixture required for different sizes.
- Separate mechanisms for assembling the shafts.
- The body has to be lifted by the operator (concerning the large-sized bodies-maximum weight-85kg)

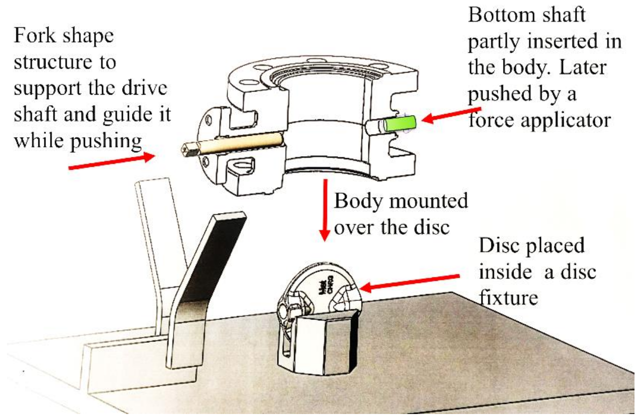


Figure 2-4: Fixture for accurate positioning of the disc and the body is mounted over the disc.

The three concepts were thoroughly discussed with the project team, and it was evident that individually the concepts lagged in fulfilling some of the design requirements. Hence, promising factors from each concept were put together to develop a better concept. The concept of placing the disc into a fixture and then mounting a body over it eliminates the complicated step of disc insertion by twisting, pushing and then adjusting to align the shaft holes. Moreover, the force needed to insert the discs is high and using the body weight gives an advantage with the force application. For pushing the shaft, the force applicator unit could be used. Moreover, using the rotating platform concept reduces the steps of handling the body and requires only one auxiliary mechanism.

Thus, the resultant concept is set up with a rotating platform and a fixture to position the disc. The disc is placed in the disc fixture which would be mounted on a rotating platform, and then the body would be pushed over the disc. Next, the shaft sub-assembly would be placed in alignment with the holes and pushed by a force applicator along with the insertion of the bottom shaft. Lastly, the rotating platform would rotate by 90° & 180° for the operator to assemble the plug-ring & fastening the ABOP respectively. The derived conceptual design seemed to satisfy the design requirements. However, it was essential to ensure the operational and manufacturing feasibility of the system. Therefore, there was a need to design and develop a prototype of the envisioned concept. This has been discussed in the upcoming section.

3 Prototype-I-Principle Testing

This section briefly illustrates the derived concept of the setup for the assembly operation. This prototype was intended to test the feasibility of the concept. Thus, a basic setup has been designed.

3.1 Design requirements and objectives

Designing a prototype which could be suitable for all the sizes was a challenge. It is evident from the proposed design of the fixture that either a large fixture would be required for all the bodies or multiple fixtures would be needed. There are possibilities of making the fixture more modular (quick and easy interchangeable parts) which would make it suitable for different variants and sizes. However, initially, it was essential to determine the feasibility and validity of the concept. Therefore, EVBS DN65 & DN 80 sizes were considered for the initial prototype testing (Smallest sizes with the same face to face thickness and slight variation in their overall dimensions). The findings from the testing would then be used for defining and developing the second prototype. The goal of testing was to determine:

- What should be the dimensions of the fixture to attain perfect alignment of shaft holes?
- How accurately could the shaft holes of the body & disc be aligned?
- How does the mounting of the body over the disc affect the alignment of shaft holes?
- The force required to insert the drive shaft in perfectly aligned holes?
- The force required to insert the drive shaft if there is a misalignment of shaft holes?
- Is there a requirement for a shaft fixture?
- Possible factors causing misalignment of shaft holes?

The design requirements for the setup were:

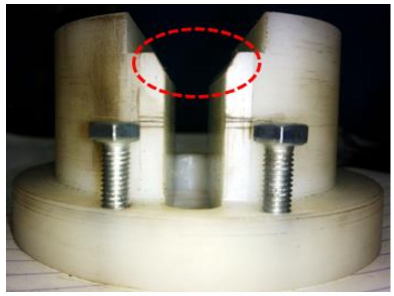
- A simple, robust and easy to manufacture design of disc fixture.
- The possibility of accurately positioning the disc inside the fixture.
- The setup must have a feature to test/measure the misalignment of shaft holes.
- A mechanism to insert the shaft inside the body and the disc.
- A fixture for hold and position the drive shaft in alignment with shaft holes.
- Feasibility of incorporating a sensor to measure the assembly forces

3.2 Test Setup:

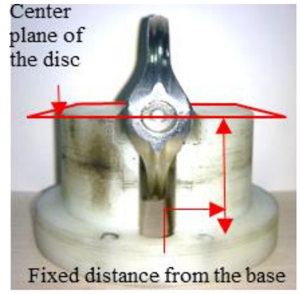
A prototype setup is designed based on the stated requirements. It comprised of eight components as seen in Figure 3-2. The design and purpose of each component are as explained:

1. ***Disc fixture:*** For DN65 and DN80 size bodies, two separate fixtures are made instead of a modular fixture in order to avoid complex design of the fixture. Their purpose is to position and support the disc while the body is being mounted over it. The fixture is symmetrical with slant faces at an angle of 150°. The cut profile is similar to the profile of the disc (for the holes); thus, it rests on the slant faces of the fixture. This makes the position of the center plane of the disc know, and thus the alignment of the holes could be accurately achieved (detailed description on the fixture is stated in Figure 3-1). Moreover, three bolts on the fixture facilitate the testing and measurement of misalignment in shaft holes. The body would be resting on the flat faces of the bolts (positioned at a known distance from the top surface of the disc), and thus, the distance between the center plane of the body and disc could be varied to attain the desired misalignment.

(a)



(b)



(c)

Figure 3-1: (a): Disc fixture with adjustment screws, (b)- The slanted profile supports the disc against the casted surface, and (c): The center plane of the disc is coincident with the top surface of the fixture. Thus the distance of the plane is known.

2. ***Shaft fixture:*** Used for positioning the shaft outside the valve body. When the shaft is being pushed, the fixture provides guidance and supports the shaft until it is partially inserted into the drive shaft hole. Another function of this fixture is act as a reference for resting the top flange of the body to check if the body is mounted without any angular misalignment.
3. ***Force sensor:*** One end of the force sensor has a 12mm pin in contact with the drive shaft, and another end is connected to the drive screw. When the drive screw is turned, it moves the sensor, and the sensor exerts a force on the shaft. Thus, the force readings are recorded.
4. ***Support fork:*** A fork-shaped component from a vulcanization mold (used for curing the rubber lining on the body) is used as a support. This fork and its support plate are used for guiding and supporting a threaded screw.
5. ***Drive lead screw:*** The lead screw is used as a force applicator. The advancement obtained by turning the screw is used for applying the driving force for inserting the drive shaft into the valve body.
6. ***Base platform:*** This provides rigid datum and support to all the other components of the setup. Each component is fixed in its predefined position. Thus it assures the desired alignment.
7. ***Base plate:*** A support fixture to easily mount and unmount the two fixtures. It has four mounting pins on which the disc fixture is mounted and could be easily replaced with the second fixture. Thus, it reduces the efforts of preparing the assembly for new testing for different sizes.
8. ***Measurement recorder:*** The unit records the force measurements from the force sensor. The readings are recorded with respect to time, and a corresponding graph is plotted. The data can then be retrieved for analysis.

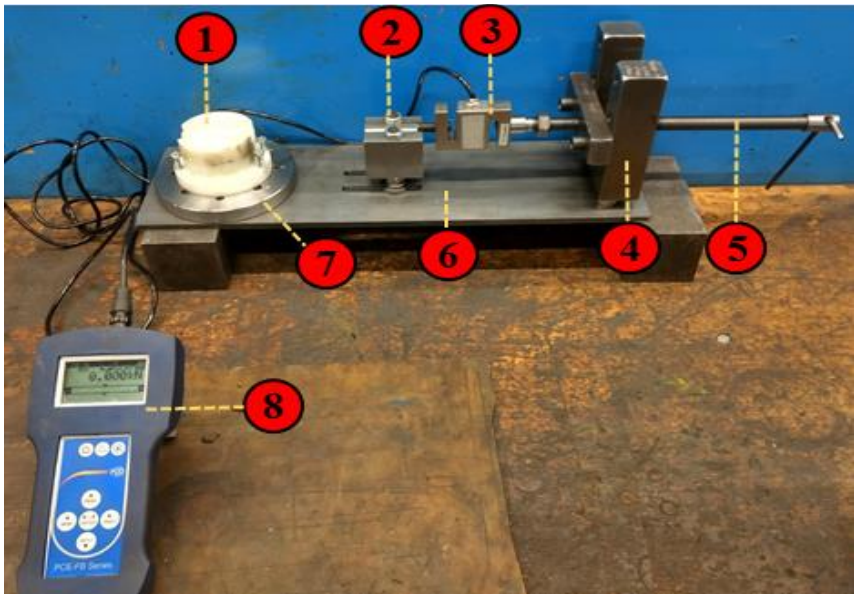


Figure 3-2: Prototype-I test setup. Components: 1) Disc fixture, 2) Shaft fixture, 3) Force sensor, 4) Support fork, 5) Drive lead screw, 6)Base platform, 7)Baseplate and 8) Measurement recorder.

3.3 Test results & findings

1. Very close alignment of shaft holes could be achieved by adjusting the screws at a height equivalent to half of the face to face dimension, with respect to the top face of the fixture (this value is 23.9mm for an EVBS body of size DN80 & DN65). However, it is difficult to quantify the accuracy of alignment.
2. With accurately aligned shaft holes, the force required to drive a 12mm shaft inside the DN80 & DN65 body is in the range of 0.25kN to 0.35kN (these values are the result of using the same body, disc & shaft combination).
3. The force required to insert the shaft in a new body and disc combination with accurately aligned holes lies in the range of 0.8kN to 1kN. Using a new body for testing means the shaft must overcome the resistance offered by fresh rubber, whereas the body undergoing multiple uses has a more relaxed rubber lining and thus resistance offered is reduced. This causes variation in the driving forces.
4. If the screws are adjusted at a height 1 to 2mm greater than half the face to face dimension of the body (i.e., between 22.9-21.9mm), then a considerable misalignment is visible.
5. Inserting the shaft in the body & disc with 1 to 2mm misalignment requires 0.75kN to 0.95kN force (these values are the result of using the same body, disc & shaft combination). Misaligned shaft holes restrict the shaft. As a result, the shaft tries to align the holes. Thus, the force required to insert the shaft increases.

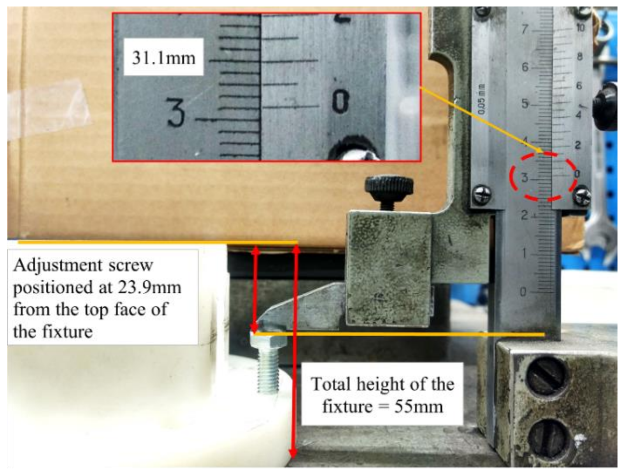
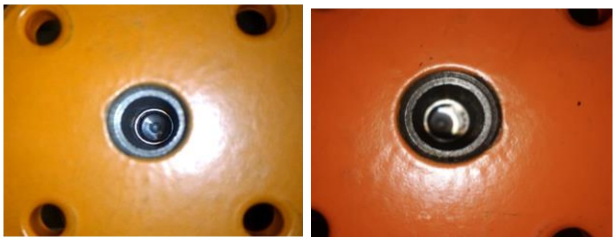


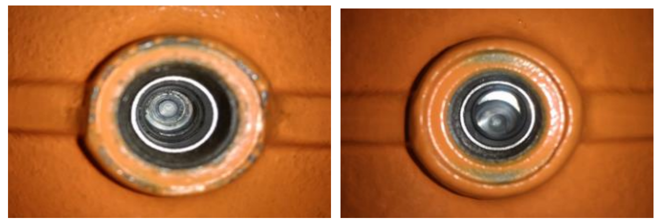
Figure 3-3: The face-to-face dimension of DN65-DN80 bodies is 47.8mm and fastening the height adjustment screw at 23.9mm from the top face of the disc fixture, assures that the shaft holes of the body and disc are accurately aligned.

6. The misalignment of shaft holes could also result from:
    a. Offset machining of the shaft holes in the body or the disc.
    b. Casting tolerances on the face where the disc rests on the fixture.
    c. Friction between the rubber lining and machined face of the disc. The disc is lifted off from the fixture when the body is pushed over it.
    d. The disc can slightly rotate about its central axis (passing through the shaft holes), and this could add to angular misalignment.
    e. Angular misalignment could be seen if the body is slightly rotated before it is mounted on the disc.



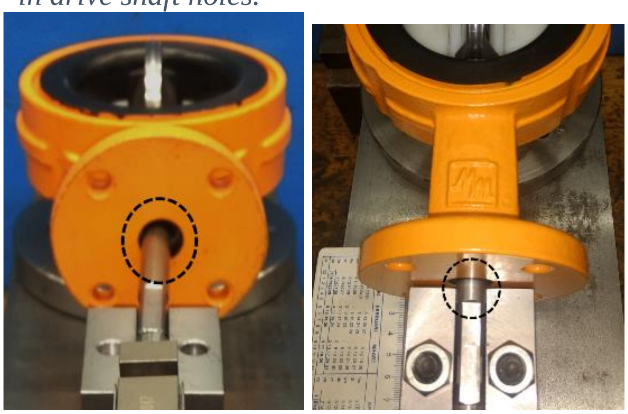
(a) (b)

Figure 3-4: a)Accurately aligned drive shaft holes of the body and the disc, b)Misalignment in drive shaft holes.



(a) (b)

Figure 3-5: a)Accurately aligned bottom shaft holes of the body and the disc. b) Misaligned bottom shaft holes



(a) (b)

Figure 3-6: (a)Angular misalignment while mounting the body over the disc lead to misalignment of the shaft and the drive shaft hole. (b) The misalignment of the holes resists the shaft, and hence, the shaft cannot be inserted completely.

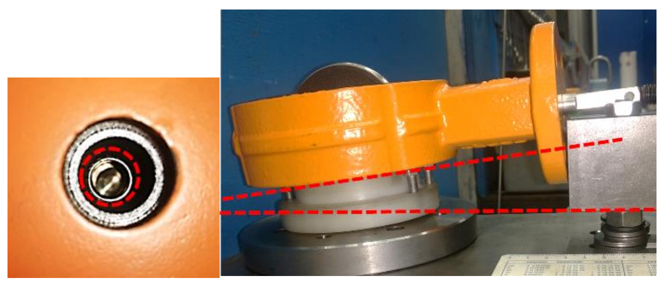


Figure 3-7: When the drive shaft holes are misaligned, the shaft tries to align the shaft hole using the driving force. This causes the body to lift off from the fixture.

From the test results, it is evident that the force required to insert the shaft inside a perfectly aligned hole is lower than the one for misaligned holes. Moreover, while inserting the shaft in misaligned holes causes moment loads on the body, and the shaft tries to uplift the body from the fixture. Thus, it could be concluded that the shaft can still be inserted into the body & disc with slightly misaligned holes, but more force must be exerted. Also, if the top reference surface of the disc fixture is coincident with the center plane of the body, the possibilities of achieving perfectly aligned shaft holes are much higher.
These results & findings have been discussed with the team, and the discussion resulted in favor of the concept being feasible for the assembly operation with satisfactory fulfillment of requirements. Thus, the next phase requirement was to develop a more robust and advanced version of the initial prototype and perform assembly operation of Euronomic series valves of size DN200.

4 Prototype-II-Inline Testing

The second prototype was designed for close resemblance with the design to be implemented on the assembly line. The intention was to let the operator use the setup to perform some assemblies and then analyze the possibilities of modification and improvement which could be incorporated in the final design. One prominent purpose was to test the assembly of a Euronomic valve. The Euronomic valves are similar to rubber lined butterfly valve of euro valve series but have hexagonal disc hole and drive shaft end with an anti-blowout plate (described as the new design of EV series valves in the previous part of the report). Thus, this test would help realize the assembly parameters for upcoming changes in the EV series valves. The prototype test setup is made with the intention of using it in future with slight modifications for different DN sizes.

Initially, the components needed for the prototype are studied and followed by the setup design. The design is then presented to the team for feedback and evaluation. Next, the setup is developed for testing purposes. The goals of testing are:

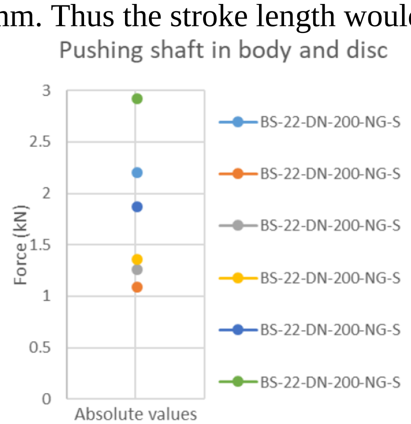
1. To confirm the feasibility of the test setup for the euronomic range.
2. Providing the setup to inline operators for using and get their feedback to determine the requirements for the final design of the setup.
3. To closely analyze the operation of the system and study the loopholes in the design.

4.1 System components

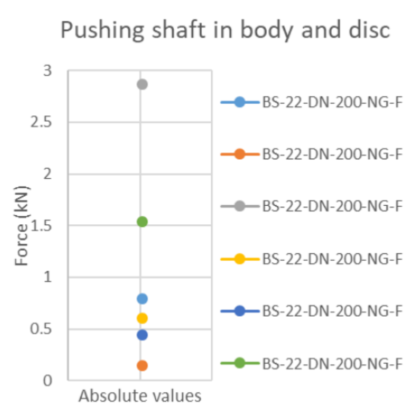
This section would briefly illustrate the research and choice of the system components. The selected components would then be included in the prototype development.

4.1.1 Electromechanical Cylinder

A downside of the initial prototype was its limitation of force application, and as described in findings it resulted in non-uniform force application. Unlike the 1st prototype, the force had to be applied by a powered mechanical force applicator. For this purpose, an electromechanical cylinder had to be selected. The testing performed during system level design showed that 2.5kN of absolute force is needed to insert a 22mm shaft inside a DN200 body without using grease. It is assumed that the force required for inserting a 30mm shaft would be higher than the tested value. Thus, with a factor of safety of 2, the cylinder should deliver approximately 5kN force. A critical parameter of the force delivered by EMC is that the delivered force reduces with an increase in stroke length. The stroke length is calculated as the difference between the shaft length of an EVBLS DN350 and EVBS DN50. The longest shaft length is approximated to be 175mm and is used in a DN350 size of EVBLS & EVTLLS type. Initially, the shaft is placed at a distance from the top flange of the body. The distance is assumed to be 50mm. Thus the stroke length would be 225mm.



(a)



(b)

Figure 4-1: Absolute value of drive force required to drive a 22mm shaft in a DN200 valve body and disc, without using grease. (a)-Maximum 2.9kN Drive force is required, when the shaft is pushed slowly, (b)-Maximum 0.28kN drive force is required when the shaft is pushed faster [4]

Figure 4-2: Electromechanical cylinder for force application to counteract the tightening torque [1].

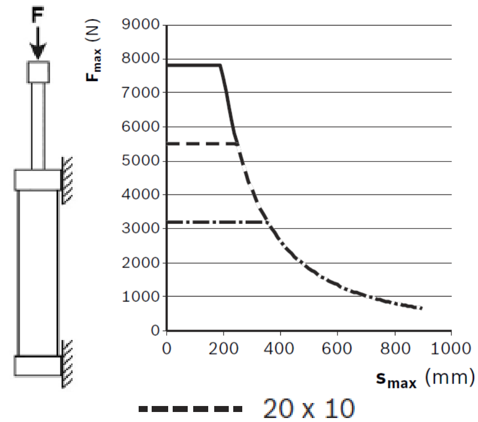


Figure 4-3: With ends fixed, the EMC-50 (20x10mm) can deliver a maximum force of 3500N for a stroke length up to 300mm (shown by dashed curve) [1].

4.1.2 Rotation platform

The rotating platform was an essential component of the proposed concept. For prototyping purpose, it was appropriate to select readily available platforms rather than making them from scratch (due to time constraint). The body had to be positioned at 0º, 90º & 180º; thus, the positioning accuracy of the platform was a critical parameter. The research was focused on selecting a simple rotational stage that could be rotated manually, rather than driving it electrically (to keep the prototype cost-effective and straightforward).

The selection of the platform was governed by:

- The size of the body that was to be tested on the test setup (Euronomic DN200).
- Total force required for pushing the body over the disc. This force would be the same as the force required to push the body into the valve body (0.44kN, tested during the system level design-shown in Figure 4-4), plus the weight of the body and disc (approximate 12kg). Thus, the total force to be carried is equivalent to 557.72N.

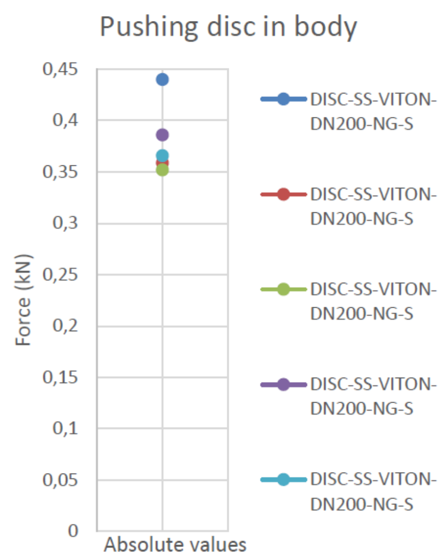


Figure 4-4: Maximum push force of 0.44kN is required for slowly pushing a stainless steel disc in a VITON rubber lined PN16 DN200 body without the use of grease [1]

Based on the two requirements, a set of rotational platforms were searched. This resulted in the choice of two platforms which could closely fulfill the requirements (shown in Figure 4-5 and Figure 4-6).

Figure 4-5: Ø4.3" Manual Rotation Stage. Load capacity of 80kg, when the stage is mounted on the horizontal surface [6].

Figure 4-6: 7R170V-190 - Vacuum Compatible Rotation Stage With a load capacity of 60kg, when the stage is mounted on the horizontal surface [5]

4.1.3 Disc Fixture

The disc fixture had to be designed for DN200 disc, and its functionality was to support the disc. The accuracy of alignment of the shaft holes was assured by maintaining the distance of the flat face (where the body rests on the fixture) from the center of the curved face (surface against which the disc is positioned) equal to 31.9mm (as shown in Figure 4-7). Moreover, the size and dimensions of the rotational platform show that the height of the disc fixture must be higher to prevent the disc from touching the platform. Increase in the height of the fixture would result in increasing the height of the force applicator unit. Moreover, the units were costly (around 222 Euros); and there is no point in investing in a platform that could not be used in the future for different sizes. Instead, the design of the fixture was changed in a manner that it could be used for performing the rotation without using a rotation platform. This was done by including a circular groove in the fixture design, which would allow the fixture to rotate about its central axis, using guidance from four guide pins (shown in Figure 4-9)

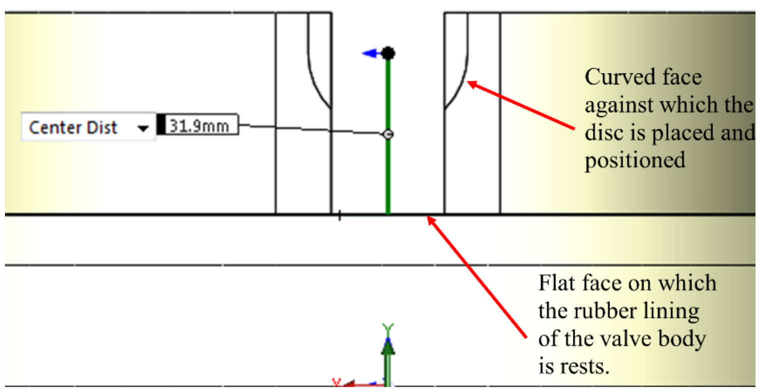


Figure 4-7: The flat face distance from the center of the disc is maintained 31.9mm which is precisely half the face to face thickness of the DN200 euronomic valve. Thus, when the body is pushed over the fixture, its center plane would be at 31.9mm from the flat face, and this would assure accurate alignment of shaft holes.

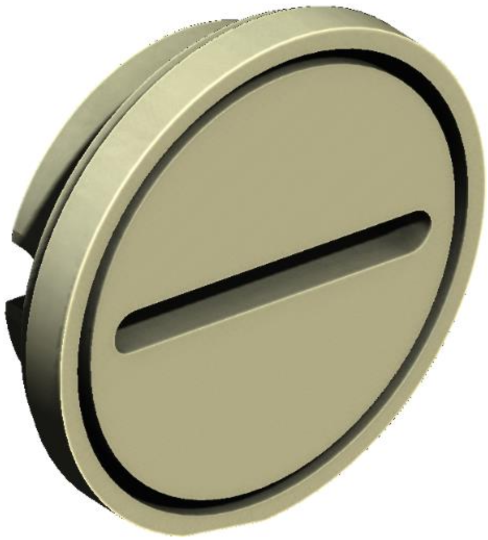


Figure 4-8: Disc fixture with a circular groove at the bottom face.

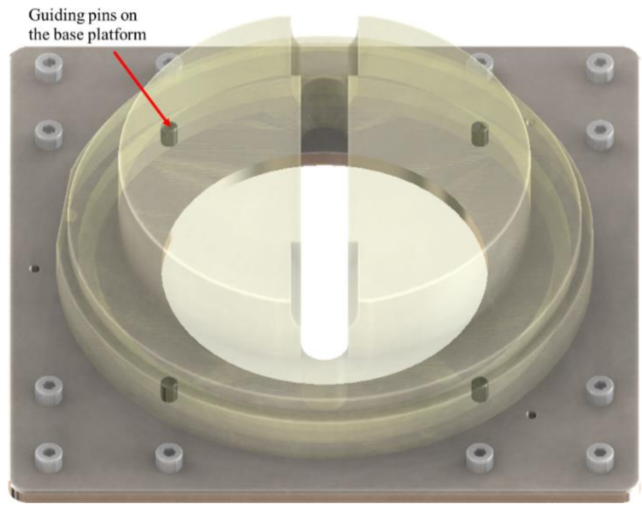


Figure 4-9: Four guiding pins on the base platform, closely fit inside the circular slot of the fixture and thus guiding rotation.

4.1.4 Linear guide system

A linear guide rail system was incorporated in the design, a modification to the selected concept. While testing the first prototype, it was observed that the rubber lining in the drive shaft hole initially resists the driving force. Thus, if the body remains stationary, the driving force can overcome the frictional force, and the drive shaft assembly could be carried out. This phenomenon could have been used for inserting the bottom shaft. The proposal was to mount the disc fixture on a sliding mechanism such that the body, disc & the fixture would translate using the driving force required to overcome the sliding friction of the rubber lining. These components would slide until obstructed by fixed support (end stop). The fixed support with a pin would drive the bottom shaft into the body, until the point where the components could not be moved any further.

Therefore, there was a need to select and develop a simple linear guide rail system. Based on the learnings of the detailed design phase, four blocks on two guide rails system was considered suitable. Moreover, linear motion designer software (from Bosch Rexroth) was used for determining the size of guide blocks to be used. The results show a 20mm guide rail and block system could be used. However, a 25mm rail and guide block system is selected with the intention of using it for testing larger valve bodies.

4.2 Prototype-II setup

The prototype is as shown in Figure 4-10. The setup comprises of following components

1. ***Disc fixture***: Designed for placing the disc to achieve accurate alignment of shaft holes. Also, the fixture has a circular slot machined at the bottom side. The slot enables the fixture to rotate by 360° with guidance from 4 pins. It is made from nylon to prevent it from damaging the disc.
2. ***Force applicator unit***: The selected cylinder is used to exert the required force for assembling the shafts. The tip of the cylinder shaft has a drive shaft socket fastened to it. The purpose of the socket is to retain the shaft orientation as per the orientation of the hexagonal hole of the disc.
3. ***Linear guide system:*** The linear guide system provides translational freedom to the system. When the drive shaft is inserted in the body, it experiences resistance from the linear bearing and runner lining. This resistance is used to freely guide all the components on the base platform until a point where the fixed support obstructs it.

4. ***Bottom shaft inserting support:*** This is a fixed block with a protruding pin. This acts as a stopper for the linear guide system and bottom shaft inserting tool. The linear guide moves until the protruding pin encounters the bottom shaft.
5. ***Base platform:*** The platform functions as a carrier attached to the linear guideways. There are three locking pins/clamps mounted on the platform which prevent lifting of the disc fixture. Moreover, it also acts as a stopper to orient the disc fixture back in accurate alignment. Also, it has four guide pins which perfectly fit inside the guiding slot of the disc fixture and assist in rotation.
6. ***Base frame:*** It is a basic frame made by welding together 50x50mm square profiled tubes. Each component of the assembly is positioned on the frame at a predefined position.

The ensure safety while operating the system, the actuation switch would be placed at a safer distance. This has not been shown in the model, yet it has been taken into consideration, and the connections would be made during the commissioning and programming of the controller unit.

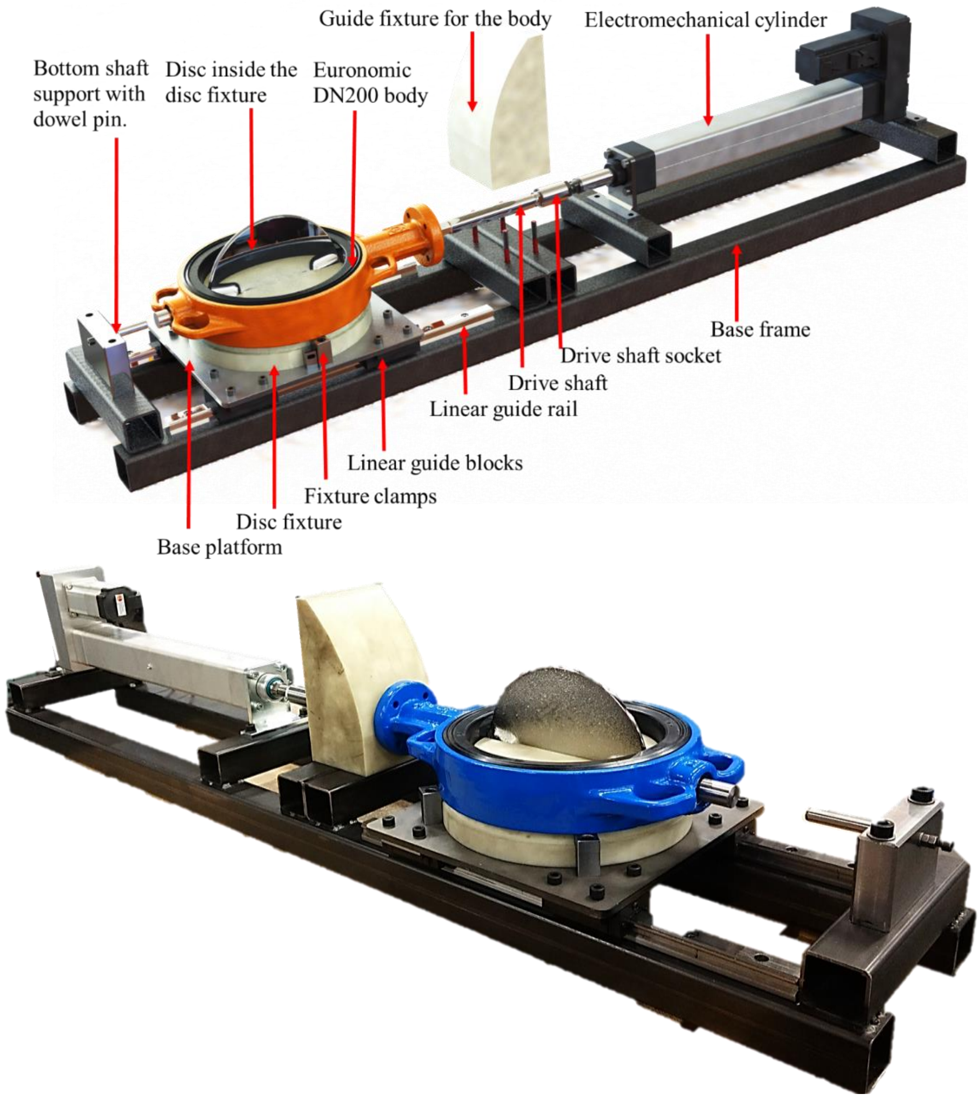
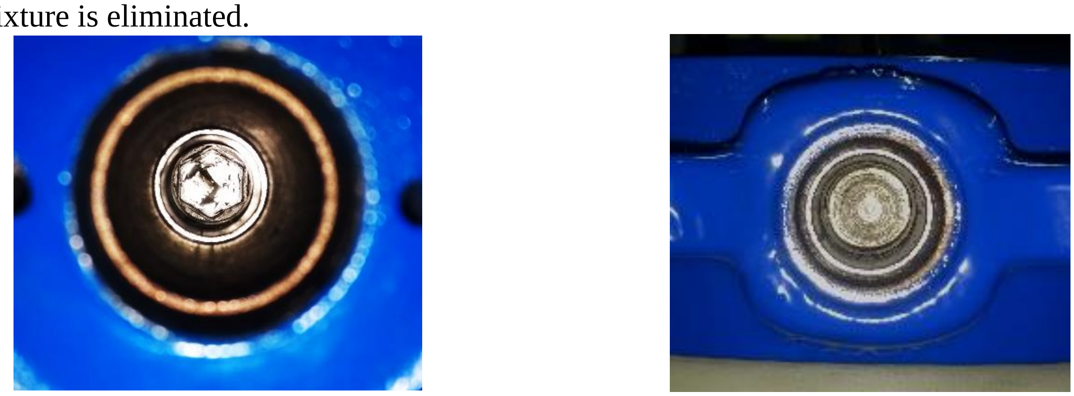


Figure 4-10: Prototype-II of the assembly setup.

4.3 Testing

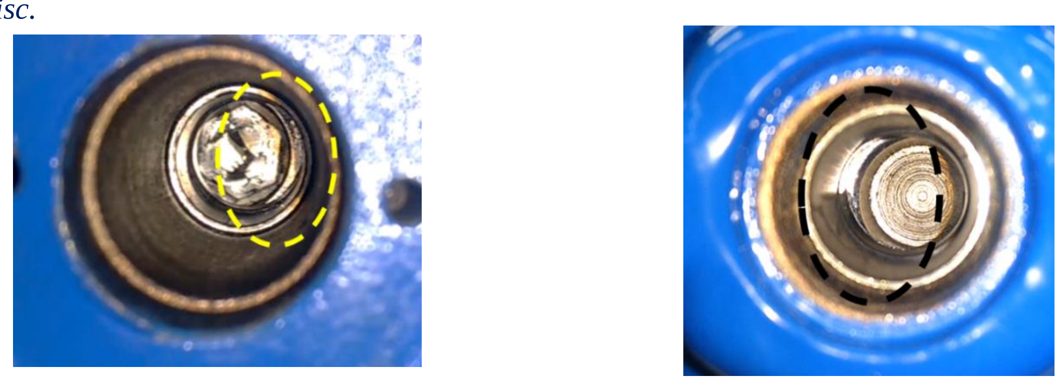
This section briefly describes the observations from the testing of the second prototype (the test procedure is described in 5.2B). These findings would be considered into the recommendation for the final stage design. The fully automated functionality of the setup could not be tested because of delay in the delivery of the components and due to damage caused to the controller unit (prior to the start of testing). However, the feasibility and validity of the setup were confirmed by assembling some valves without the force applicator. The testing demonstrated:

- The shaft holes of the body and the disc could be accurately aligned (as shown in Figure 4-11) if the assembly is carried out slowly with particular attention towards the orientation of the body with respect to the disc.
- Change in the orientation of the hexagonal end of the drive shaft or the shaft hole of the disc could cause a severe rise in force requirement(Figure 4-12 (a)). This could also damage the shaft and the disc.
- Application of excessive force could lead to the disc making indentations in the rubber lining which could lead to leakage.
- The curved end of guide fixture for the body is not fully effective in guiding the body over the disc onto the fixture. Moreover, demands complicated handling of the body and it adds undesired sequence in operation, the operators might not accept this. In addition, the body slips over the curved profile.
- The flat end of the guide fixture is effective in eliminating the misalignment of shaft hole arising from improper mounting of the body over the disc. This is possible because the flange of the body is coincident with the flat end of the fixture and thus, the rotational misalignment of the body over the fixture is eliminated.



(a) *(b)*

Figure 4-11: No misalignment observed in the drive shaft hole (a) & bottom shaft hole (b) of the body and the disc. Also, no rotational misalignment/ changed orientation was observed for the hexagonal hole of the disc.



(a) *(b)*

Figure 4-12: Misalignment observed in the drive shaft hole (a) & bottom shaft hole (b) of the body and the disc. Also, rotational misalignment/ changed orientation was observed for the hexagonal hole of the disc.

5 Discussion; Conclusion, and recommendations

The following chapter is dedicated to discussing and stating the conclusions derived during the research and development phase. However, the satisfactory conclusion could not be derived because of limited testing. Lastly, the second part of the chapter would provide some valuable recommendations that would help in the next phase of development.

5.1 Discussion and Conclusions

The research questions were:

1. Which assembly steps would be performed by machines/mechanisms?
   - The study of the manual and proposed semi-automated assembly process shows that the forces required for inserting a drive shaft, bottom shaft and the disc are comparatively higher than the force required for fastening the anti-blowout plate and the plug & ring. Apparently, the operators are using a power tool to perform the fastening operations. Thus, the conclusion was to assign the operation sequence with higher force requirement to a force applicator mechanism.
2. What size and type of bodies would be considered under the scope of prototyping?
   - The RECap project considered the DN40-DN350 sizes of all the nine variants of the valve and thus, the same consideration was adopted. However, for prototype development and testing was constrained to size DN65, DN80 of EVBS and DN200 size of a euronomic.
3. What mechanism would be used to perform the assembly?
   - The primary focus of the project was to minimize the errors caused due to handling and also reduce the exertion of operators. The proposed concepts demonstrated that horizontal orientation of the body minimizes the handling of the body and in this orientation, the force application direction is vertical and horizontal (linear). Thus, the conclusion was to consider a servo driven linear actuator unit proposed during the system level design as the force applicator mechanism for the system.
4. Could the designed assembly setup perform the assembly operation as per expectations?
   - The conclusions derived from the testing of the first prototype are:
     - It is difficult to assure accurate alignment of the shaft holes because of different parameters. These parameters are mainly: machining and casting tolerances on the disc & the body, wear of the fixture; the improper procedure of assembling the valves, etc.
     - Accurate (co-axial) alignment of the shaft holes of the body and disc could be attained with modifications in the design of the disc fixture.
     - A misalignment of the shaft holes in the range of 1mm-2mm could be overcome by increasing the driving force required to insert the drive shaft.
   - The conclusions derived from the elementary testing of the prototype-II are:
     - With the modified design of the disc fixture, the shaft holes could be accurately aligned.
     - The guide block fixture makes it feasible to eliminate rotational misalignment of the body with respect to the disc fixture.
     - The system is not tested with the force applicator cylinder, and thus fulfillment of the envisioned functionality of the system cannot be stated.
     - The operators are yet to use the setup, and their perspective remains unanswered.

Thus, the findings and learnings gained from the testing phase reveal that the current design of the setups could perform the assembly operation as per expectation. However, more testing has to be performed which would help develop a final setup that is fully functional and capable of performing the assembly operation.

5.2 Recommendation

The second prototype had some significant shortcomings, and the modification possibilities are described henceforth.

1. The prototype was operated under supervision with complete awareness about safety, yet the design lagged safety parameters. Hence, the next phase of designing should be performed with considerations of safety and with a design for safety approach (safety of the operator and the product).
2. The second prototype setup assembling showed that the design was not good from a perspective of assembling and disassembling. Thus, next setup should be made modular, compatible for different sizes, easy to assemble and disassemble.
3. Currently, the Euronomic DN 200 could be assembled on the setup. It is recommended to test size DN 200 of EVBS and EVBLS (or EVS, EVCS, EVTLS, and EVTLLS, based on availability). This will give insight on how effectively the pinholes are aligned for the current shaft design.
4. The current design had three clamps to prevent the liftoff of the fixture. The new design must have a more robust solution for quick fix and release of the fixture.
5. The system could be made smart and reliable by including a vision check system in the design to monitor the alignment of shaft holes of the body and the disc.
6. The current setup is designed for assembling DN200 size valves. However, the final assembly setup must be designed for assembling all the different sizes and type of valves under the scope of the project. For instance, the disc fixture could be made modular for sizes having the same face to face dimensions.
7. There is considerable variation in the distance between the flat face of the body and center of the shaft holes. Thus, the position of the force applicator and bottom shaft push support could be fixed, and the slide rail mechanism could be mounted on a platform with a vertical height adjustment mechanism.
8. Similarly, as per the initial concept, the disc fixture is to be mounted on a rotating platform. Currently, the fixture was rotated manually; thus, further research must be done on possibilities of using a universal (could be used for sizes from DN40-DN350) rotating platform.

References

[1] Bosch Rexroth AG,. (2018, April). *Electromechanical Cylinders EMC; R999000493; [Catalog]*. Opgehaald van https://www.boschrexroth.com/en/xc/products/product-groups/linear-motion-technology/linear-motion-systems/actuators/emc

[2] Company, M. V. (Producent). (2017). *Milwaukee Valve Rubber Lined Butterfly Valve* [Film]. Opgehaald van https://youtu.be/iymM9VVVhA0

[3] Ho-Cun (Producent). (2017). *Butterfly Valve Assembly* [Film]. Opgehaald van https://youtu.be/wner3Ef75ok

[4] Nijensteen, G. ((September 2017 – July 2018). *Design and validation for automated assembly of Eurovalve butterfly valves.* Losser: Wouter Witzel.

[5] STANDA LTD. (sd). *Vacuum Compatible Rotation Stage*. Opgehaald van http://www.standa.lt/products/catalog/vacuum_compatible_stages?item=382

[6] THORLABS. (sd). *Manual Rotation Stages.* Opgehaald van https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=992

[7] TWS, V. (Producent). (2018). *Bushings assembly for wafer butterfly valve* [Film]. Opgehaald van https://youtu.be/K62wEgAP4sI

Appendix

A Prototype-I Testing

A.1 Test procedure

The test procedure followed to check the feasibility of proposed conceptual design is as follows.

1. Adjust the height adjustment screws to the desired height (in this case 23.9mm) using height gauge and place the fixture onto the base plate (Figure. A-1).
2. Place the disc into the disc fixture and adjust its position to have an accurate alignment (Figure. A-2).
3. Position the body over the fixture. Before mounting the body, visually check if the shaft holes seem aligned and adjust the position of the body to have an accurate alignment. The machined profile of the disc should be used as a reference to determine if the shaft holes are in alignment (Figure. A-3).
4. Push the body over the disc into the fixture. The body must be pushed until it rests on the height adjustment screws and cannot be pushed any further (Figure. A-4).
5. Visually confirm the alignment of the shaft holes. Use a bright light for obtaining a clearer view.
6. Next, place the drive shaft on the shaft fixture outside the shaft hole of the body.
7. Set the measurement recorder value back to zero. Moreover, start the reading the moment you start applying force.
8. Drive the lead screw supported in the fork support to push the drive shaft into the body until the shaft is completely inserted (Figure.A-5).
9. Try to keep the force application motion consistent to reduce noise in the readings.
10. Repeat the procedure ten times to get a set of value for better analysis.

After this, the height adjustment screws are adjusted to a height of 22.7mm which is 1.2mm lesser than the previous adjustment. This is done to misalign the shaft holes beyond the point where the chamfer on the shaft end will not guide the shaft into the shaft hole. The purpose of misalignment was to check what is the variation in force to push the shaft into the body for a certain range of misalignment. Moreover, how does it affect the entire assembly process?
The steps of assembling the disc & shaft are repeated, and the force values are recorded for another ten samples.

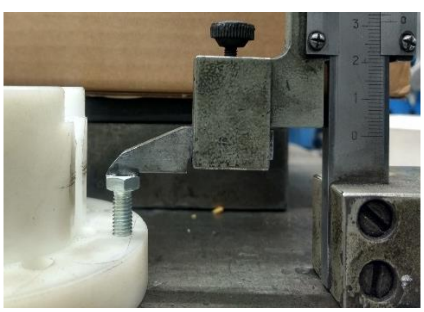


Figure. A-1: Adjusting the leveling screw to the desired height using a height gauge(in this case 23.9mm – half of the face to face thickness of an EVBS DN 80 valve)

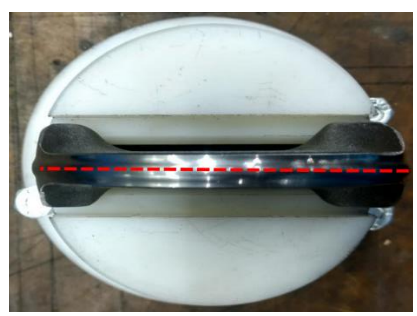


Figure. A-2: Disc accurately centered in the disc fixture and the red line denotes the center line of the disc, with a machined face as a reference edge.

Figure. A-3: Aligning the body over the disc using the center line as a reference (Figure. A-2) to attain an accurate alignment of shaft holes.

Figure. A-4: Body being pushed over the disc to assure the body rests against the height adjustment screws to eliminate misalignment errors.

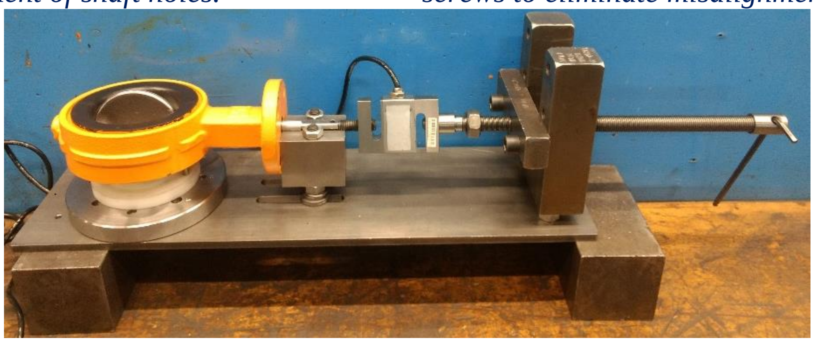


Figure.A-5: The force applicator unit being used for driving the shaft into the valve body. The force sensor in the center is being used to record the force values.

A.2 Test Results

The testing was performed for sizes DN80 and DN65. The measurements were then copied to an excel file and a force (in kN) vs. time (in milliseconds) is plotted (as seen in Figure. A-6 to Figure. A-8). Figure. A-6 shows that push force in the range of 0.25kN to 0.35kN is required to insert a 12mm shaft in an EVBS DN80 valve body (when the shaft holes are accurately aligned). Similarly, the results for the second test with a 2mm misalignment between the shafts holes is shown in Figure. A-7. It is clear from the results that the force required to insert the shaft in misaligned holes is approximately increased by a factor of two, ranging from 0.7kN to 0.9kN. The prototype test setup had an elementary model of force applicator (the drive screw). Since the mechanism was hand driven, the force applied is inconsistent and non-uniform; this is evident in all the graphs, in the form of multiple peaks.

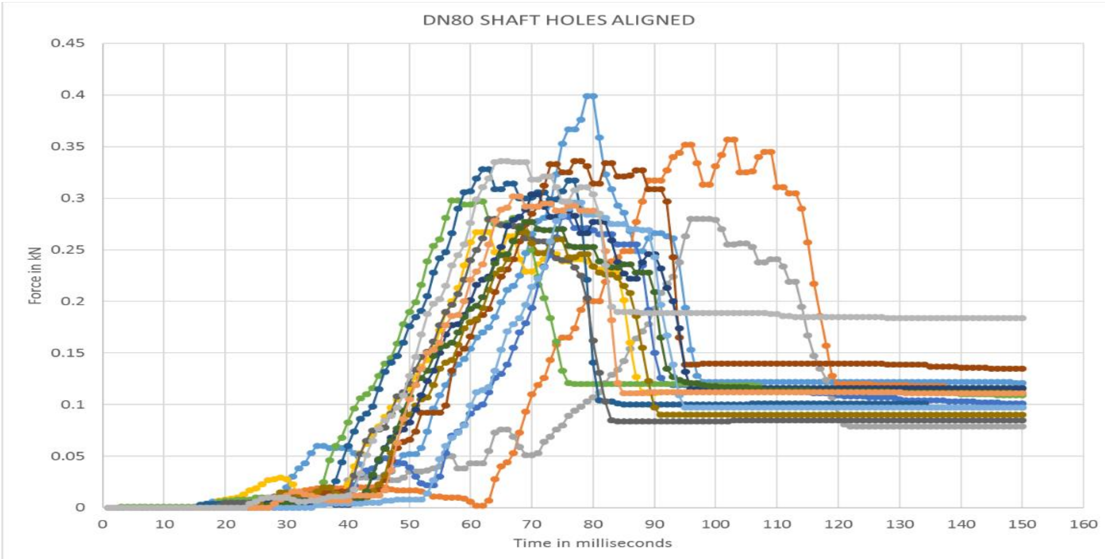


Figure. A-6: The driving force required to insert a 12mm diameter shaft in the accurately aligned shaft holes of a body and a disc (size DN80). The force lies in the band of 0.25kN to 0.35kN. The multiple peaks in the graph are a result of an inconsistent force application.

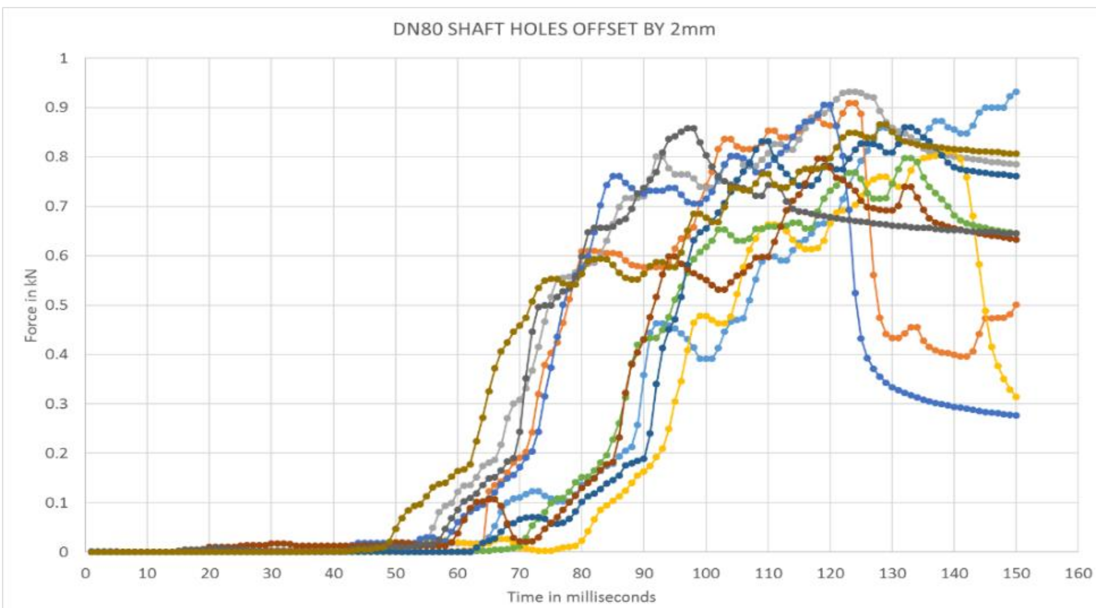


Figure. A-7: The driving force required to insert a 12mm diameter shaft the body and disc with a 2mm misalignment of shaft holes (size DN80). The force lies in the band of 0.7kN to 0.9kN.

The Figure. A-6 & Figure. A-7 shows clustered result; this is the outcome of multiple tests performed on the same set of body and disc. However, when the same test procedure was performed with DN65 bodies (Different set of body and disc for each reading), the results are distributed. This is caused because of the high resistance experienced by the drive shaft duet the rubber lining of a new valve. Therefore, the results are scattered under the band of 0.2kN to 0.6kN

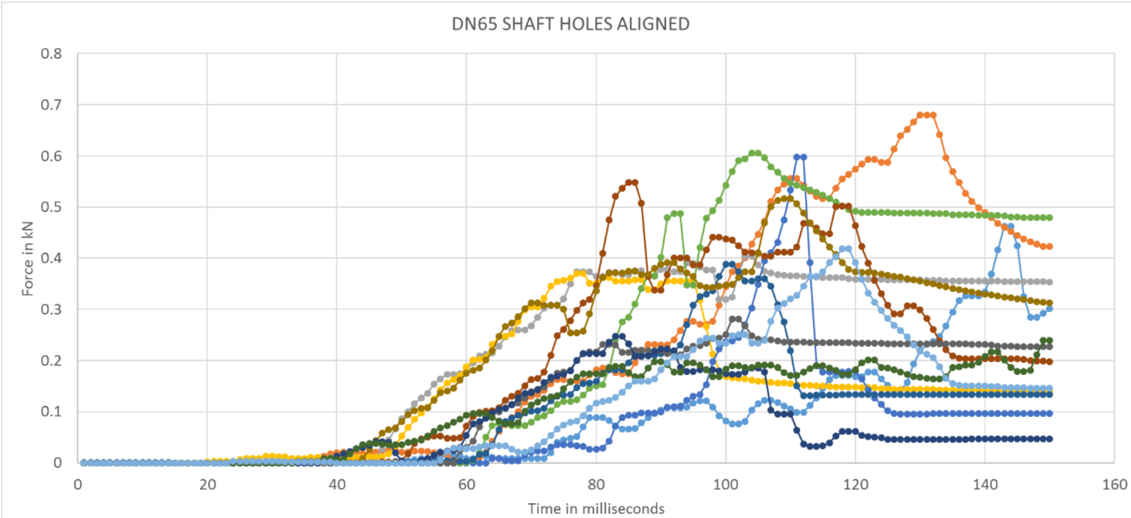


Figure. A-8: The driving force required to insert a 12mm diameter shaft in an accurately aligned shaft hole of a body and a disc (size DN65). The force lies in the band of 0.15kN to 0.55kN; the variation is caused because every time a new body and disc combination has been used for testing.

B Prototype-II Testing

B.1 Prototype-II: Test procedure

This prototype is a step closer towards the final design. The goal of testing was to determine the problems that could be encountered for a hexagonal hole & shaft assembly.
What is the impact of misoriented hexagonal hole or shaft on the assembly process and the setup? And how much misorientation could be tolerated?
Could the system accurately imitate the manual operation?

The assembled setup was readily used for testing purpose. The test procedure (shown from Figure. B-1 to Figure. B-5) was as follows:

1. The disc is placed in the disc fixture with the hexagonal shaft hole facing the force applicator cylinder.
2. The body is picked and rested on the guide fixture to mount it over the disc.
3. Once in position, the body is pushed over the disc until the liner rubber rests against the disc fixture and cannot be pushed any further.
4. Next, the bottom shaft is partly inserted in the bottom hole of the body, and the drive shaft is placed inside the shaft holding socket.
5. Once, all the components are in place; a push button actuates the EMC cylinder.
6. The EMC guides the drive shaft into the body. The drive shaft experiences resistance after encountering the linear bearing and the rubber covering it. This resistance and the driving force from the EMC cause the entire platform to slide over the guide rails.
7. The linear movement is obstructed when the bottom shaft support fixture hits the bottom shaft.
8. This support fixture counteracts the force applied by EMC. Thus, the drive shaft and bottom shaft are inserted simultaneously.
9. After the shafts are completely inserted, the EMC shaft retracts to its original position. The entire platform with the partly assembled body is moved back to its original position.
10. The disc fixture (with all the components) is rotated counterclockwise by 90°, and the plug & sealing ring is fastened, followed by fastening the anti-blowout plate.

11. The assembled body is then removed from the fixture and kept aside for testing.
12. Finally, the fixture is rotated and positioned in its original orientation. Thus, the setup is ready for assembling the next valve.

Figure. B-1: Placing the disc in the disc fixture with a hexagonal hole of the disc towards the force applicator cylinder.

Figure. B-2: Positioning the body over the disc fixture to check and adjust the alignment of the shaft holes with respect to the disc.

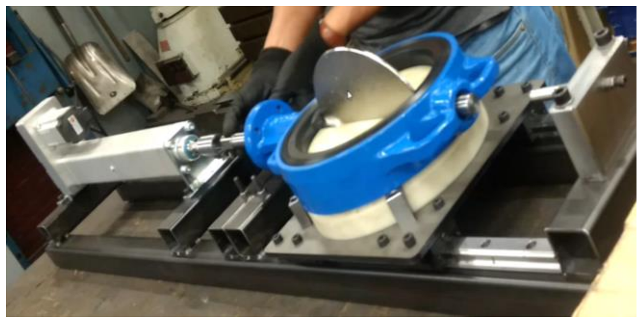


Figure. B-3: Bottom shaft partially placed inside the shaft hole followed by the placement of the drive shaft (in this case it was manually placed inside the drive shaft hole and not in the shaft socket adaptor).

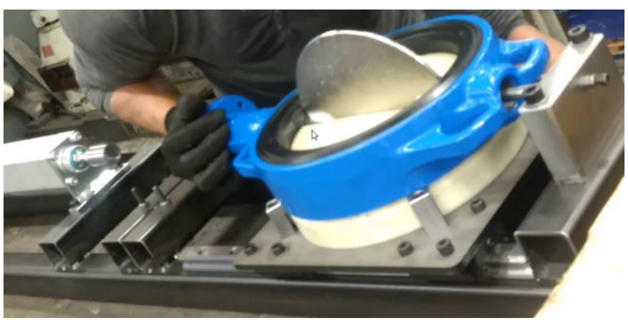


Figure. B-4: Imitation of the force applicator unit to apply the driving force to insert the drive shaft and the bottom shaft simultaneously.

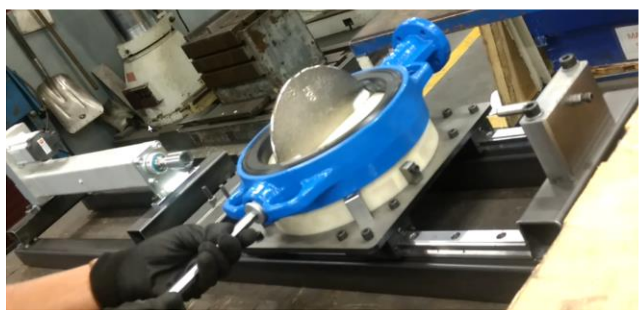
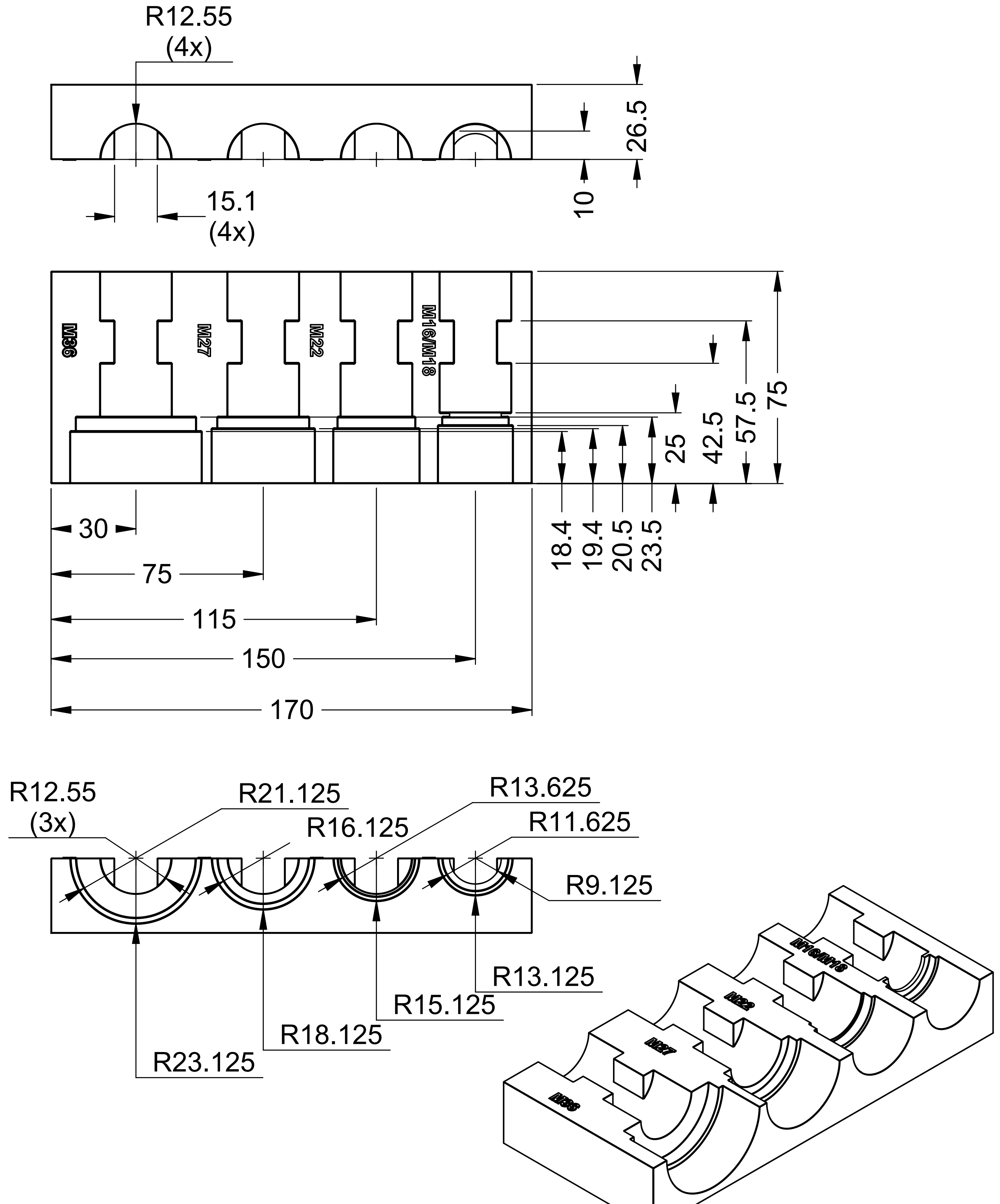


Figure. B-5: The partially assembled body along with the disc fixture is rotated by 90°, followed by fastening of the threaded plug

TECHNICAL DRAWING

Part-A

L: Technical Drawings



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
Nylon PA-12	0.07 KG		√	

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

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DATE : 14-09-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP503-P&R-AS-01-01-01-02-Plug-ring & tool bit fixture

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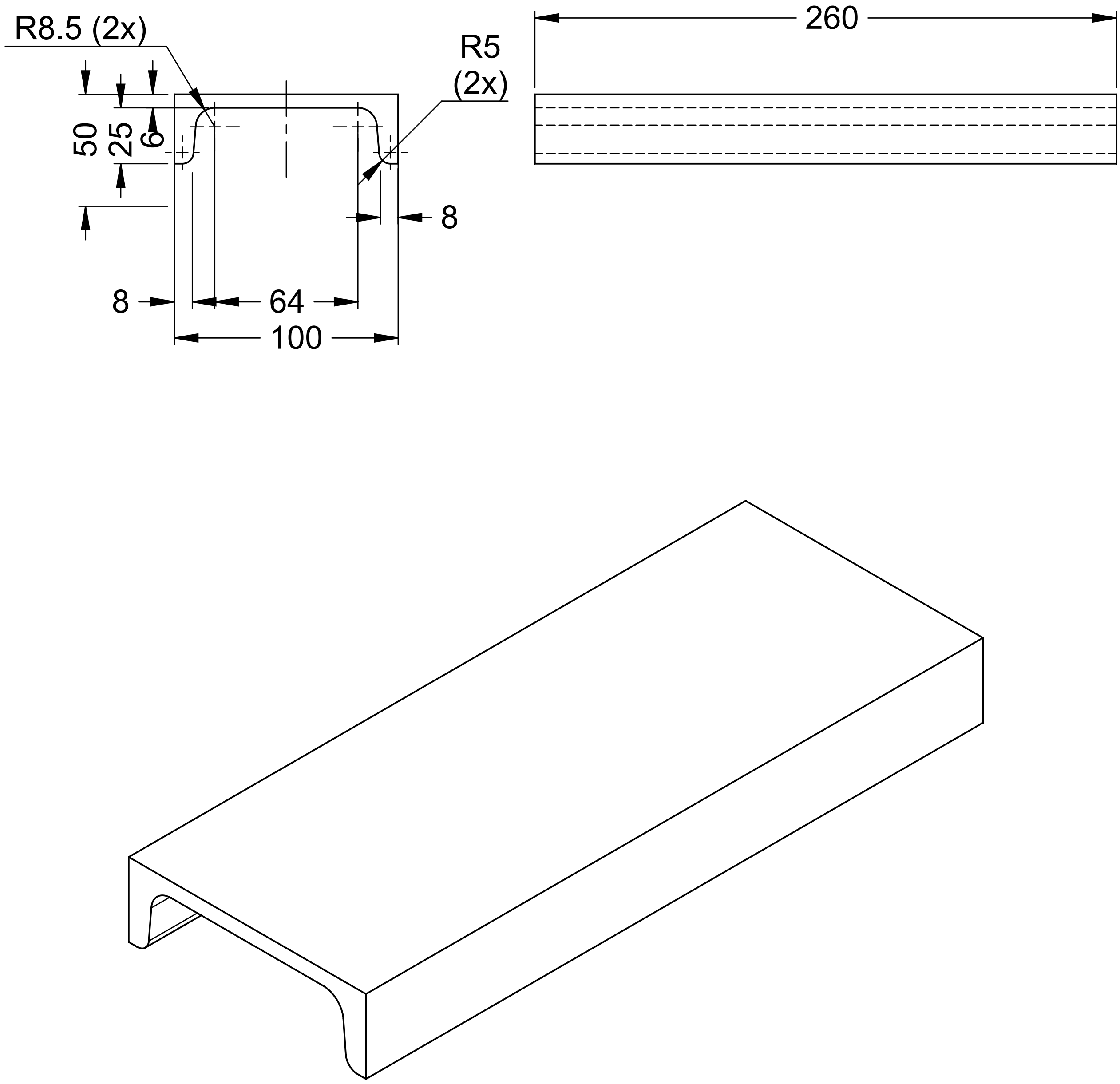

REMOVE SHARP EDGES

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1.0038 (S235 JR G2)	1.5 KG		

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

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DRAWN : Amit S Desai
APPROV:

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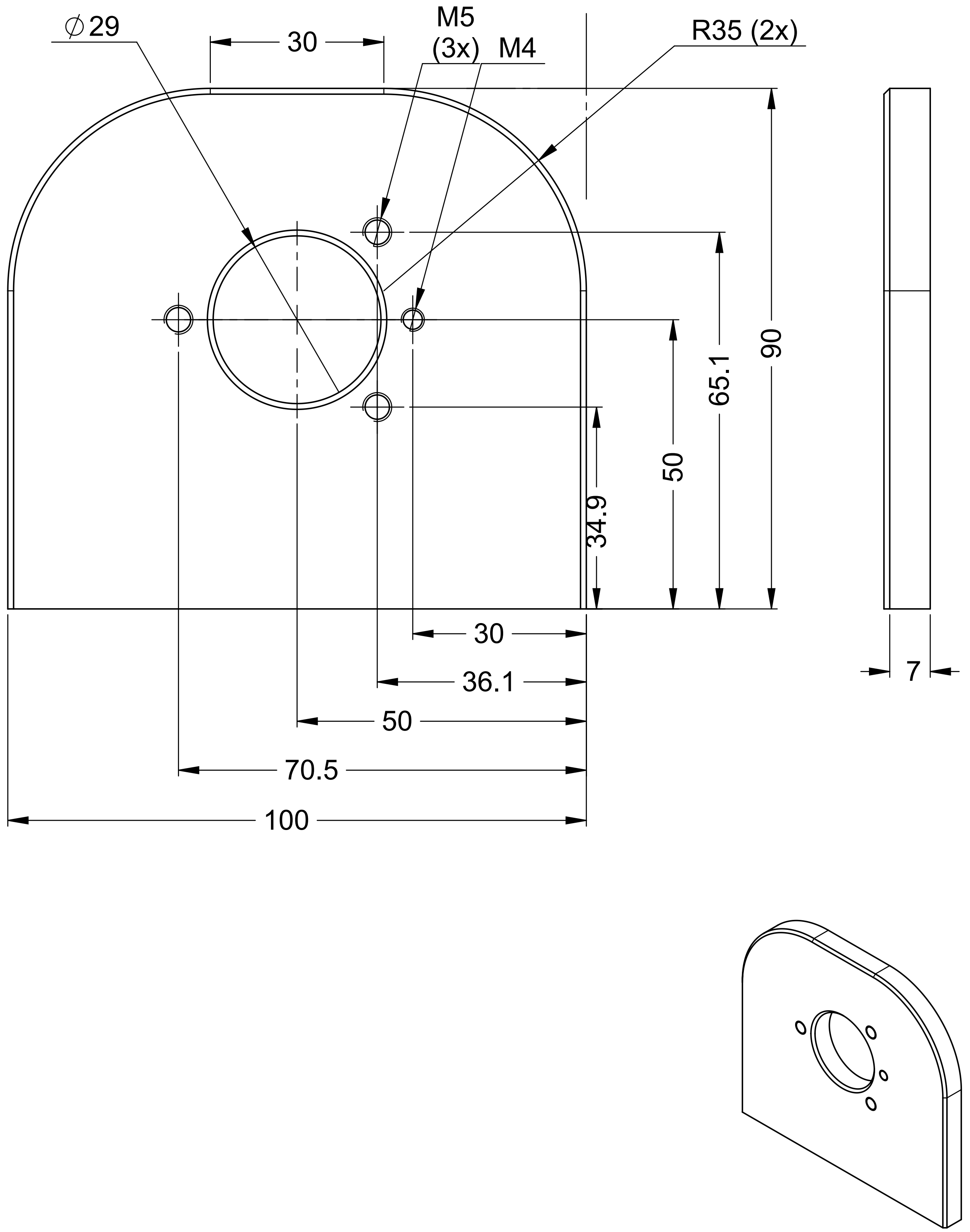

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DRAWN : Amit S Desai
APPROV:

TITLE: WP503-P&R-AS-01-09-02-02-Fixture plate-2

WOUTER WITZEL VALVE TECHNOLOGY

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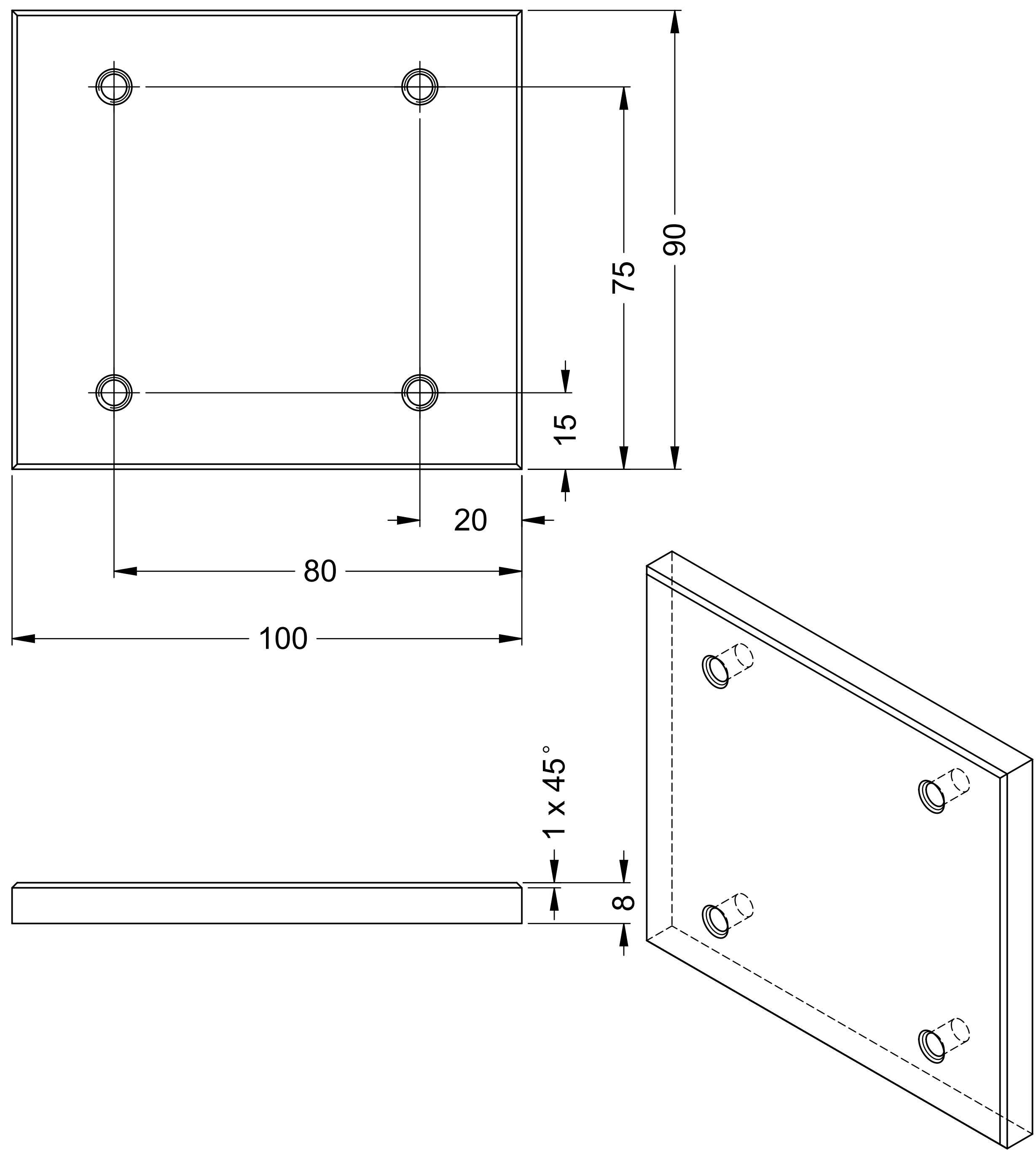
SIZE: A4



± MASS	ISO 128 - A	ISO 1302 Ra (μm)
0.55 KG		√

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

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SCALE : 1:1.25
DATE : 4-12-2018
DRAWN : Amit Desai
APPROV:

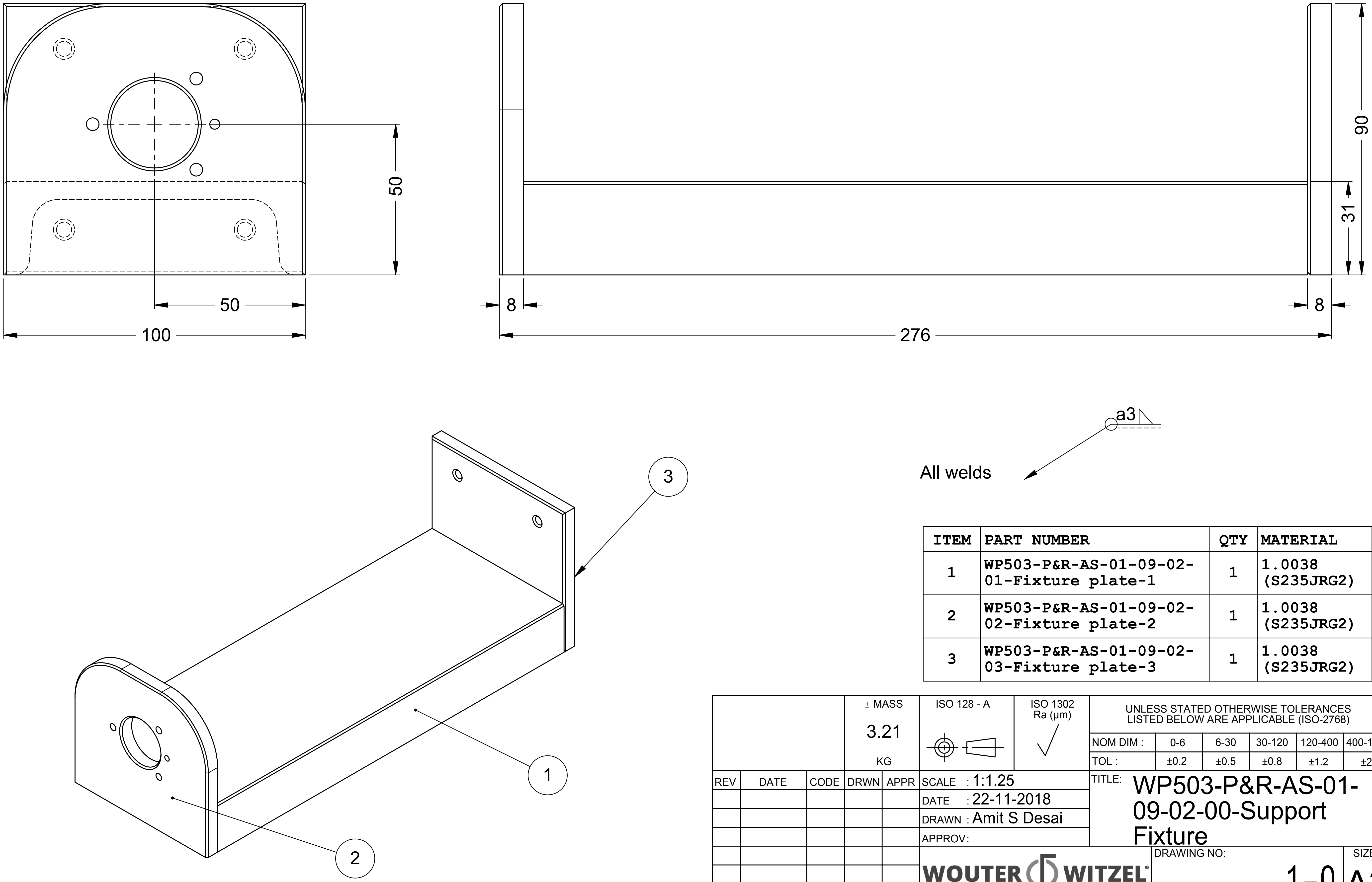
TITLE: WP503-P&R-AS-01-09-02-03-Fixture plate-3

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4

12/4/2018



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3	WP503-P&R-AS-01-09-02-03-Fixture plate-3	1	1.0038 (S235JRG2)

± MASS 3.21 KG

ISO 128 - A

ISO 1302 Ra (µm)

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

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SCALE : 1:1.25

DATE : 22-11-2018

DRAWN : Amit S Desai

APPROV:

TITLE: WP503-P&R-AS-01-09-02-00-Support Fixture

WOUTER WITZEL VALVE TECHNOLOGY

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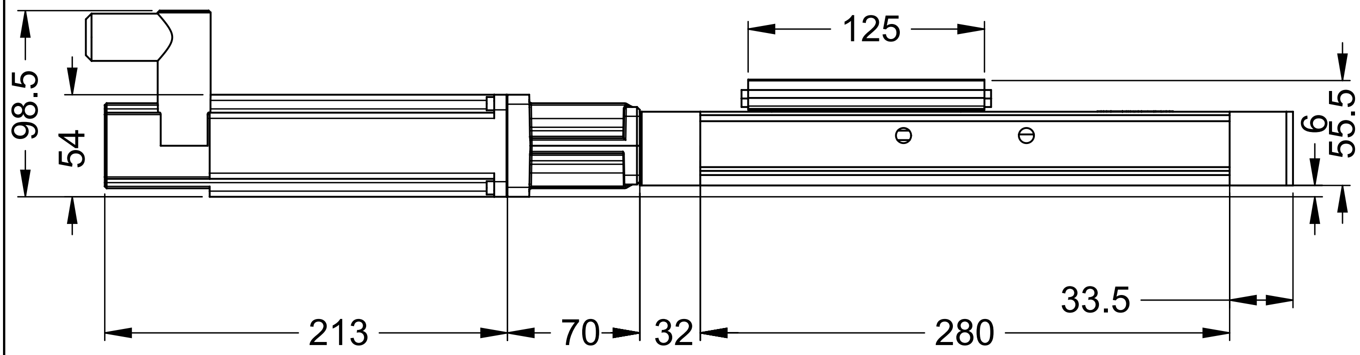

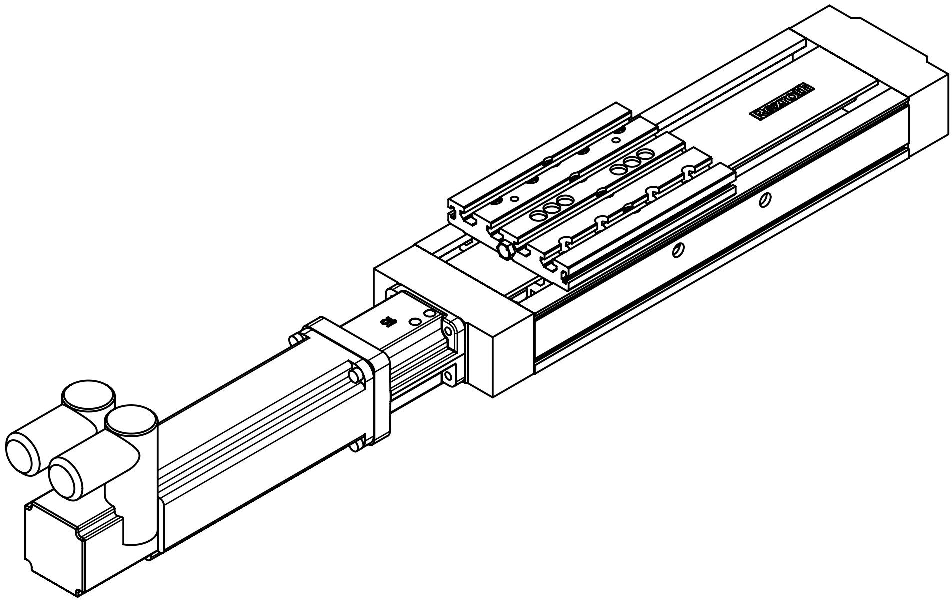

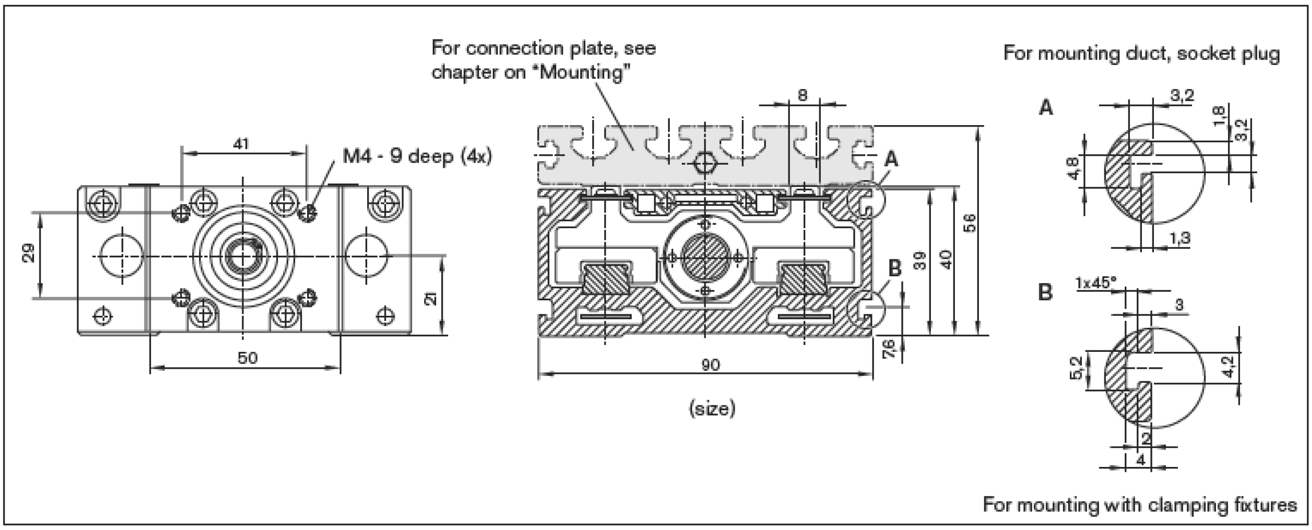

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6 KG			

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DATE : 30-09-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP503-P&R-AS-01-03-01-00-LINEAR MODULE-Z-Stroke 150mm

WOUTER WITZEL VALVE TECHNOLOGY

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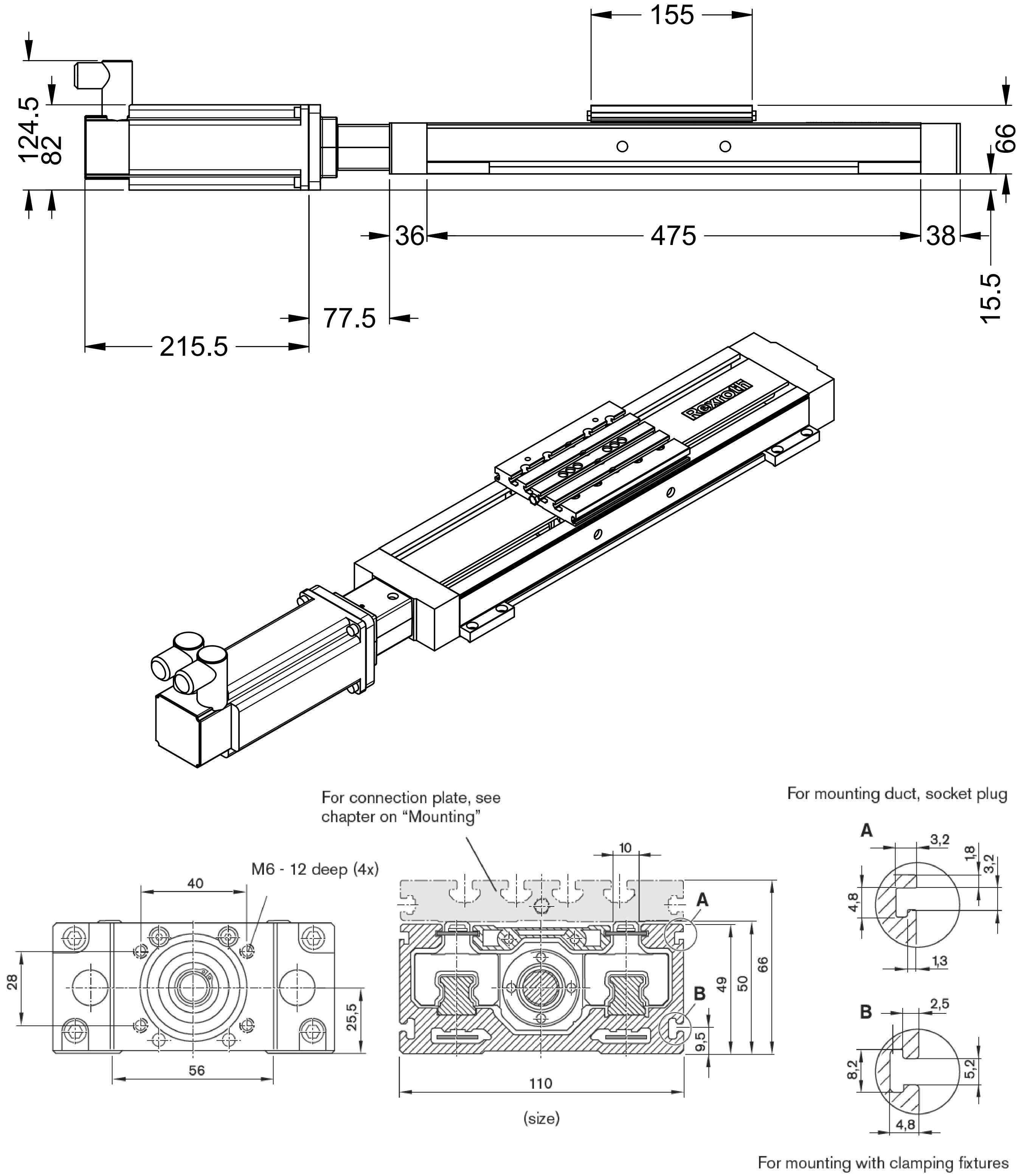

REMOVE SHARP EDGES

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					DATE : 30-09-2018
					DRAWN : Amit S Desai
					APPROV:

TITLE: WP503-P&R-AS-01-03-02-00-LINEAR MODULE-X-Stroke-300mm

WOUTER WITZEL VALVE TECHNOLOGY

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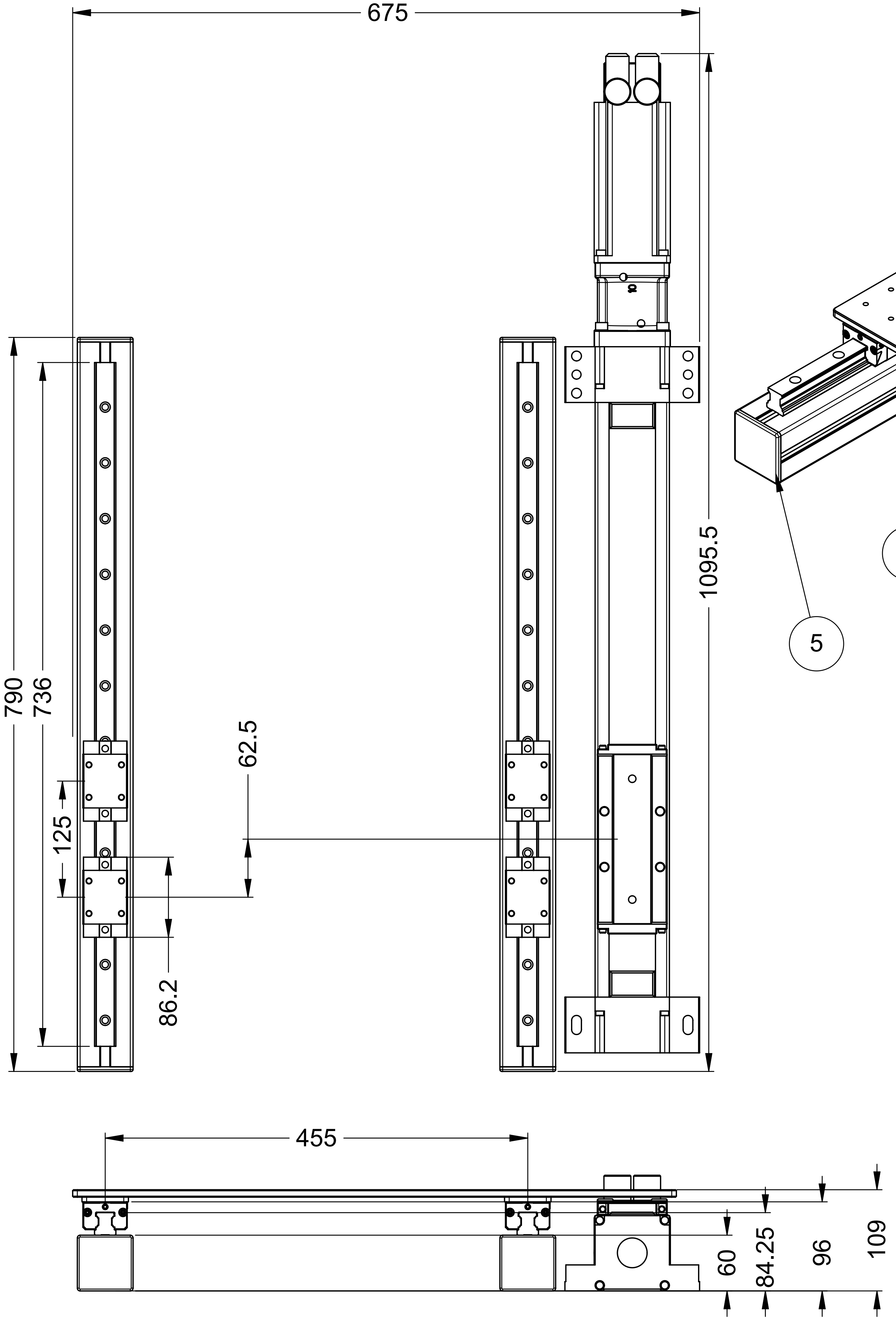

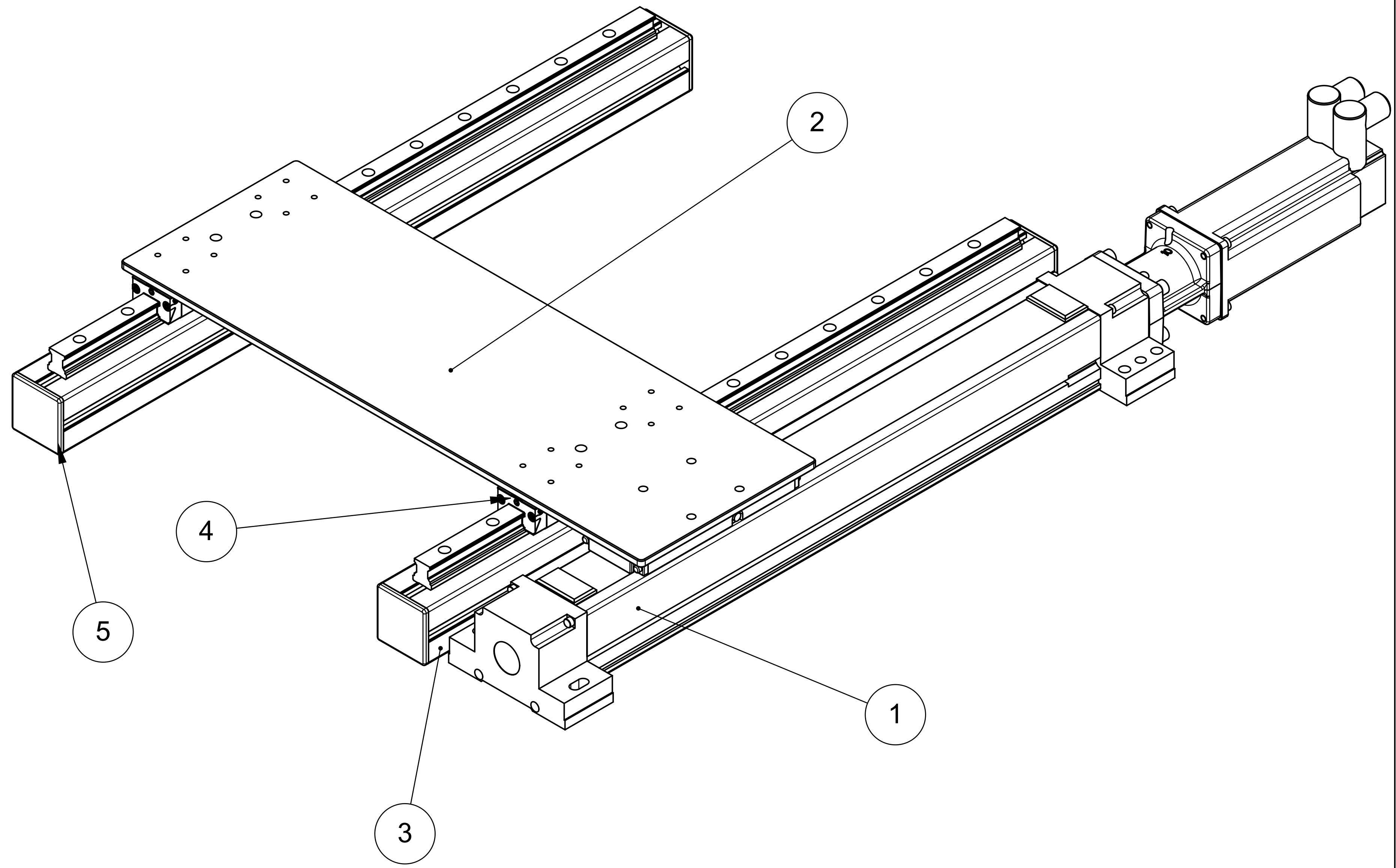

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3	2	WP503-P&R-AS-01-03-03-02-STRUT_PROFILE_60X60-1000mm
4	2	Y-MODULE-02-00-Guide rail and Runner Block
5	4	60X60

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
	20 KG		√	

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

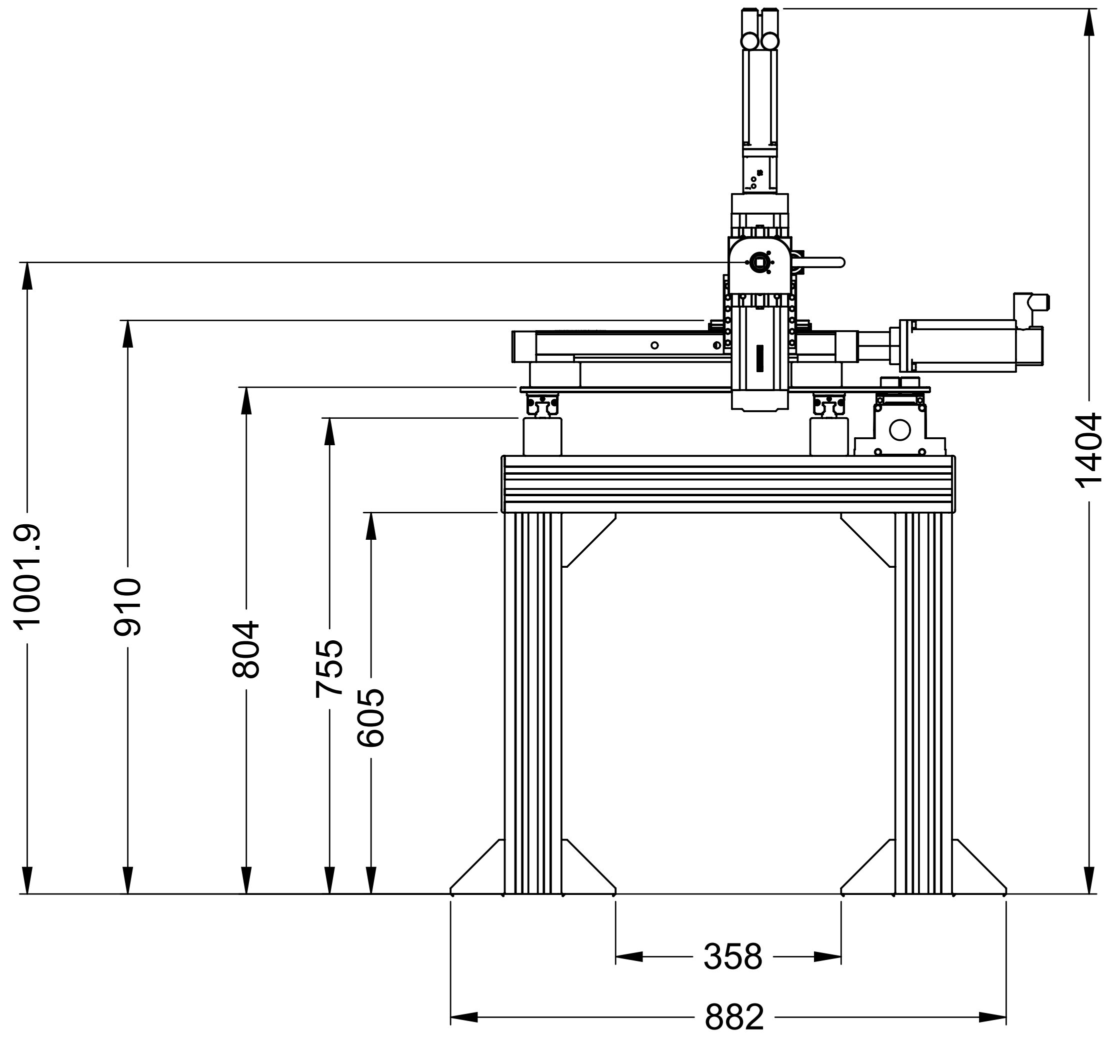
SCALE : 1:5.5
DATE : 30-09-2018
DRAWN : Amit S Desai
APPROV:

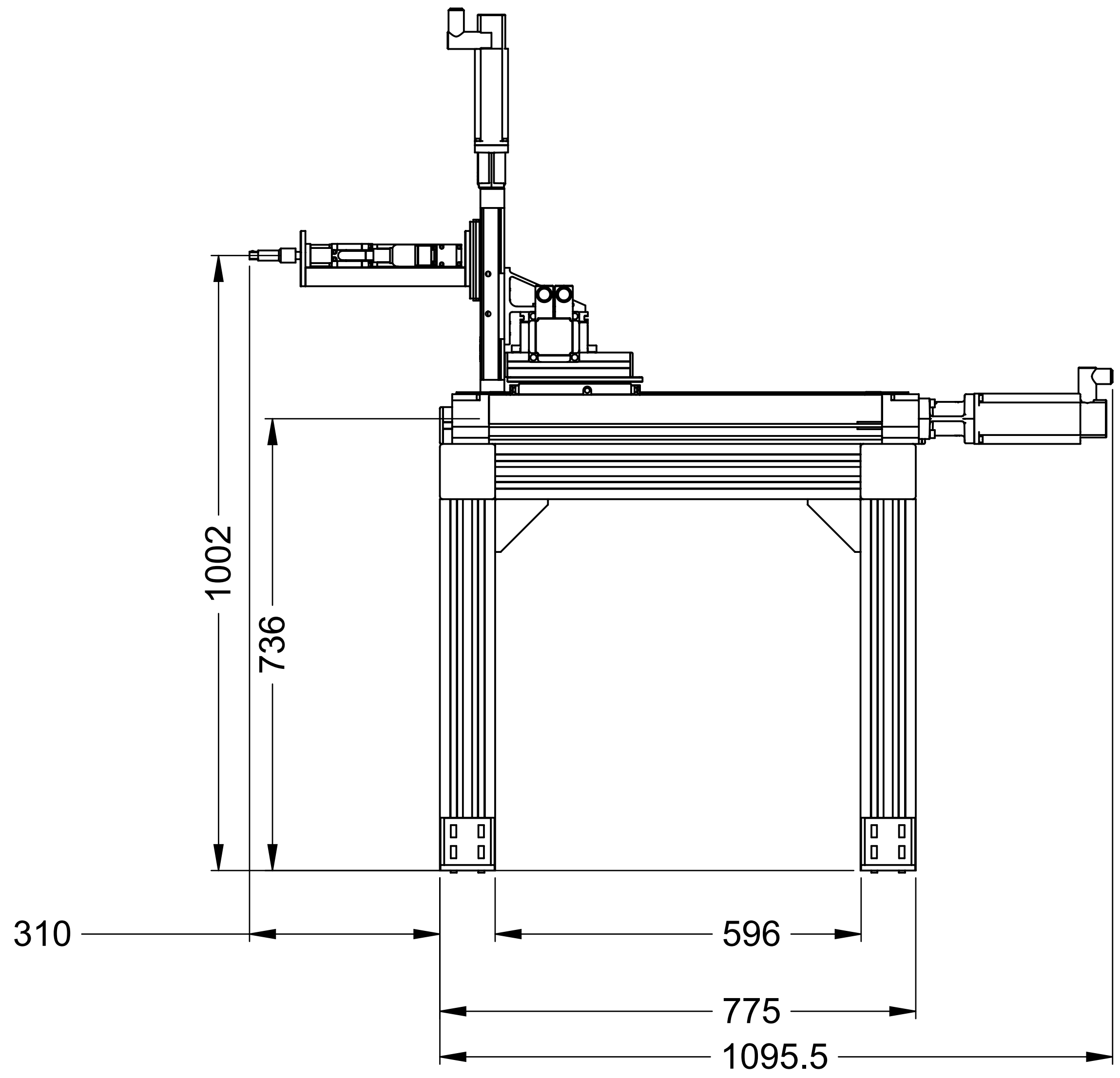
TITLE: WP503-P&R-AS-01-03-03-00-LINEAR MODULE-Y

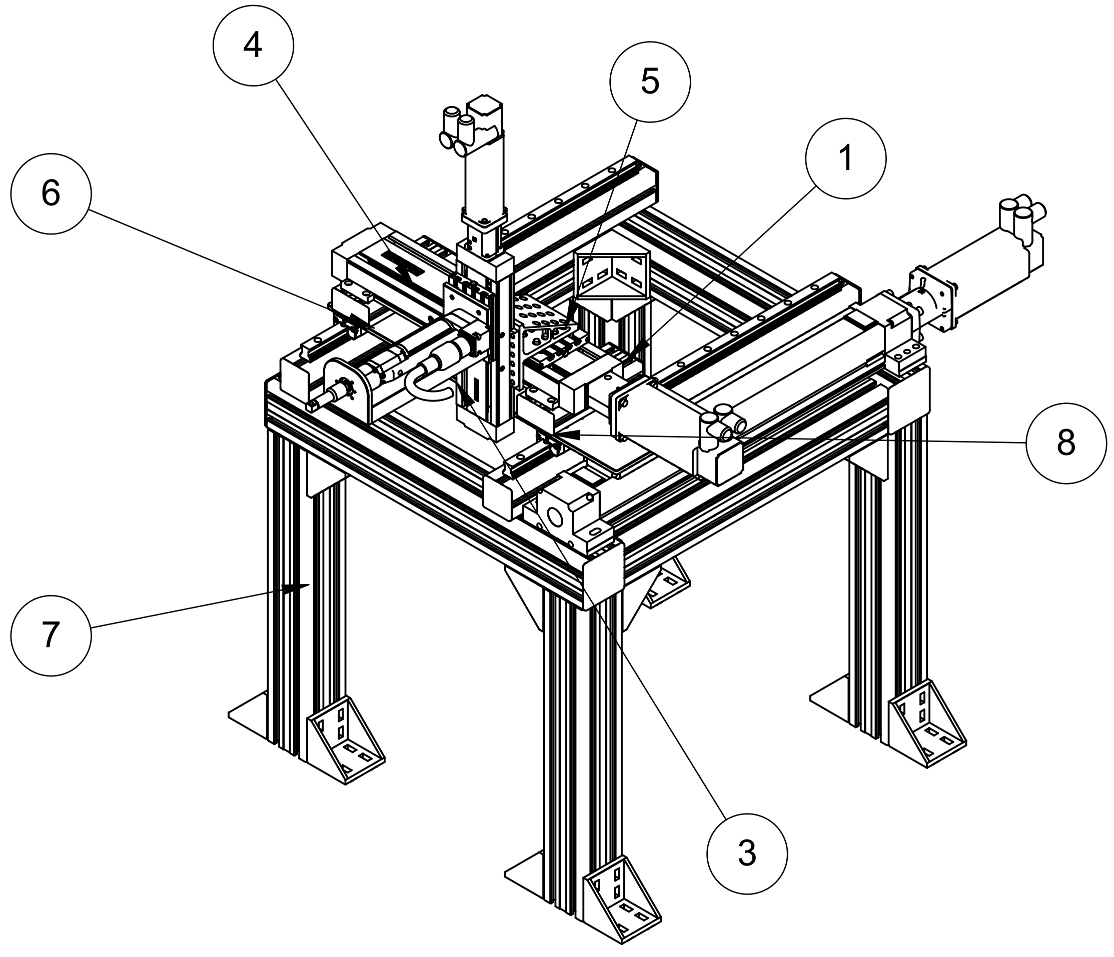
WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A3







ITEM	QTY	PART NUMBER
1	2	WP503-P&R-AS-01-03-06-STRUT_PROFILE_40X80L-200mm
2	1	WP503-P&R-AS-01-09-00-NutRunner & Fixture
3	1	WP503-P&R-AS-01-03-01-00-LINEAR MODULE-Z-Stroke 150mm
4	1	WP503-P&R-AS-01-03-02-00-LINEAR MODULE-X-Stroke-300mm
5	1	WP503-P&R-AS-01-03-02-01-00-CONNECTOR Z Module to X-Module
6	1	WP503-P&R-AS-01-03-03-00-LINEAR MODULE-Y
7	1	WP503-P&R-AS-01-03-04-00-Support_ Base Stand
8	4	WP503-P&R-AS-01-03-07-Cover_40X80

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
	KG		

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

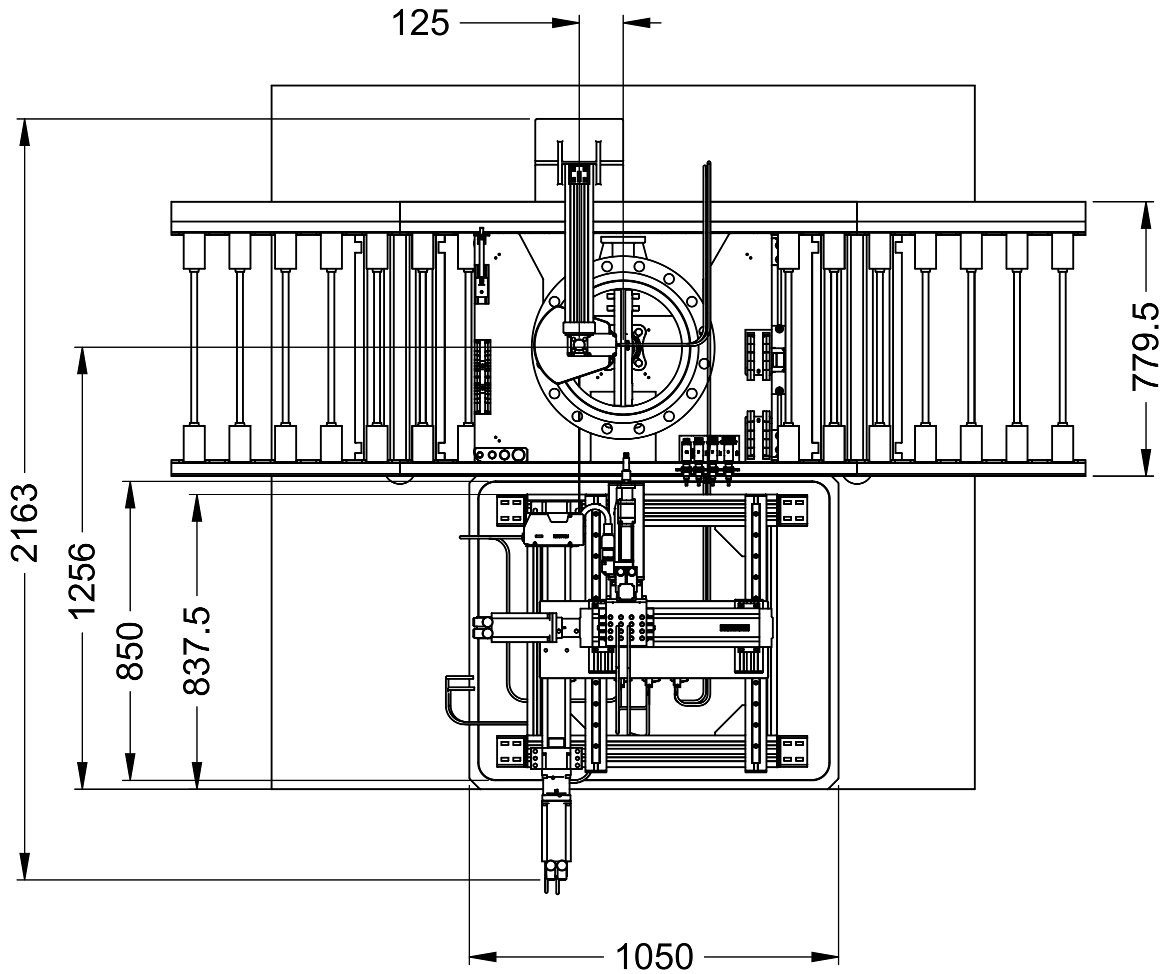
SCALE : 1:12
DATE : 14-09-2018
DRAWN : Amit S Desai
APPROV:

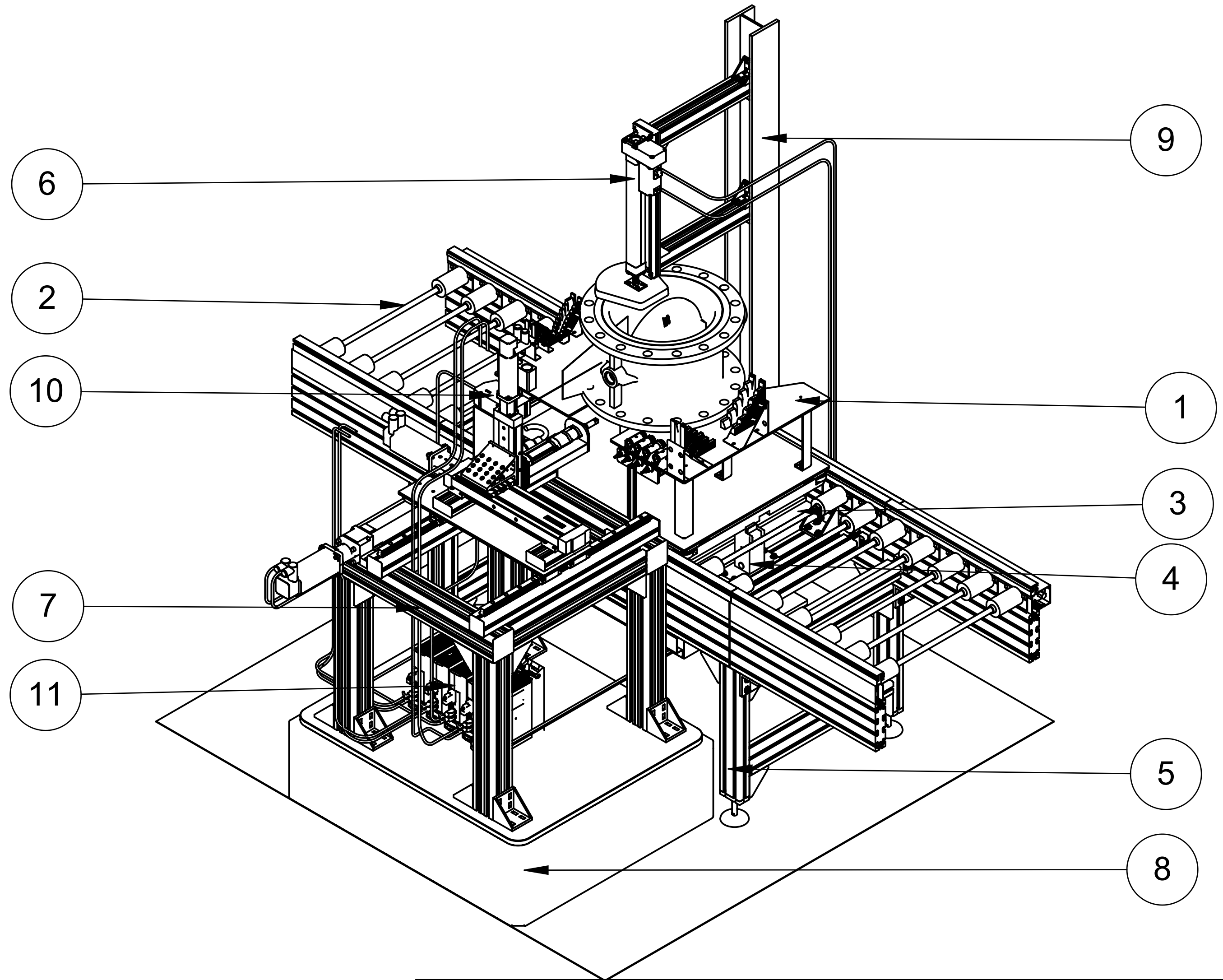
TITLE: Cartesian System

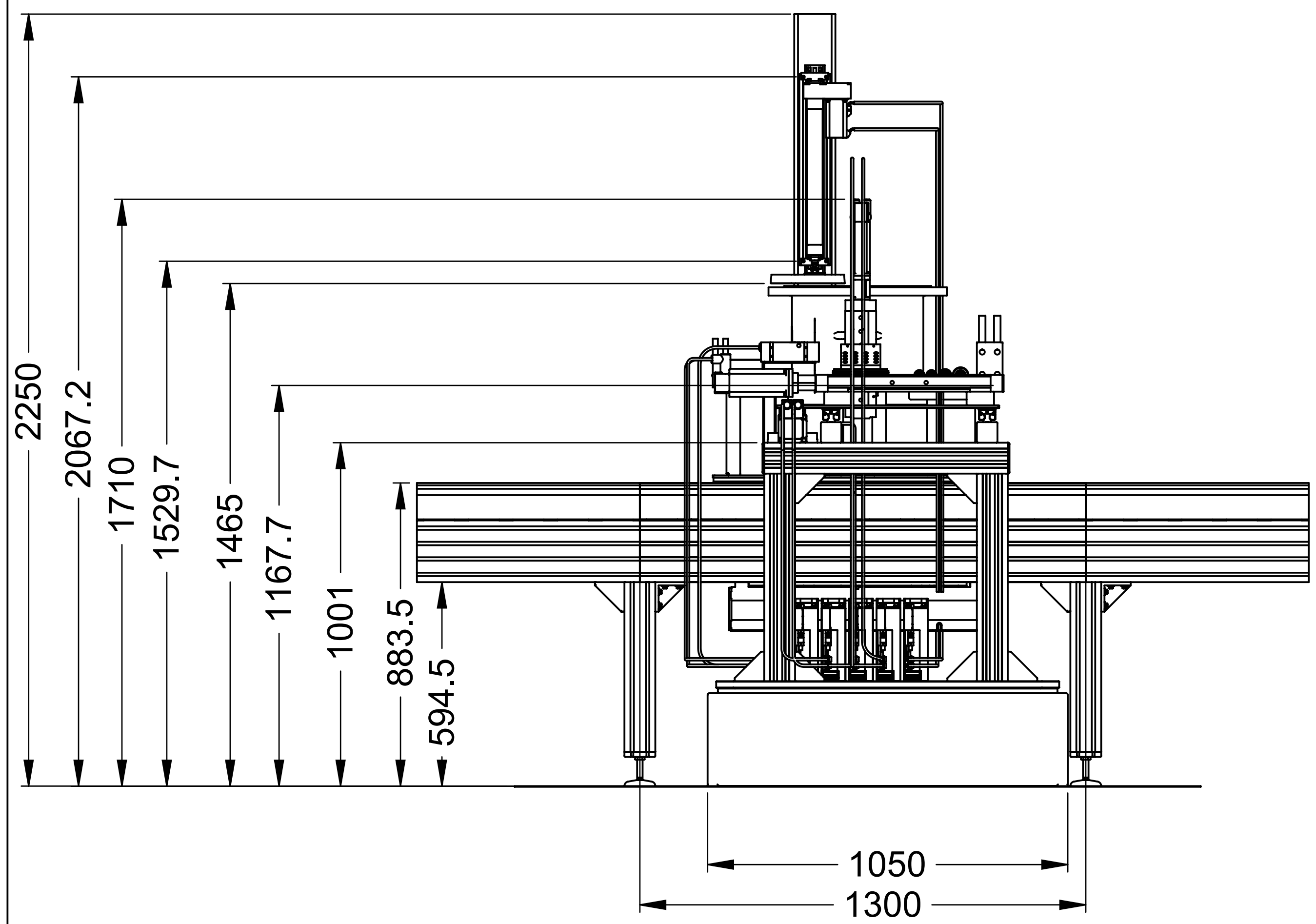
WOUTER WITZEL® VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A3







BOM Table		
ITEM	QTY	PART NUMBER
1	1	WP503-P&R-AS-01-01-00-PRODUCT CARRIER
2	4	WP503-P&R-AS-01-02-00-CONVEYOR SYSTEM
3	1	WP503-P&R-AS-01-05-00-POSITIONING_UNIT
4	1	WP503-P&R-AS-01-06-00-STOP GATE
5	2	WP503-P&R-AS-01-07-00-SUPPORT LEGS
6	1	WP503-P&R-AS-01-04-00-COUNTER TORQUE MECHANISM
7	1	WP503-P&R-AS-01-03-00-CARTESIAN SYSTEM
8	1	WP503-P&R-AS-01-11- Base Platform
9	1	WP503-P&R-AS-01-10-Support Pillars
10	1	WP503-P&R-AS-01-08-00-2D SENSOR
11	5	WP503-P&R-AS-01-10-00-CONTROL UNIT

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (μm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
	KG			

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:21.5
DATE : 17-09-2018
DRAWN : Amit S Desai
APPROV:

TITLE: Plug & Sealing Ring assembly station

WOUTER WITZEL VALVE TECHNOLOGY

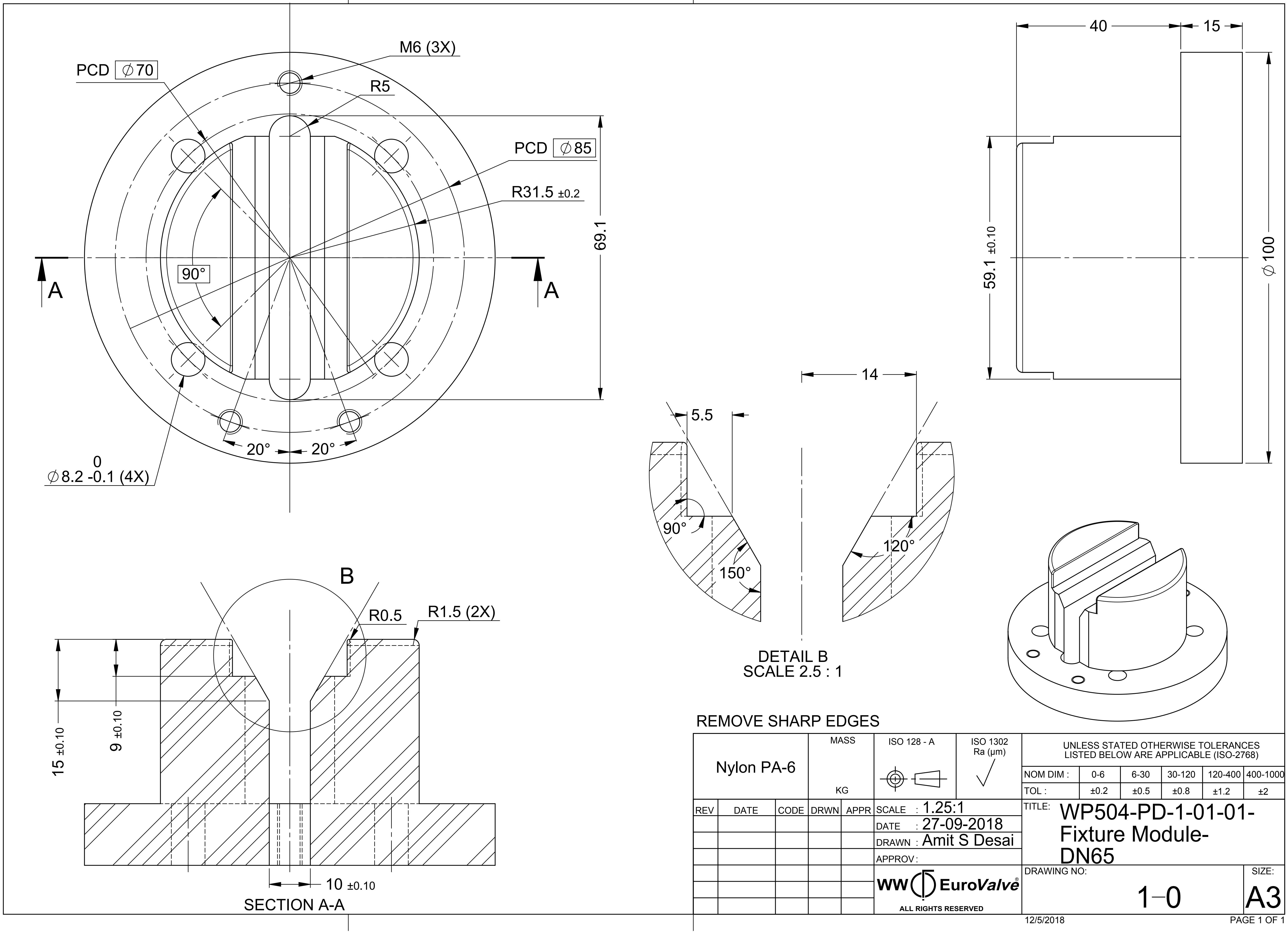
DRAWING NO: 1-0

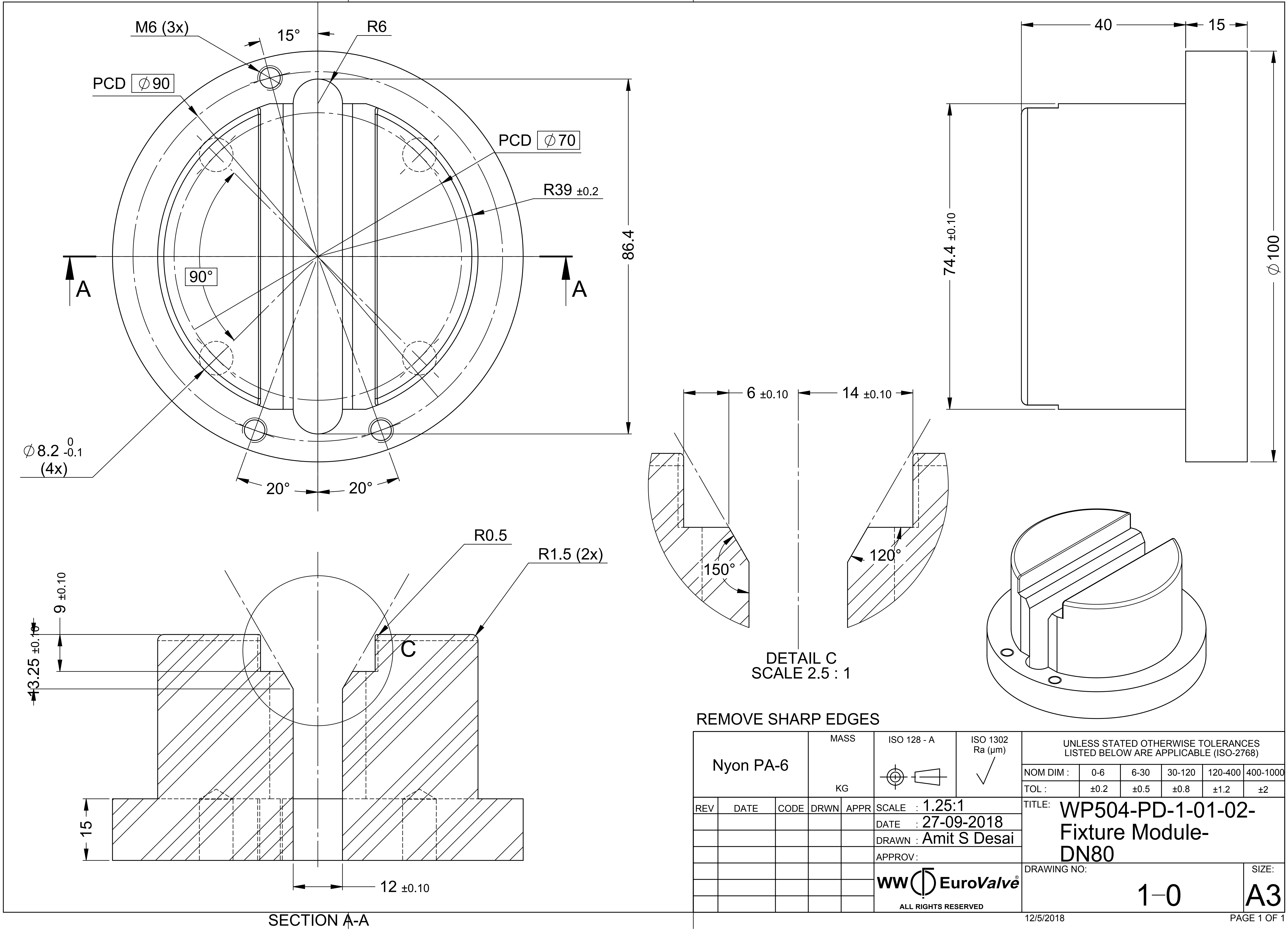
SIZE: A3

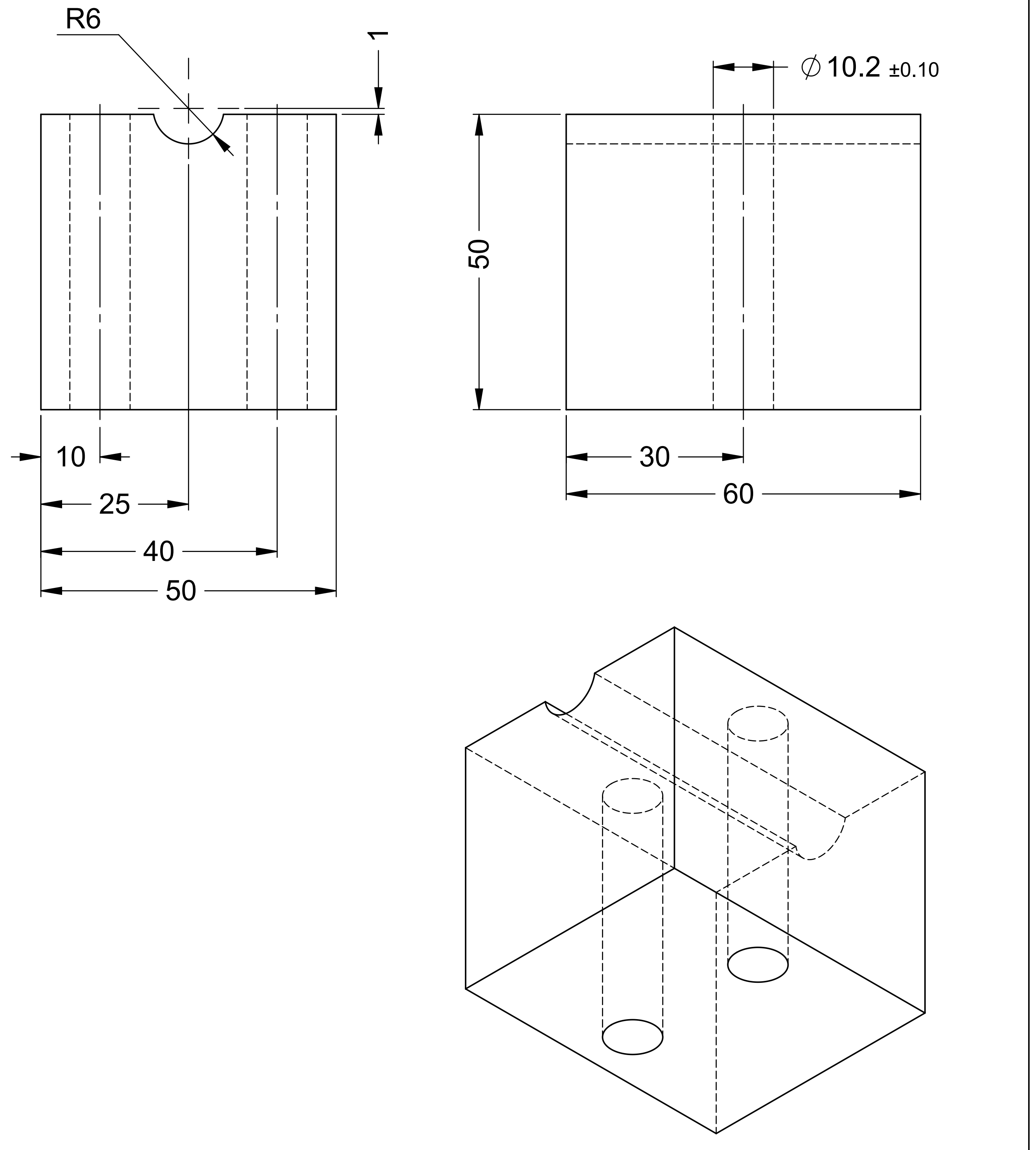
TECHNICAL DRAWING

Part-B

Prototype-I


M6 (3X)
PCD ∅70
R5
PCD ∅85
R31.5 ±0.2
69.1
90°
A
A
20°
20°
0
∅8.2 -0.1 (4X)
40
15
59.1 ±0.10
∅100
14
5.5
90°
150°
120°
DETAIL B
SCALE 2.5 : 1
B
R0.5
R1.5 (2X)
15 ±0.10
9 ±0.10
10 ±0.10
SECTION A-A
REMOVE SHARP EDGES
Nylon PA-6
MASS
KG
ISO 128 - A
ISO 1302
Ra (µm)
UNLESS STATED OTHERWISE TOLERANCES
LISTED BELOW ARE APPLICABLE (ISO-2768)
NOM DIM : 0-6 6-30 30-120 120-400 400-1000
TOL : ±0.2 ±0.5 ±0.8 ±1.2 ±2
REV DATE CODE DRWN APPR
SCALE : 1.25:1
DATE : 27-09-2018
DRAWN : Amit S Desai
APPROV :
TITLE: WP504-PD-1-01-01-
Fixture Module-
DN65
DRAWING NO:
1-0
SIZE:
A3
WW EuroValve
ALL RIGHTS RESERVED
12/5/2018
PAGE 1 OF 1


M6 (3x)
15°
R6
PCD ∅90
PCD ∅70
R39 ±0.2
86.4
90°
A
A
∅8.2 0 -0.1
(4x)
20°
20°
40
15
74.4 ±0.10
∅100
6 ±0.10
14 ±0.10
150°
120°
DETAIL C
SCALE 2.5 : 1
R0.5
R1.5 (2x)
9 ±0.10
13.25 ±0.10
C
15
12 ±0.10
SECTION A-A
REMOVE SHARP EDGES
Nyon PA-6
MASS
KG
ISO 128 - A
ISO 1302
Ra (µm)
UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
NOM DIM : 0-6 6-30 30-120 120-400 400-1000
TOL : ±0.2 ±0.5 ±0.8 ±1.2 ±2
REV DATE CODE DRWN APPR
SCALE : 1.25:1
DATE : 27-09-2018
DRAWN : Amit S Desai
APPROV :
TITLE: WP504-PD-1-01-02-Fixture Module-DN80
DRAWING NO: 1-0
SIZE: A3
WW EuroValve
ALL RIGHTS RESERVED
12/5/2018
PAGE 1 OF 1



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
S235 J2G3	KG			NOM DIM :	0-6	6-30	30-120	120-400	400-1000
				TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:1

DATE : 01-10-2018

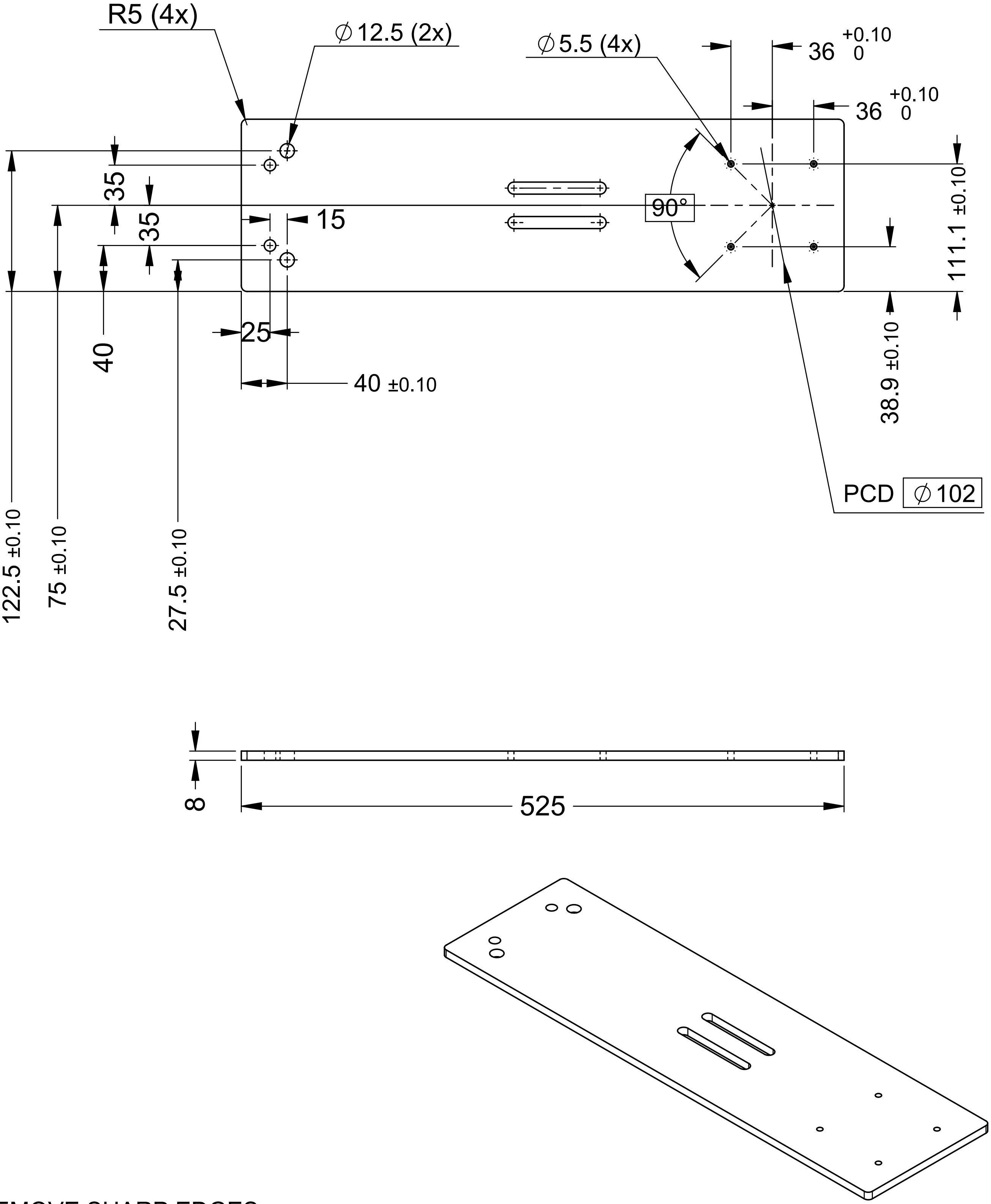
DRAWN : Amit S Desai

APPROV:

TITLE: WP504-PD-1-01-03-Shaft Fixture

DRAWING NO: 1–0

SIZE: A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
1.0038 SR235JRG2	4.77 KG		

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

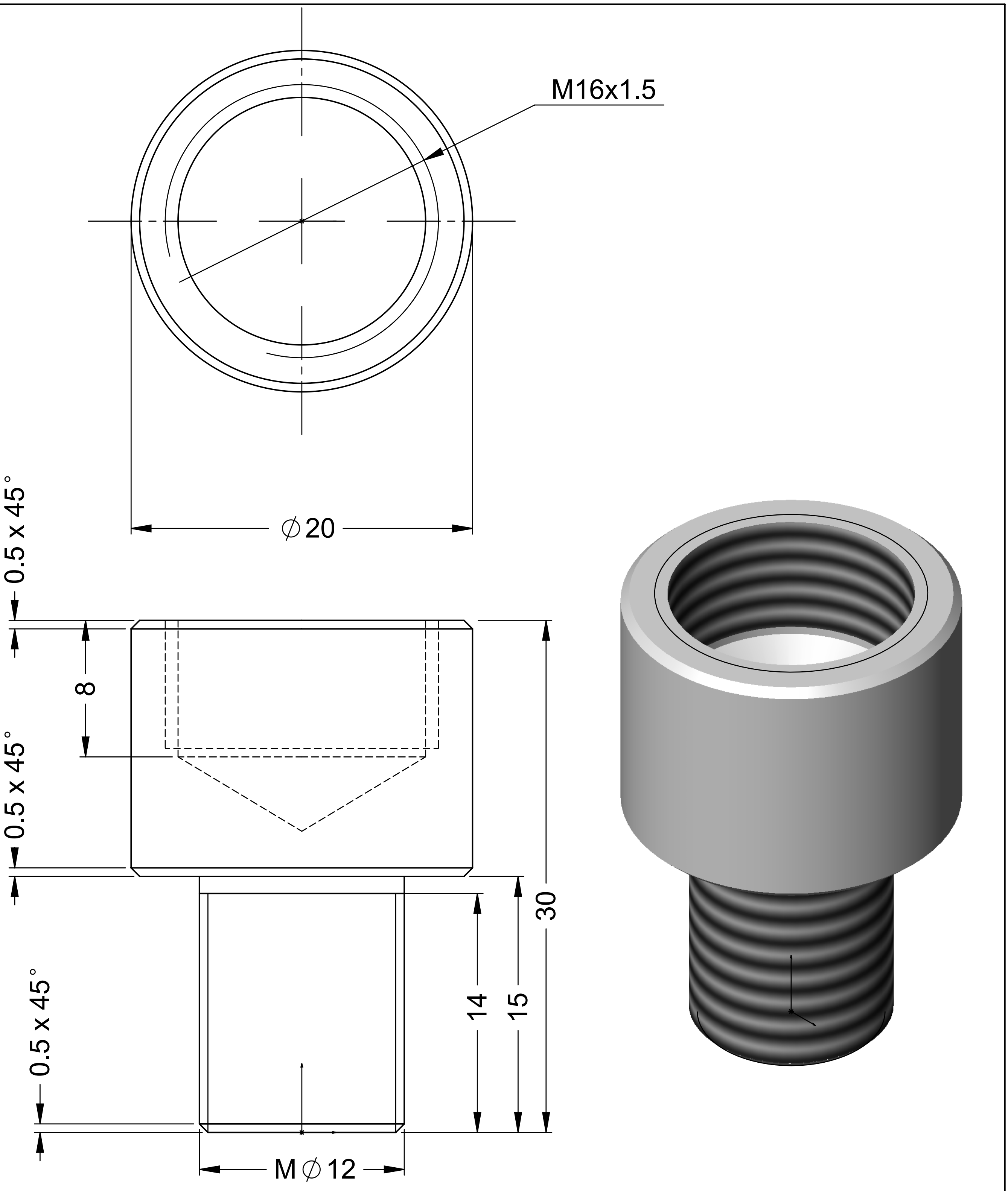
REV	DATE	CODE	DRWN	APPR
1	16-10-2018		Amit D	

SCALE : 1:5
DATE : 01-10-2018
DRAWN : Amit S Desai
APPROV :

TITLE: WP504-PD-1-01-04- Base Platform

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO:	SIZE:
1–1	A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
1.0038 (S235JRG2)	0.04 KG		√	NOM DIM :	0-6	6-30	30-120	120-400	400-1000
				TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 3:1

DATE : 03-10-2018

DRAWN : Amit S Desai

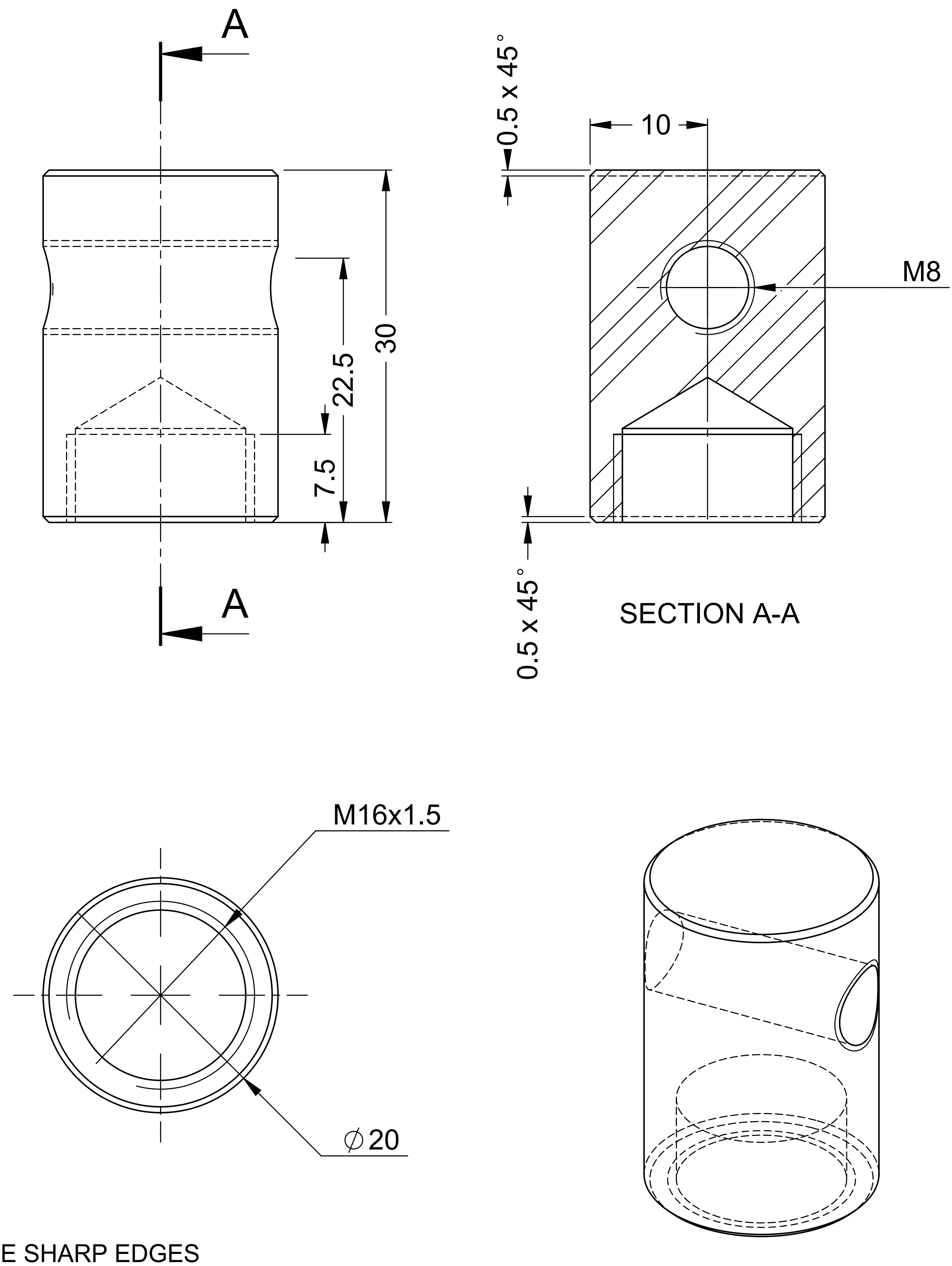
APPROV:

TITLE: WP504-PD-1-01-08-Connector Unit-Sensor & Drive

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
1.0038 (S235JRG2)	0.06 KG		√	

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

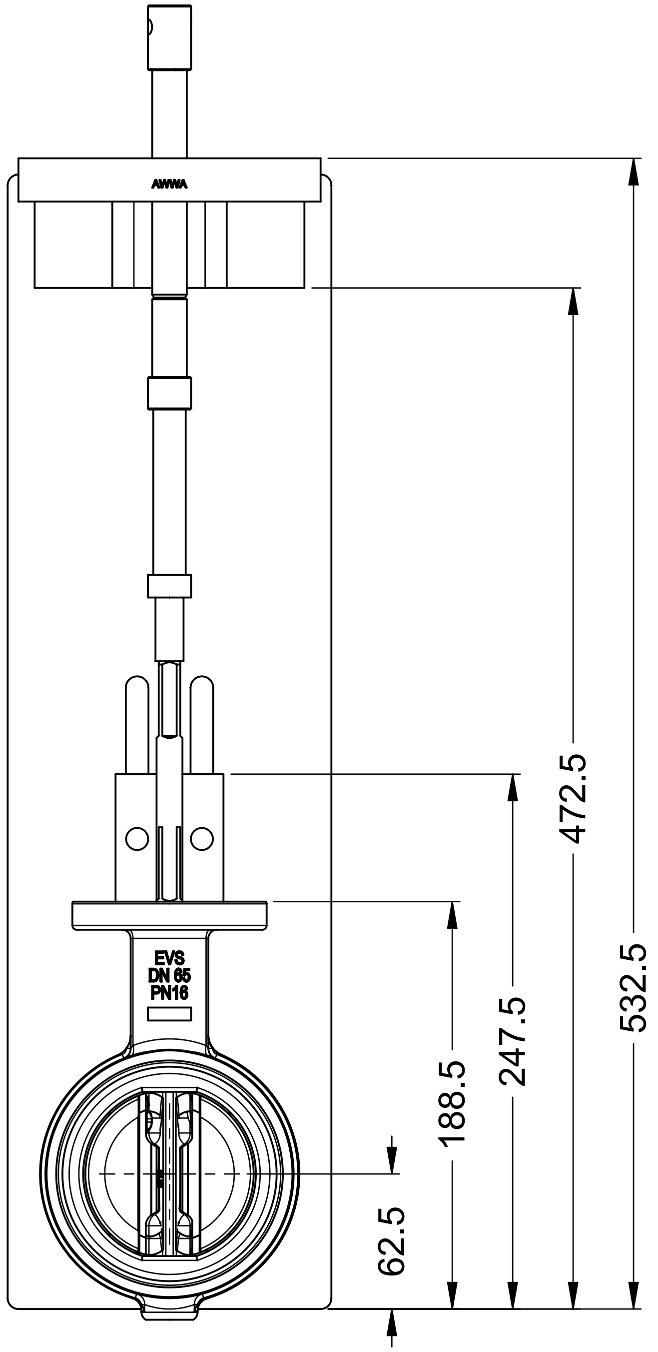
SCALE : 2:1
DATE : 03-10-2018
DRAWN : Amit S Desai
APPROV:

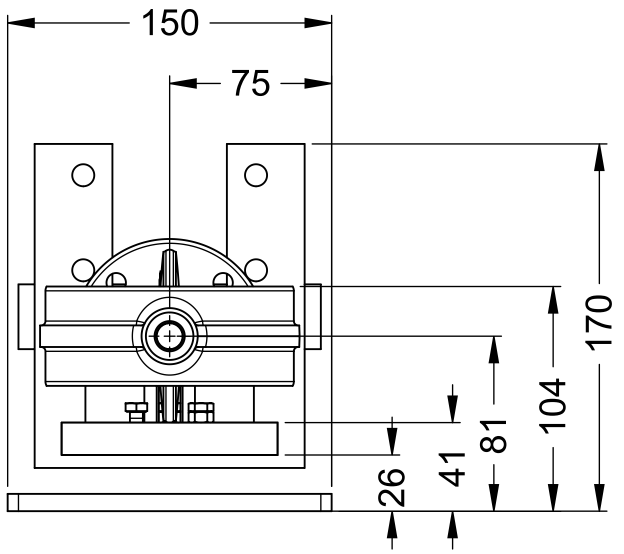
TITLE: WP504-PD-1-01-09-Drive Screw Handle

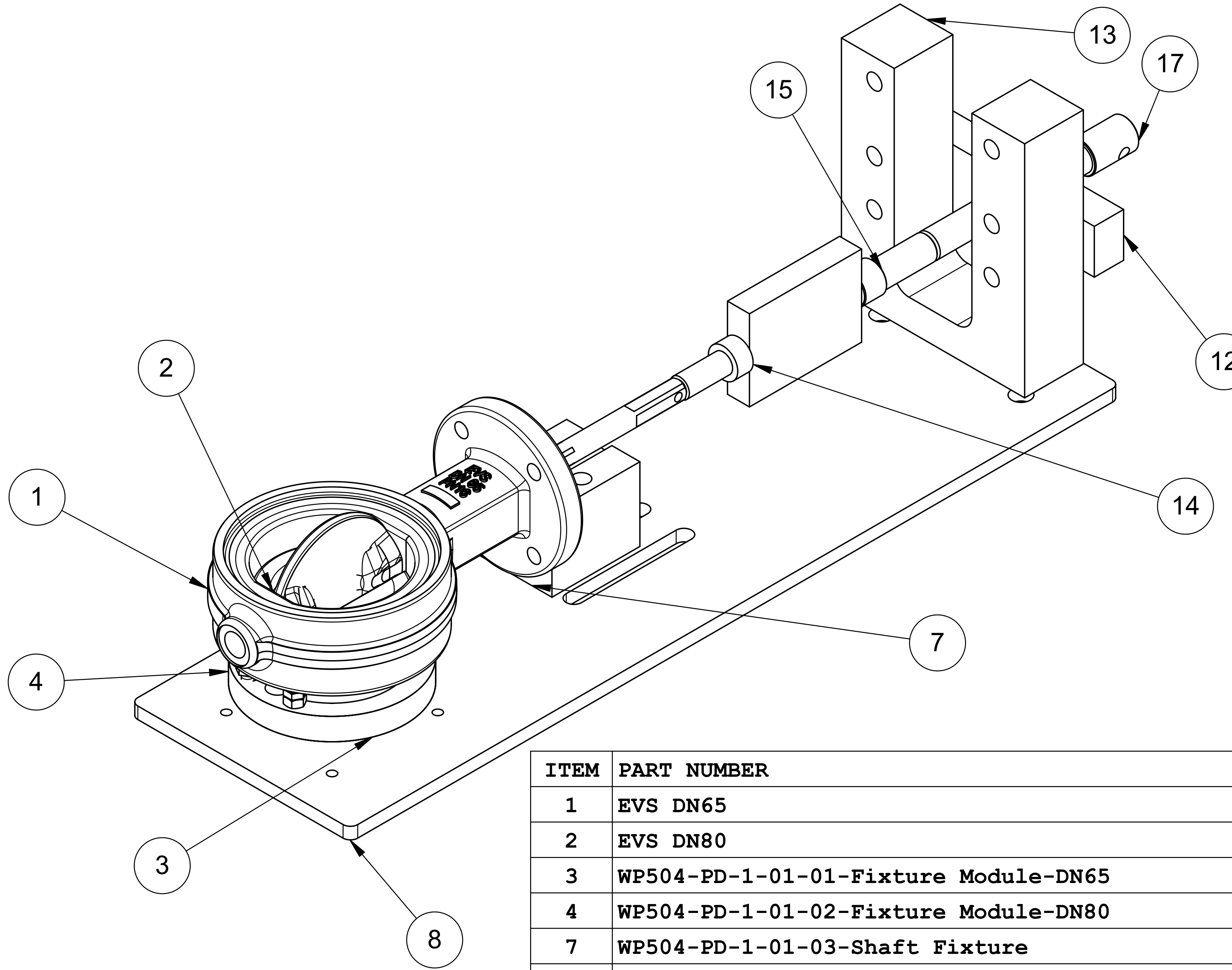
WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4







ITEM	PART NUMBER	QTY
1	EVS DN65	1
2	EVS DN80	1
3	WP504-PD-1-01-01-Fixture Module-DN65	1
4	WP504-PD-1-01-02-Fixture Module-DN80	1
7	WP504-PD-1-01-03-Shaft Fixture	1
8	WP504-PD-1-01-04-Base Platform	1
12	WP504-PD-1-01-07-Screw Support plate-On Fork	1
13	WP504-PD-1-01-06-Support Fork	1
14	WP504-PD-1-01-05-Sensor model	1
15	WP504-PD-1-01-08-Connector Unit-Sensor & Drive	1
17	WP504-PD-1-01-09-Drive Screw Handle	1

± MASS 14.13 KG

ISO 128 - A

ISO 1302 Ra (µm)

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:3.5

DATE : 15-10-2018

DRAWN : Amit Desai

APPROV:

TITLE: WP504-PD-1-01-00-Concept Validation Test Prototype

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A3

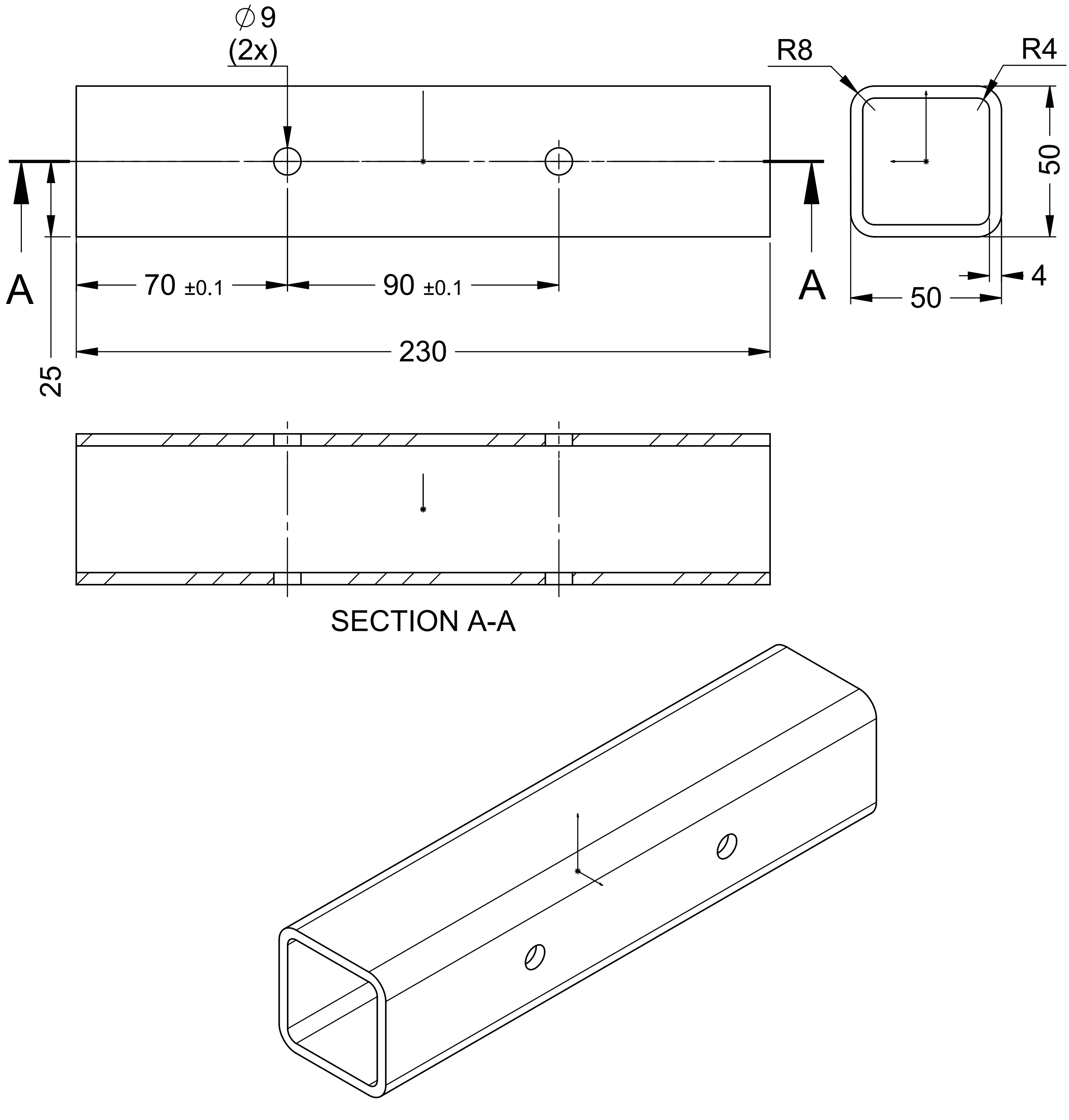
12/5/2018

PAGE 1 OF 1

TECHNICAL DRAWING-

Part-B

Prototype-II



REMOVE SHARP EDGES

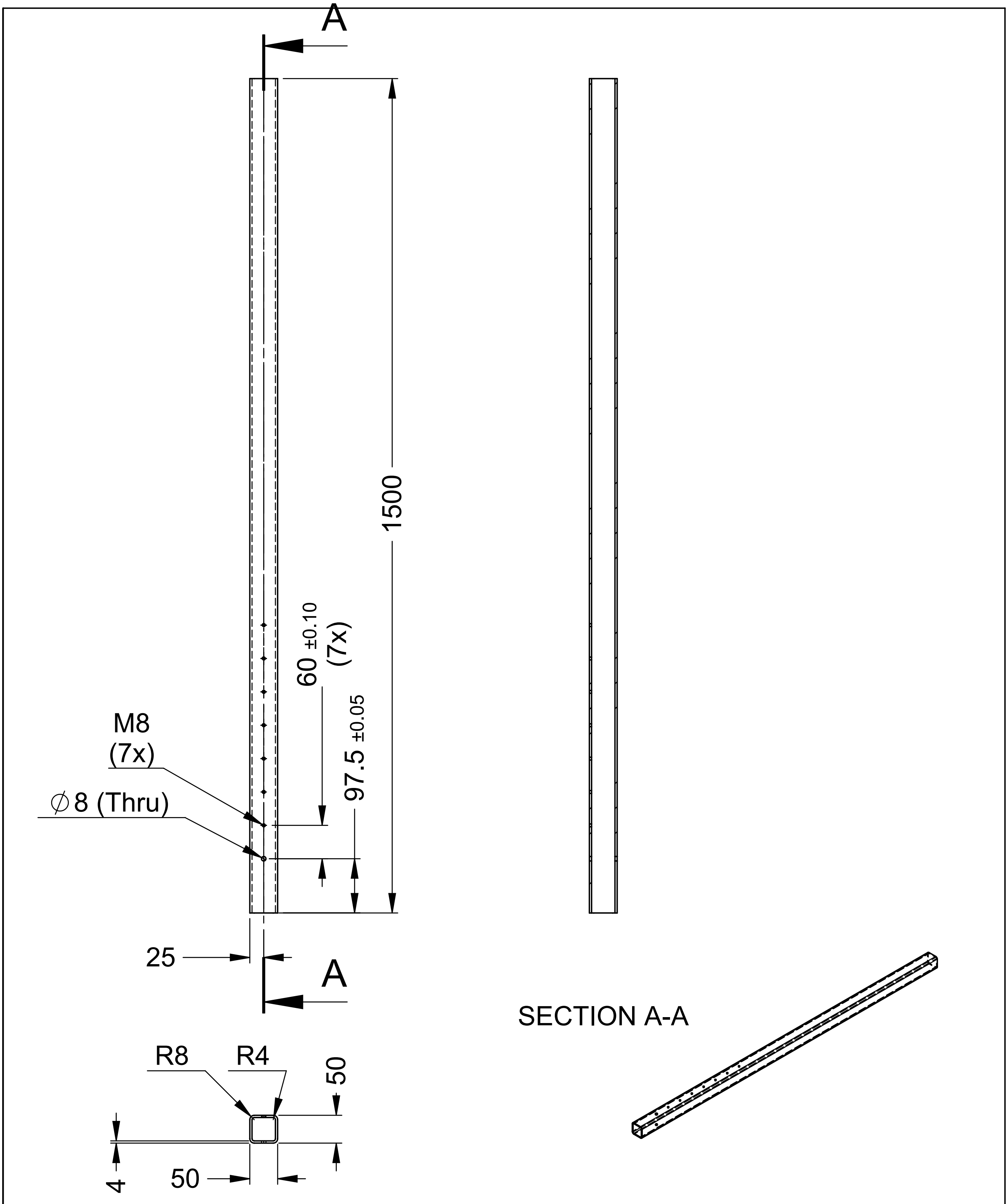
MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (μm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
1.0035 (S185)	8.11 KG		√	NOM DIM :	0-6	6-30	30-120	120-400	400-1000
				TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR	
					SCALE : 1:2
					DATE : 11-05-2018
					DRAWN : Amit S Desai
					APPROV:

TITLE: WP504-PD-2-01-01-Square profile 230mm tube

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO:	SIZE:
1–0	A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
1.0038 (S235JRG2)	8.12 KG		√	NOM DIM :	0-6	6-30	30-120	120-400	400-1000
				TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

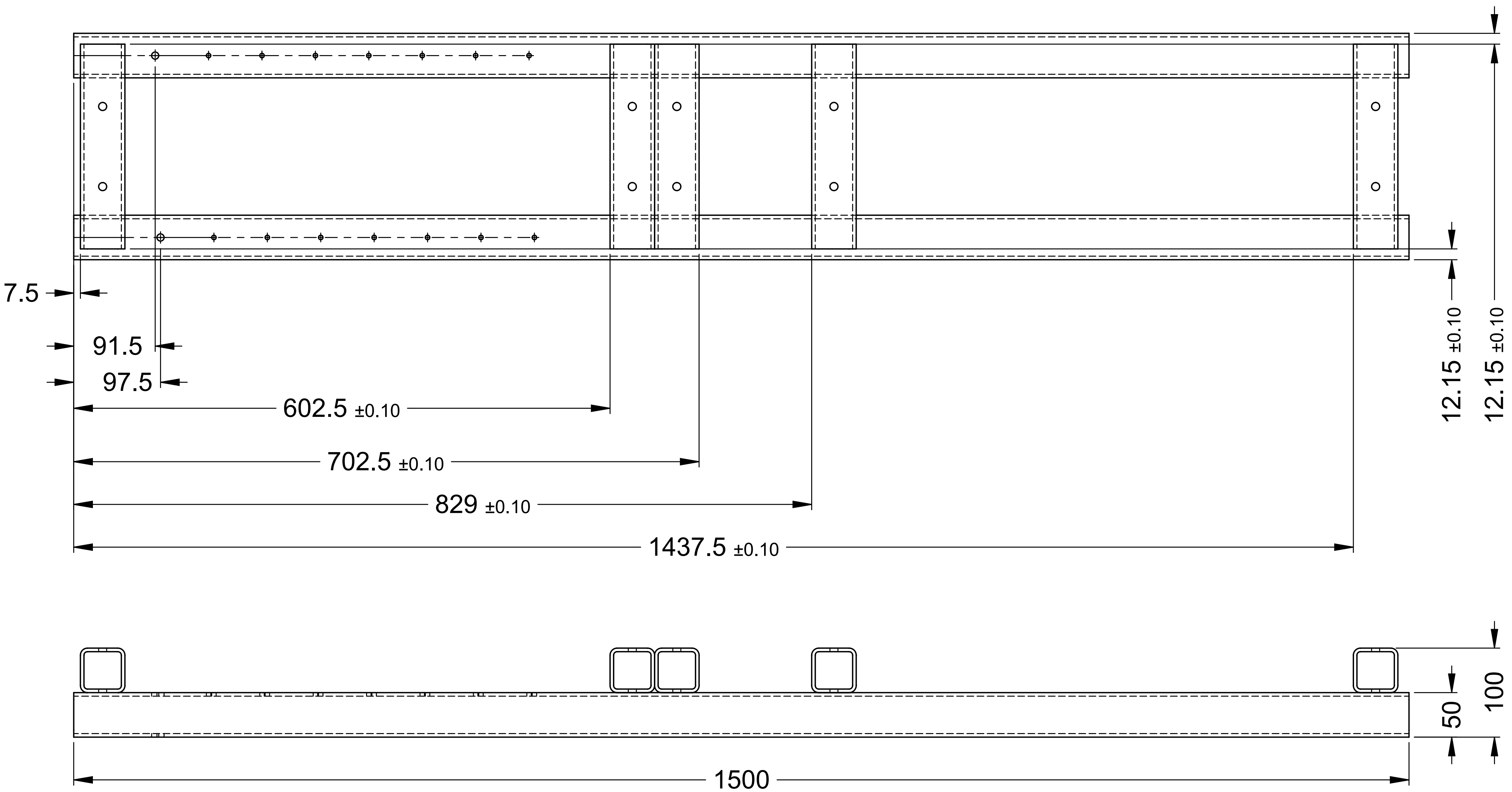
SCALE : 1:10
DATE : 11-05-2018
DRAWN : Amit S Desai
APPROV :

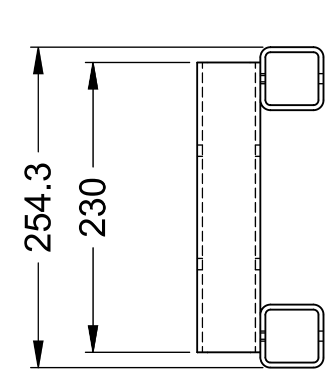
TITLE: WP504-PD-2-01-01-Square profile 1500mm tube

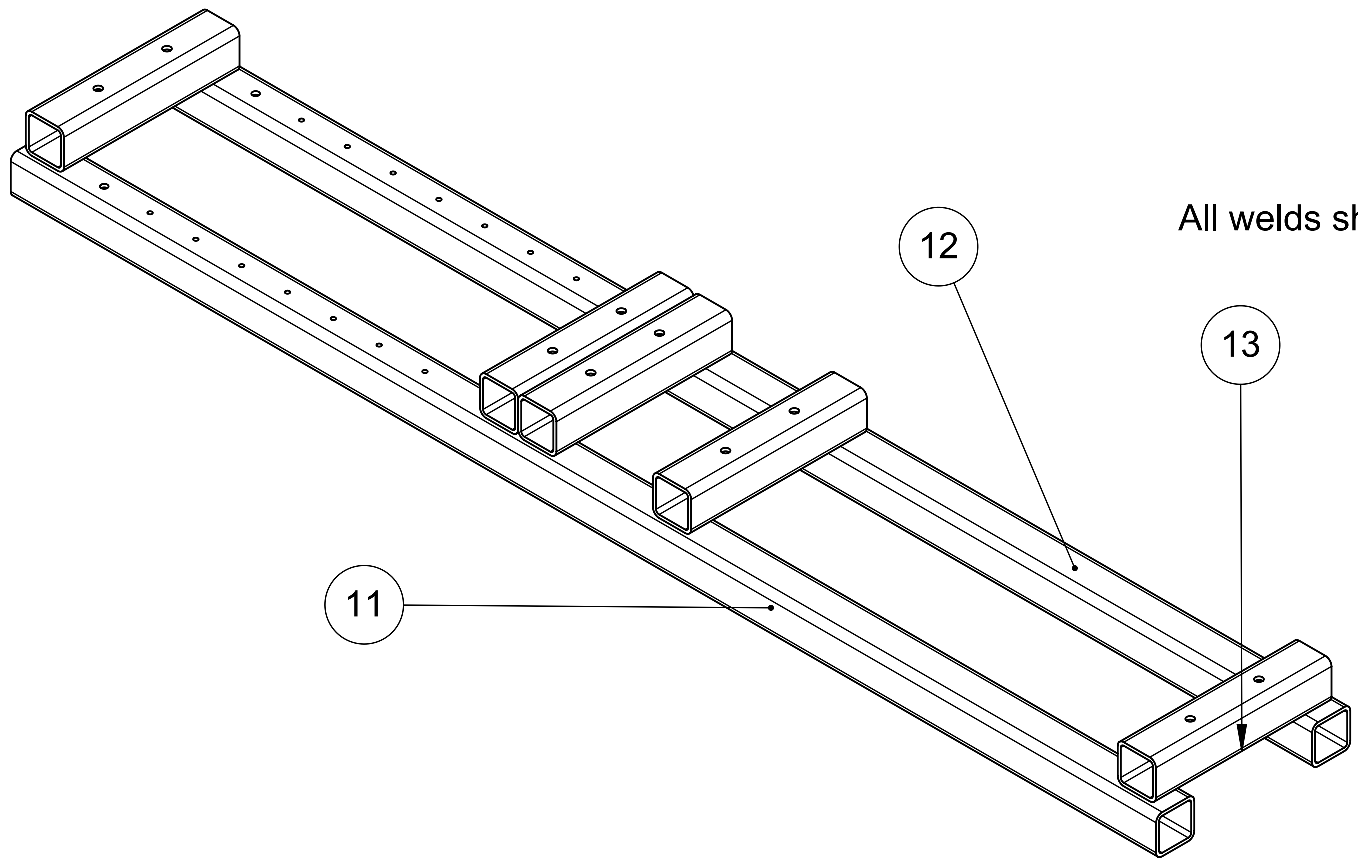
WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

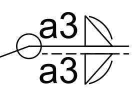
SIZE: A4







All welds should be:



ITEM	PART NUMBER	QTY
11	50*50-1500-1	1
12	50*50-1500-2	1
13	50*50-230	5

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
	69.86 KG		

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

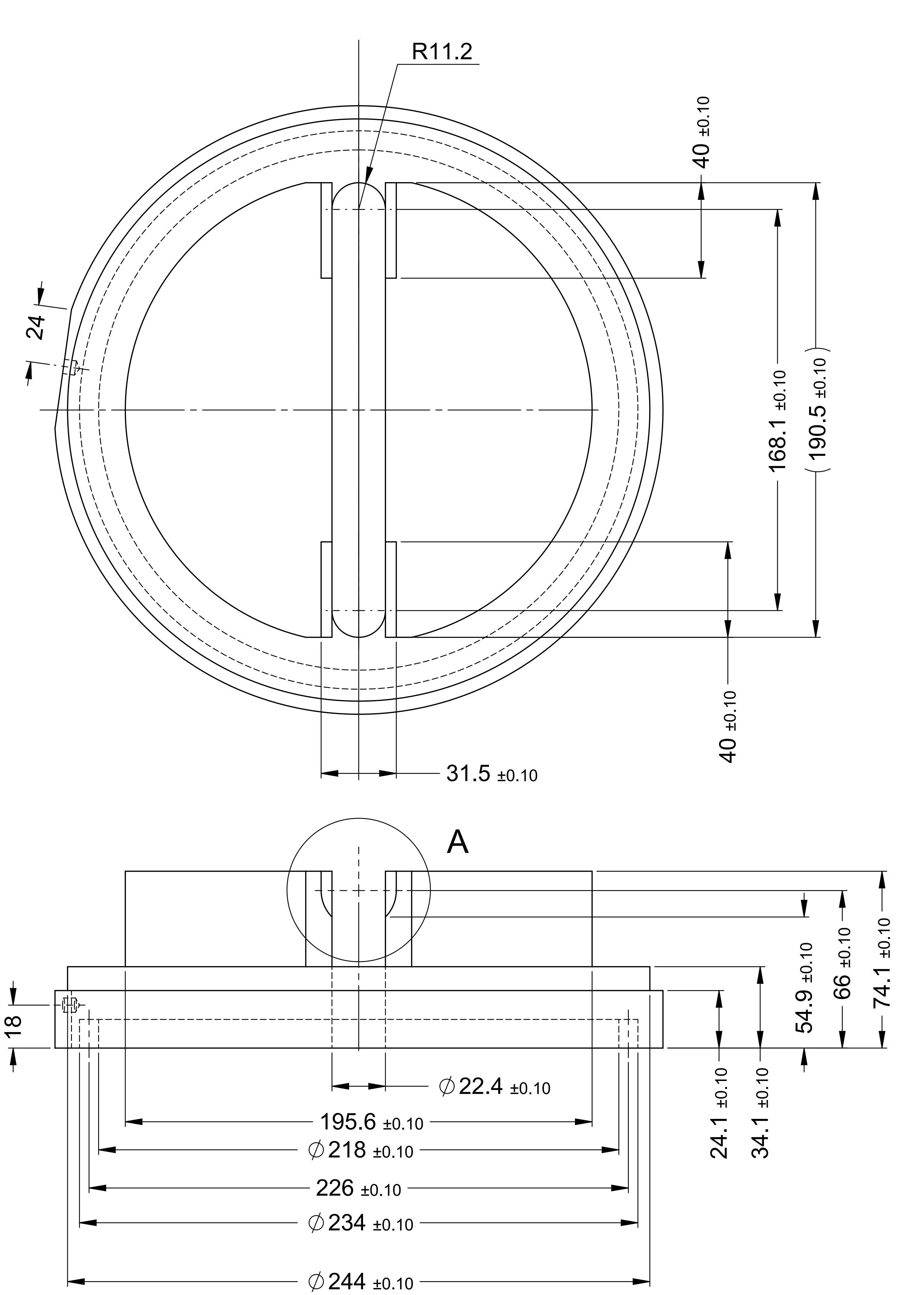
SCALE : 1:6
DATE : 08-11-2018
DRAWN : Amit S Desai
APPROV:

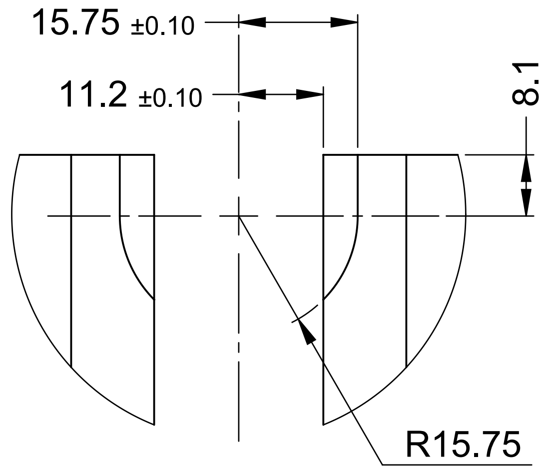
TITLE: WP504-PD-2-01-00-Test Prototype-Base frame

WOUTER WITZEL® VALVE TECHNOLOGY

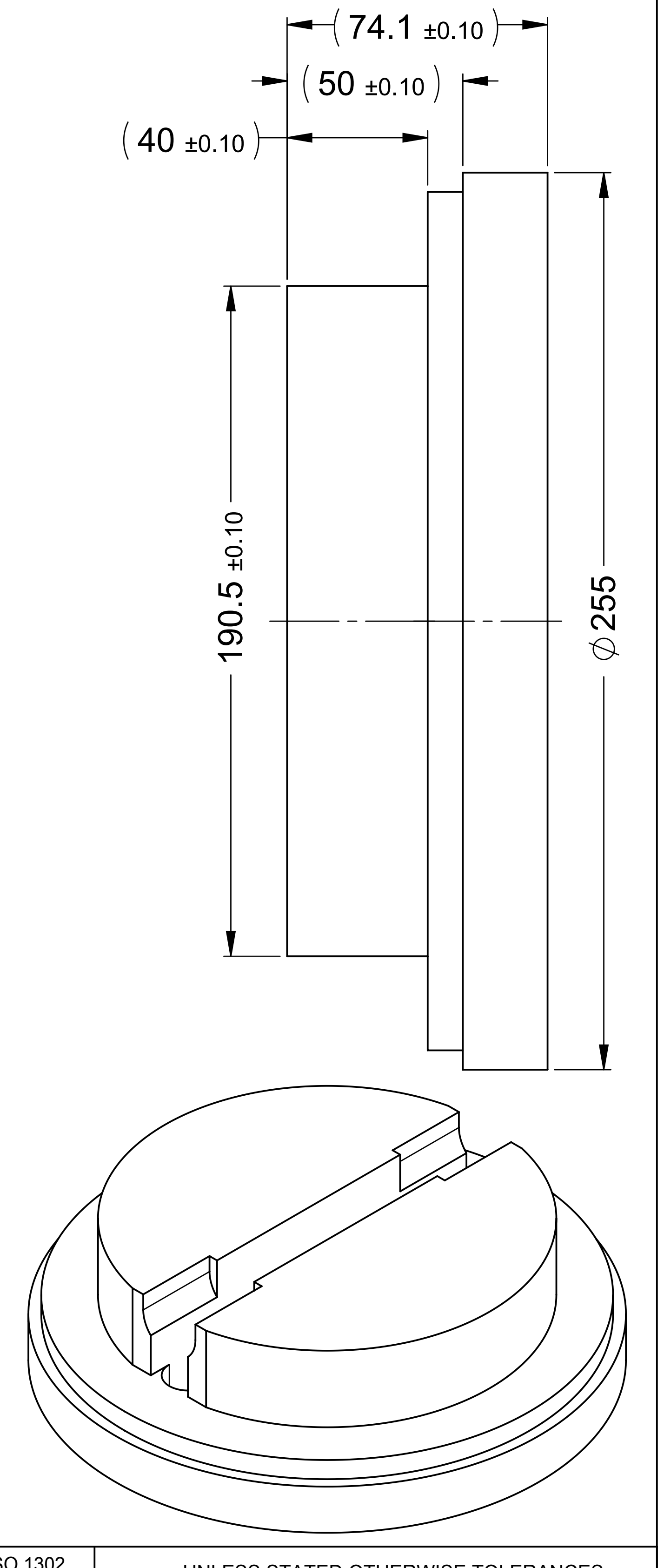
DRAWING NO: 1–0

SIZE: A3





DETAIL A
SCALE 1 : 1



REMOVE SHARP EDGES

Nylon PA-6	MASS KG	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR
1	22-11-2018	01	Amit	

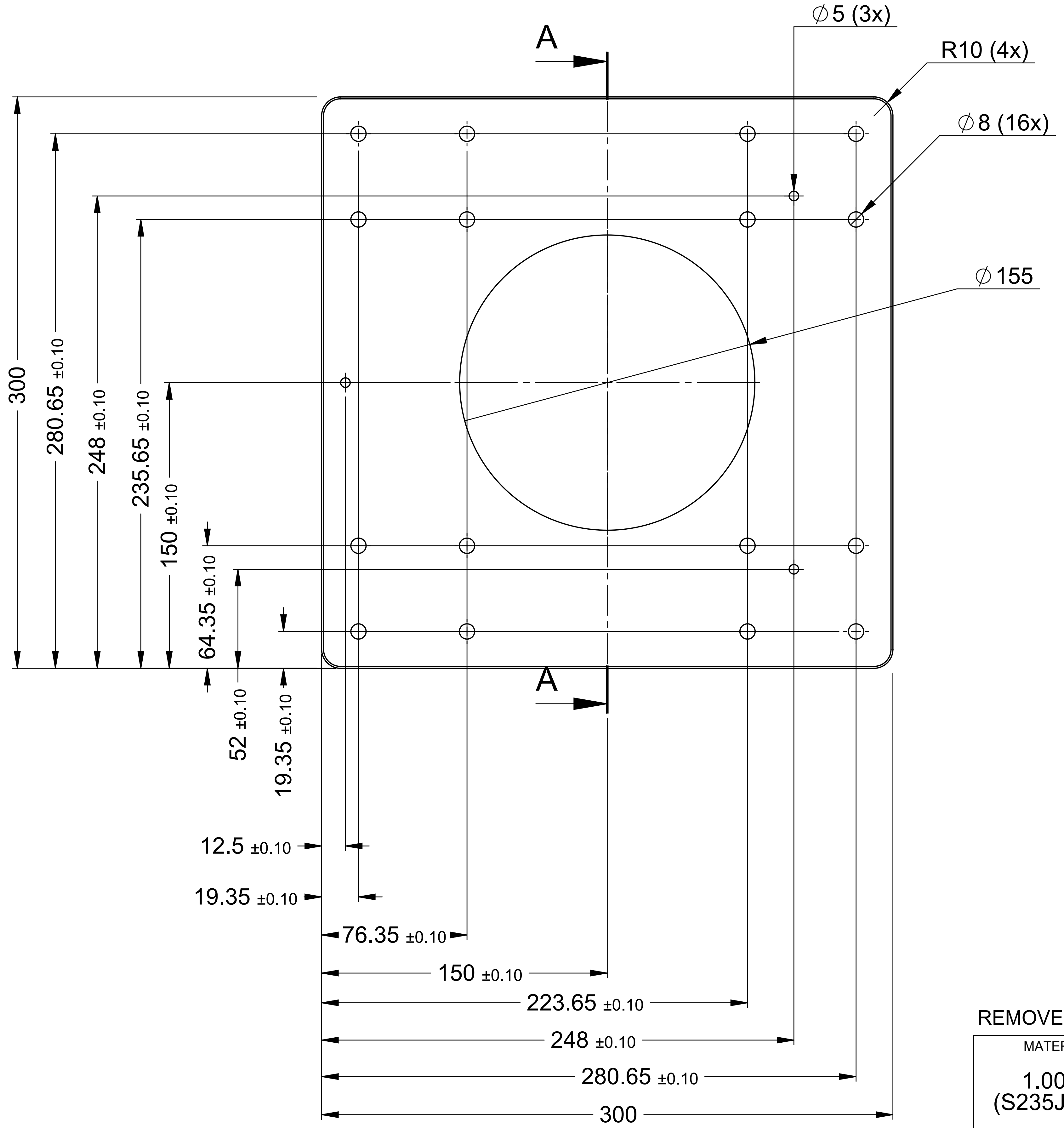
SCALE : 1:2
DATE : 11-05-2018
DRAWN : Amit S Desai
APPROV :

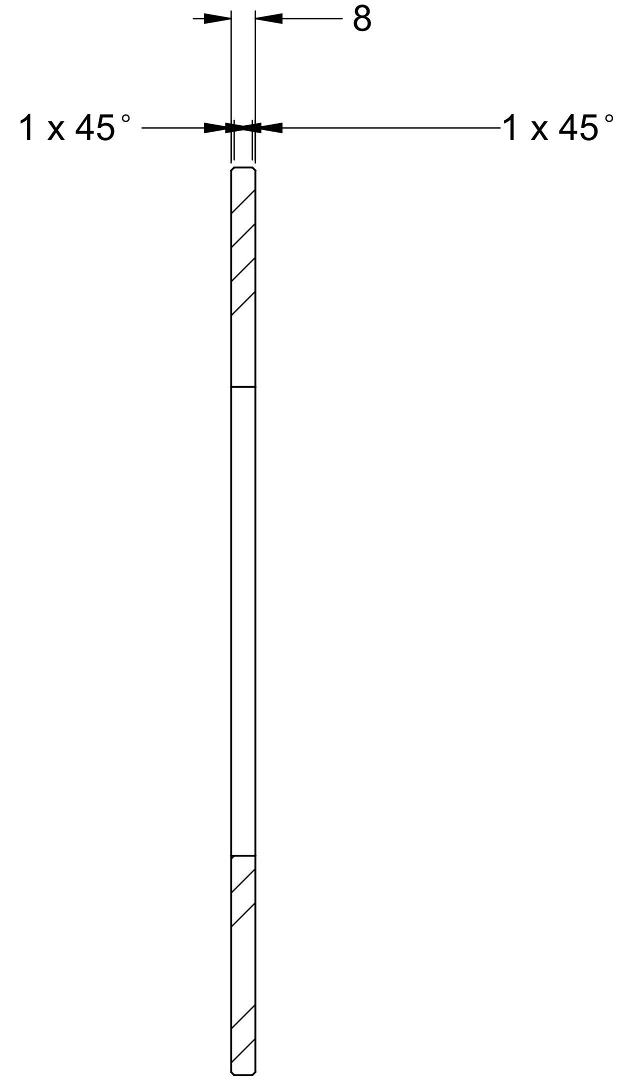
TITLE: WP504-PD-2-01-03-Disc Fixture-DN200

WW EuroValve®

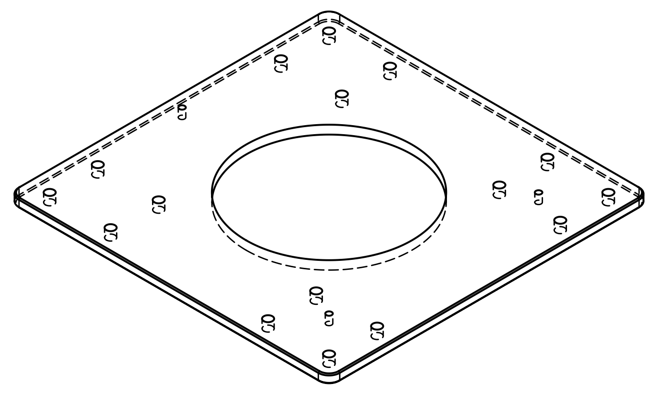
DRAWING NO: 1-1

SIZE: A3





SECTION A-A



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (μm)
1.0038 (S235JRG2)	4.37 KG		√

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

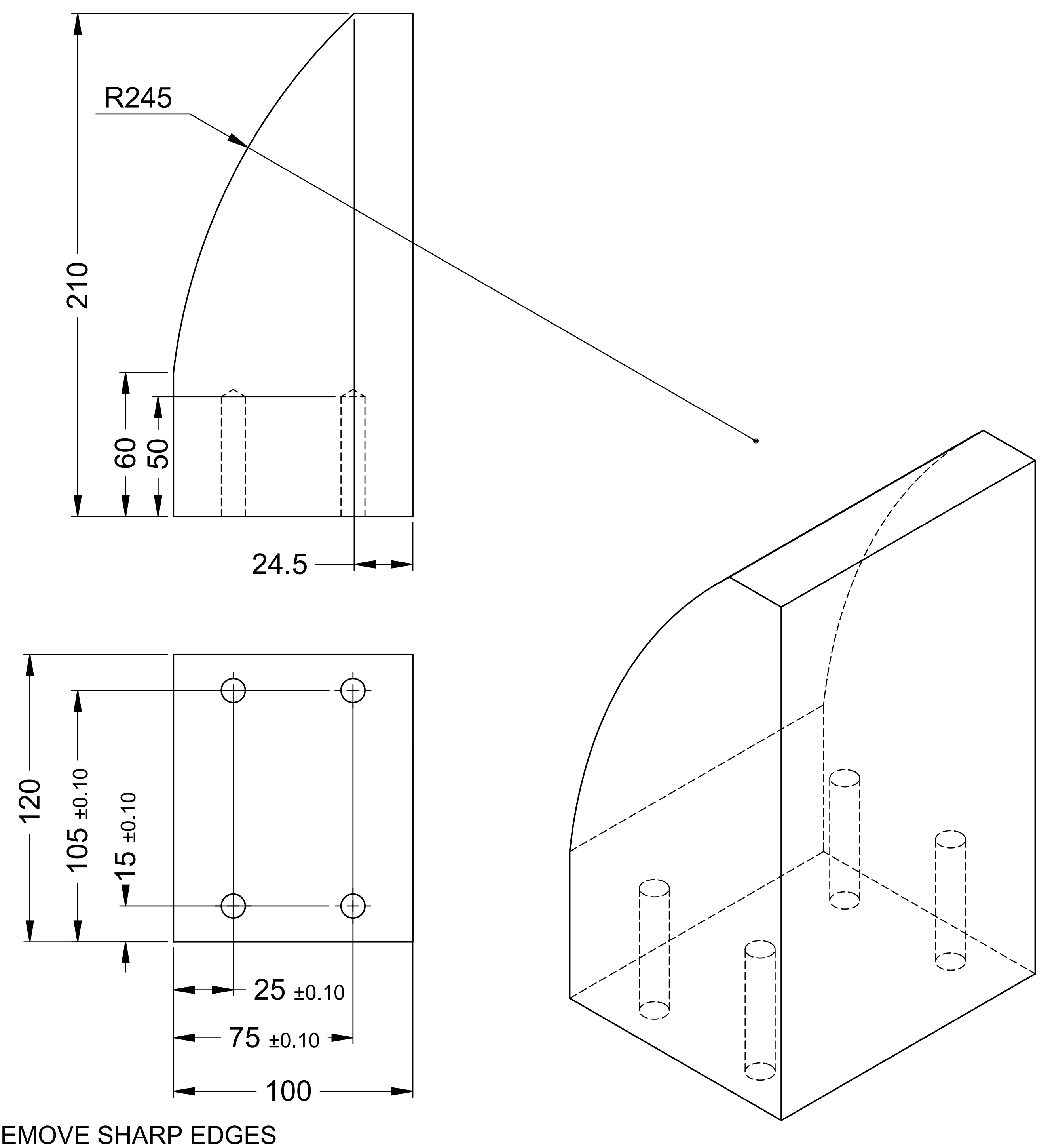
SCALE : 1:2.5
DATE : 11-05-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP504-PD-2-01-05-Base Platform

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A3



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
Nylon PA-6	2.07 KG		√

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

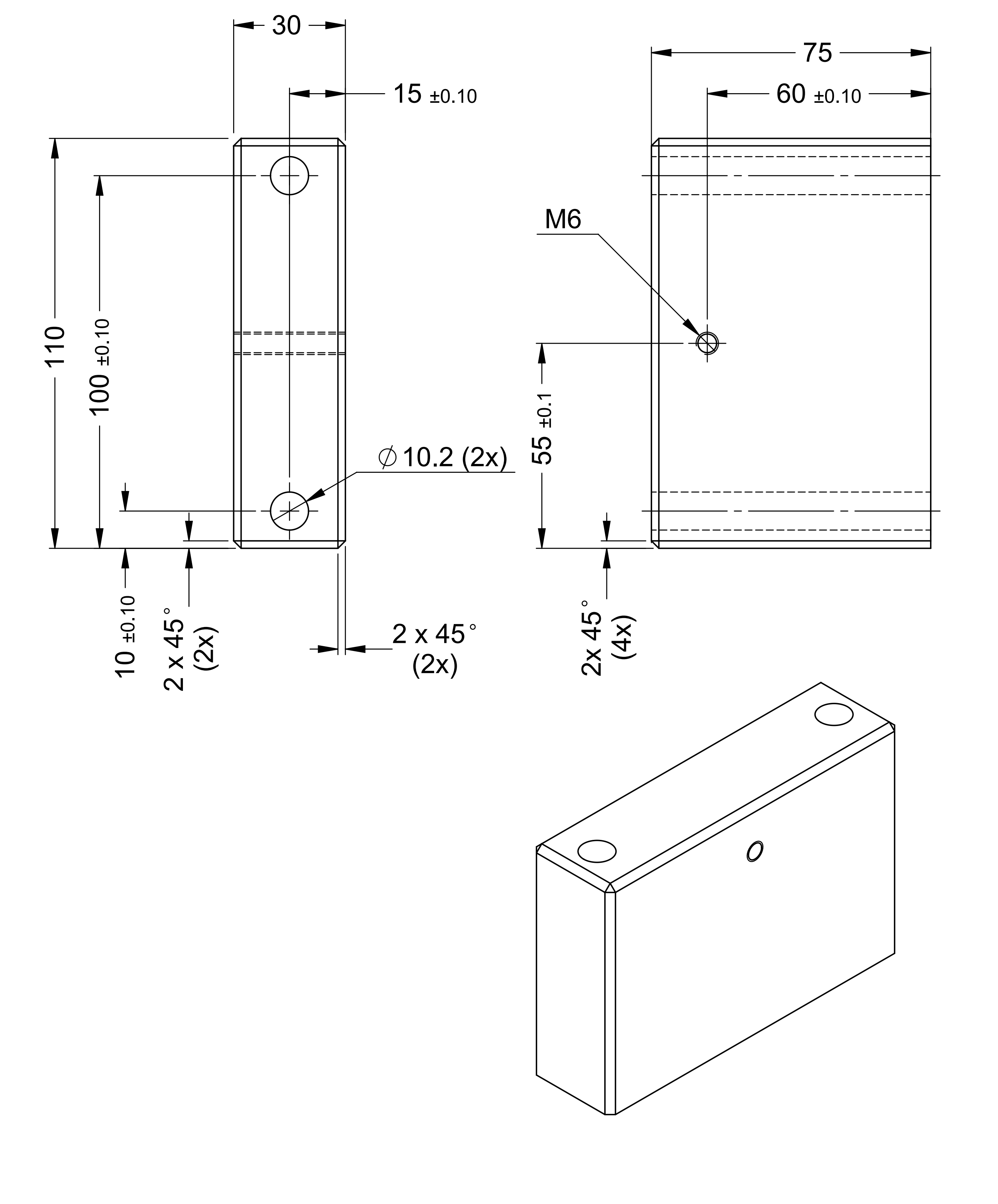
SCALE : 1:2.5
DATE : 15-11-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP504-PD-2-01-04-Fixture to guide the body

WOUTER WITZEL® VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
1.0038 (S235JRG2)	1.82 KG		

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:1.5

DATE : 11-05-2018

DRAWN : Amit S Desai

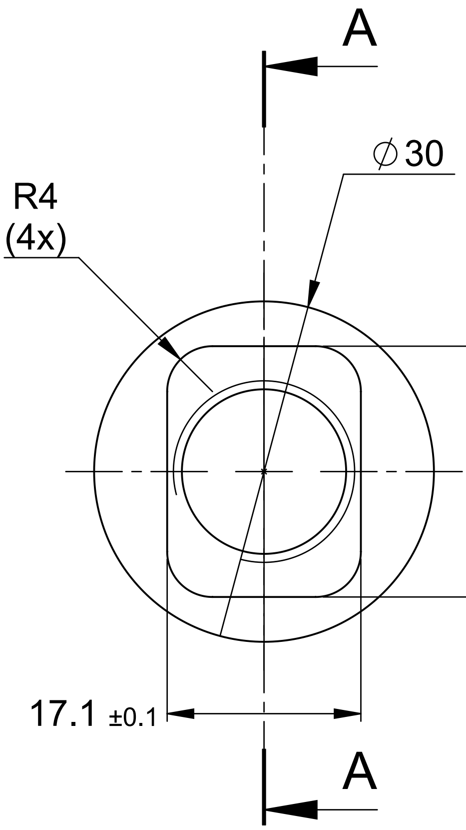
APPROV:

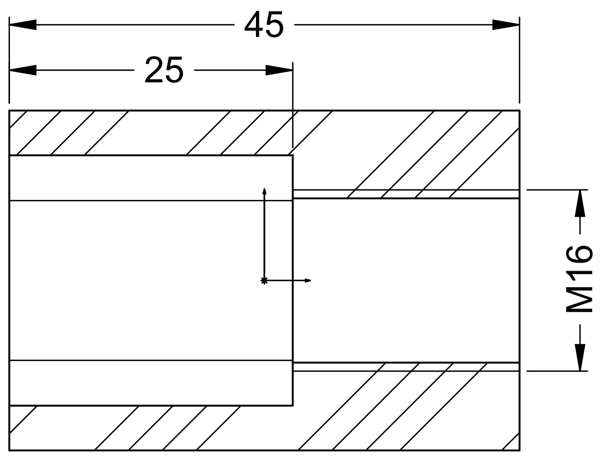
TITLE: WP504-PD-2-01-06-Bottom shaft push support

WOUTER WITZEL VALVE TECHNOLOGY

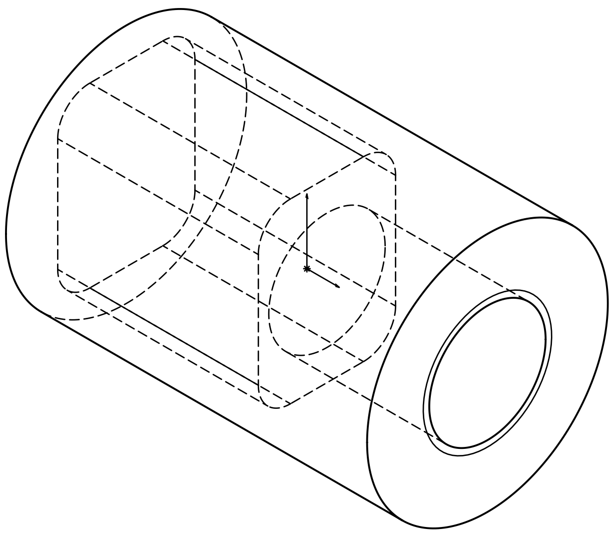
DRAWING NO: 1–0

SIZE: A4





SECTION A-A



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
1.0038 (S235JRG2)	0.15 KG			NOM DIM :	0-6	6-30	30-120	120-400	400-1000
				TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

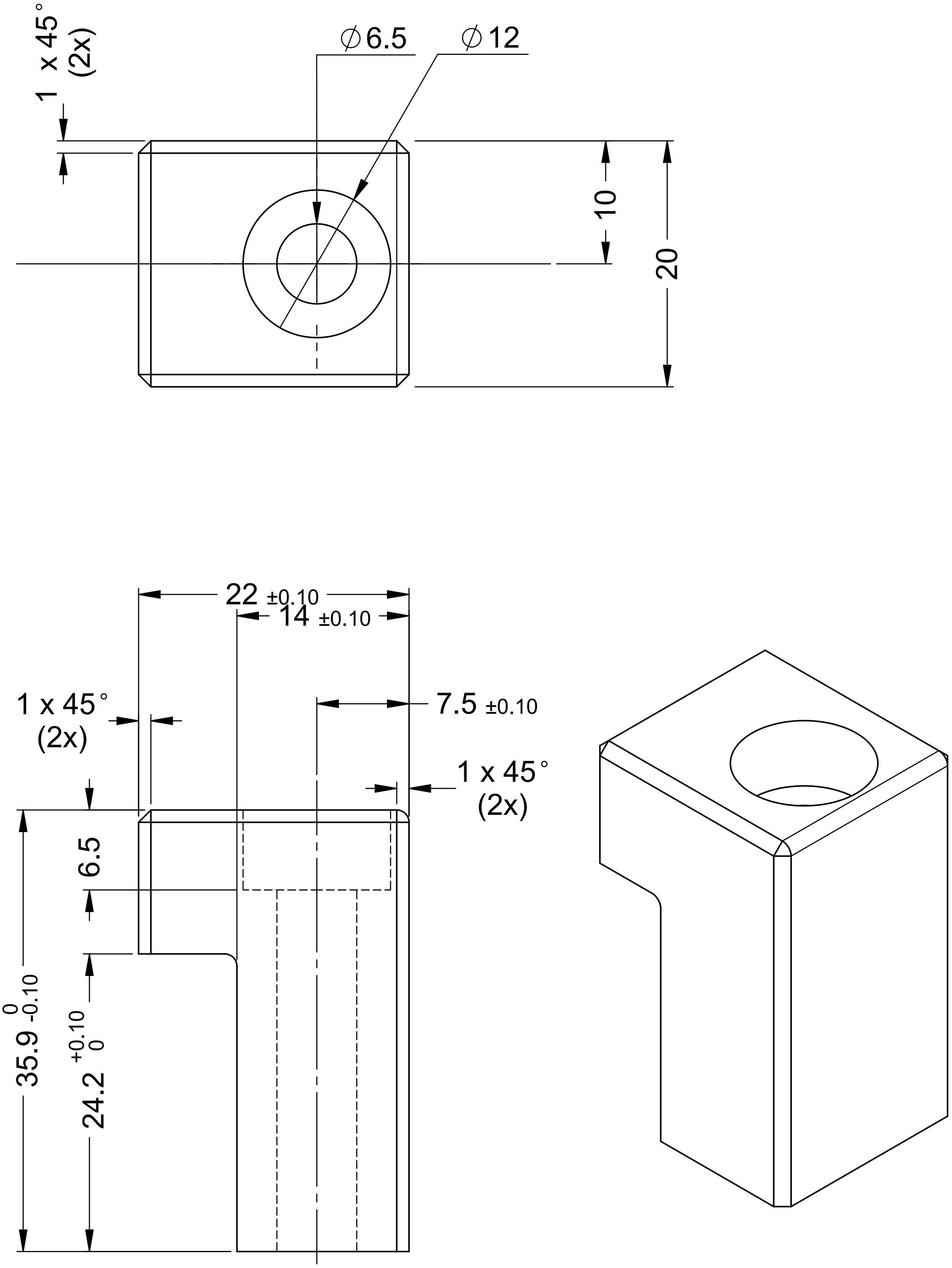
SCALE : 1.5:1
DATE : 11-05-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP504-PD-2-01-07-Drive shaft socket

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4



3 Stukken

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)
1.0570 (S355J2G3)	0.08 KG		√	

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

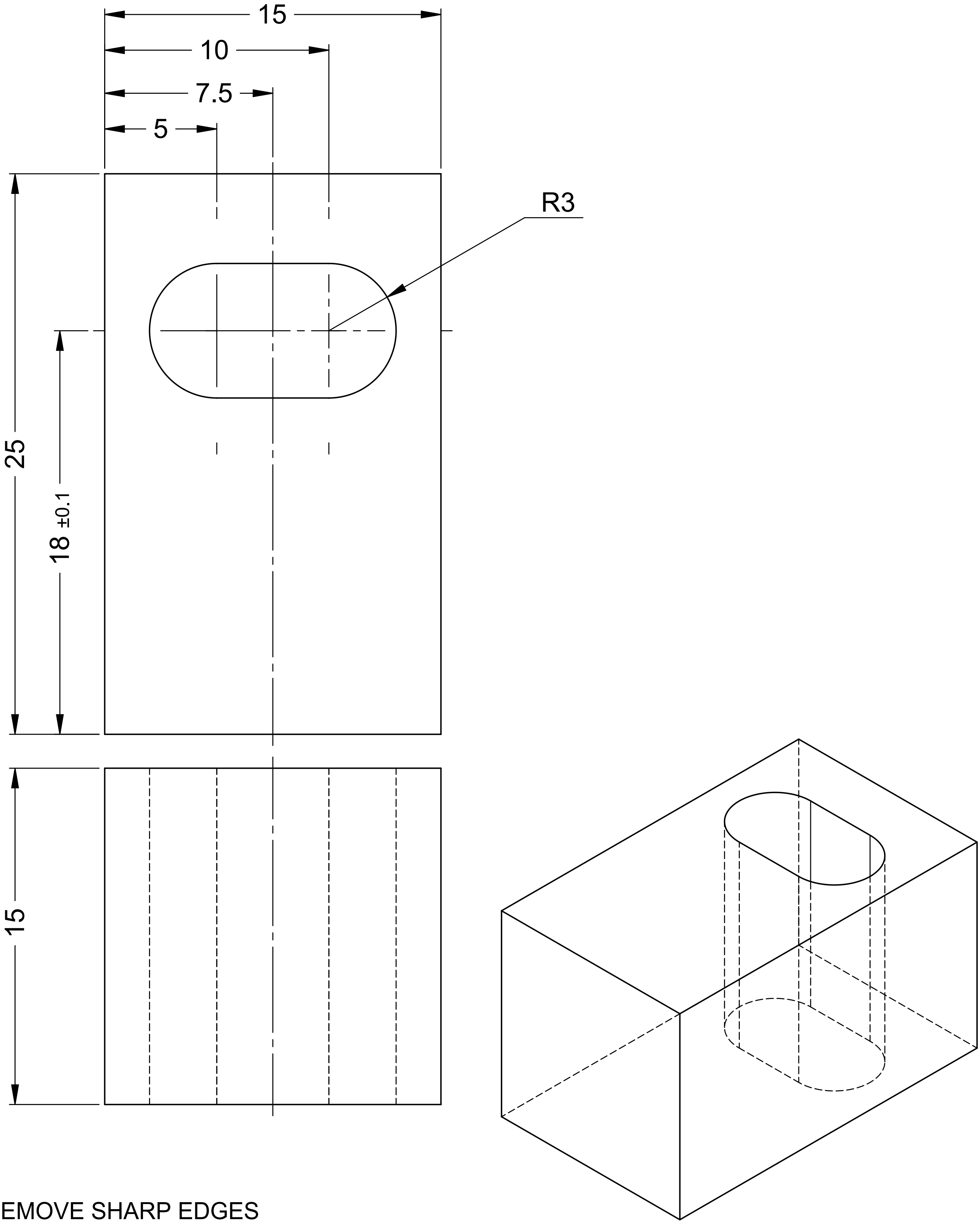
SCALE : 2:1
DATE : 11-05-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP504-PD-2-01-09-lock

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4



REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
1.0570 (S355J2G3)	0.04 KG		√

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

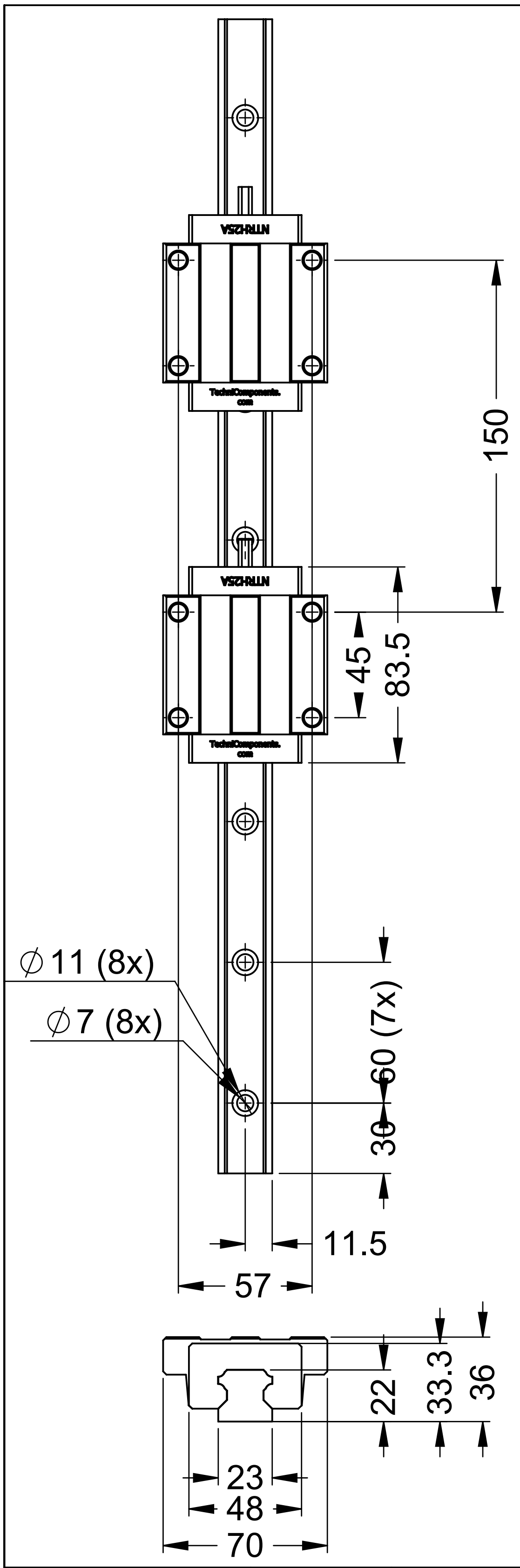
SCALE : 4:1
DATE : 09-11-2018
DRAWN : Amit S Desai
APPROV :

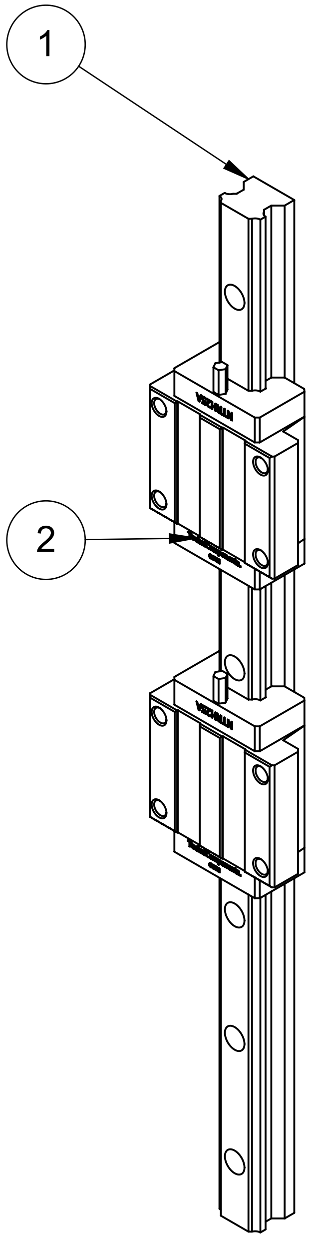
TITLE: WP504-PD-2-01-10-Stopper

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4





ITEM	PART NUMBER	QTY
1	WP504-PD-2-01-03-01-Guide Rail	1
2	WP504-PD-2-01-03-02-Guide Block	2

± MASS	ISO 128 - A	ISO 1302 Ra (μm)	UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)					
2.18 KG			NOM DIM :	0-6	6-30	30-120	120-400	400-1000
			TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:3

DATE : 10-11-2018

DRAWN : Amit Desai

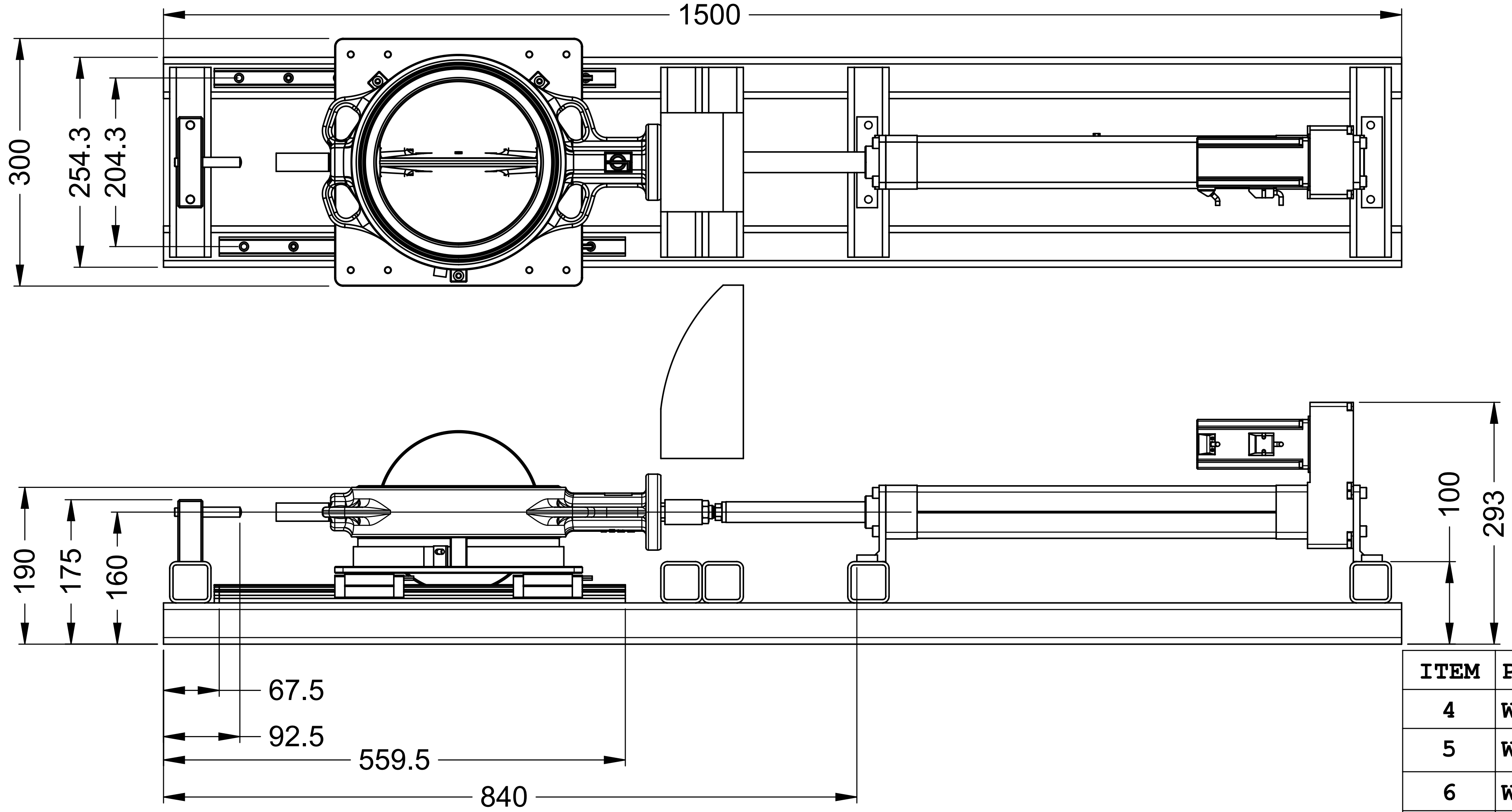
APPROV:

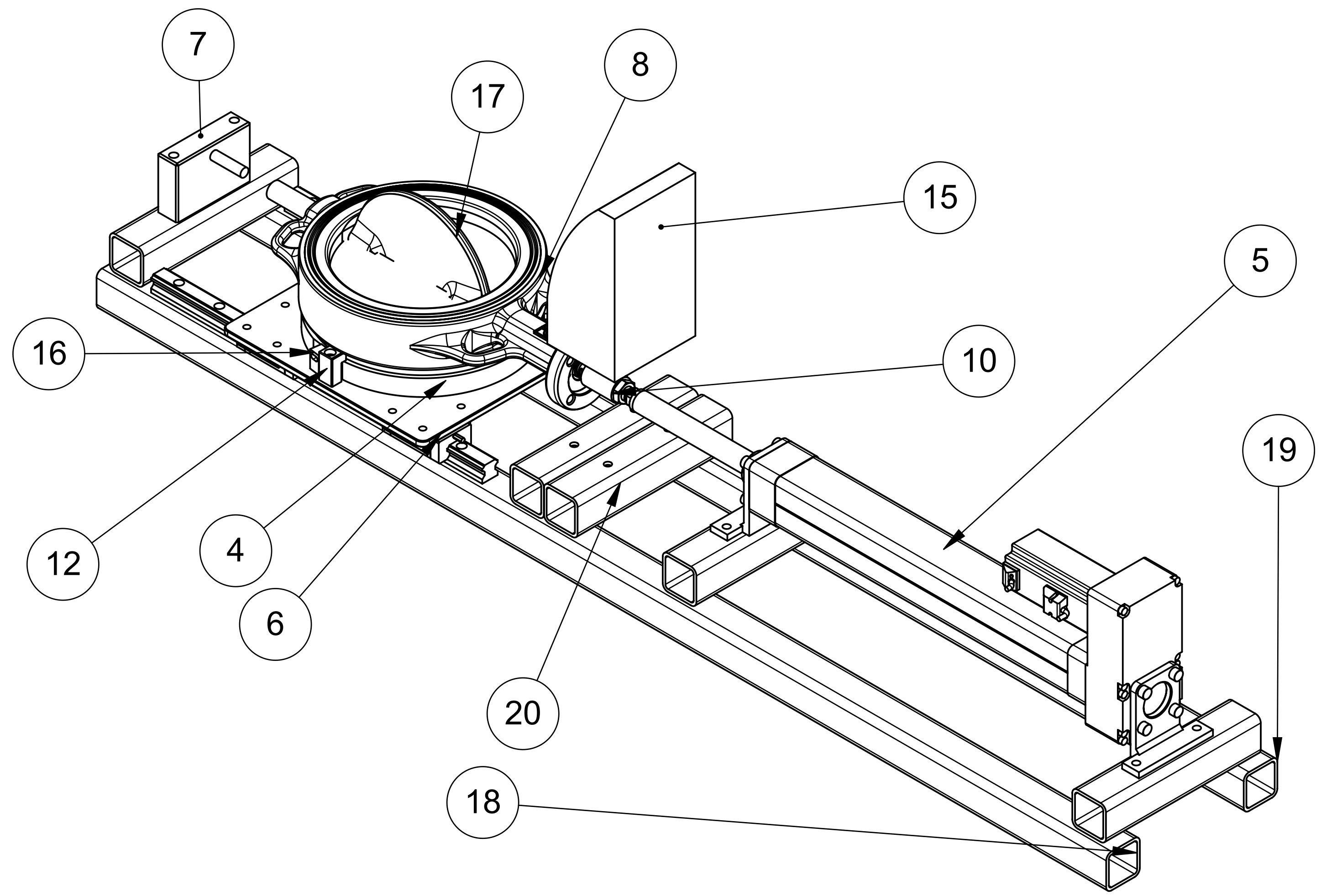
TITLE: WP504-PD-2-01-03-00-Linear Guide Unit

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A4





ITEM	PART NUMBER	QTY
4	WP504-PD-2-01-03-Disc Fixture	1
5	WP504-PD-2-01-02-00-Electromechanical Cylinder	1
6	WP504-PD-2-01-03-00-Linear Guide Unit	2
7	WP504-PD-2-01-06-Bottom Shaft push support	1
8	WP504-PD-2-01-01-00-Euronomic DN200	1
10	WP504-PD-2-01-07-Drive shaft socket	1
11	WP504-PD-2-01-08-Base platform	1
12	WP504-PD-2-01-09-lock	3
13	NXD9383	1
15	WP504-PD-2-01-04-Fixture to guide the body	1
16	WP504-PD-2-01-09-lock-2	1
17	WP504-PD-2-01-01-03-Euronomic-DN200-Convex disc	1
18	50*50-1500-1	1
19	50*50-1500-2	1
20	50*50-230	5

REMOVE SHARP EDGES

MATERIAL	± MASS	ISO 128 - A	ISO 1302 Ra (µm)
	69.86 KG		√

UNLESS STATED OTHERWISE TOLERANCES LISTED BELOW ARE APPLICABLE (ISO-2768)

NOM DIM :	0-6	6-30	30-120	120-400	400-1000
TOL :	±0.2	±0.5	±0.8	±1.2	±2

REV	DATE	CODE	DRWN	APPR

SCALE : 1:7.25
DATE : 08-11-2018
DRAWN : Amit S Desai
APPROV:

TITLE: WP504-PD-2-01-00-Inline Assembly Test Prototype

WOUTER WITZEL VALVE TECHNOLOGY

DRAWING NO: 1–0

SIZE: A3