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ANALYSIS AND DESIGN OF AN AUTOMATED SYSTEM FOR TUMBLER PACKET ASSEMBLY

Engineering and Natural Sciences
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ABSTRACT

Tatu Tykkyläinen: Analysis and design of an automated system for tumbler packet assembly
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Most industrial assembly processes are done by hand. Reasons for selecting manual assembly are the size of a production batch, product life-cycle and required automation investment. Manual assembly can account for 50 % of product costs and 40 % of labor costs. Companies are constantly trying to find ways of using automation in their production to reduce costs.

Realizing part feeding and quality inspections for automatic product assembly are especially difficult. For an automatic assembly to work quality of parts must remain constant and they have to be fed in the same orientation. In manual assembly, a person can adapt to changes and inspect part while assembling it. Automatic assembly maintains product quality constant, because machine will reject all faulty parts. In manual assembly faulty parts might pass.

Abloy Oy wanted to investigate a possibility of automating their tumbler packet assembly process. Currently it is done manually. In this thesis, the tumbler packet assembly was studied and methods for automating it with general automation equipment, like industrial robots, were proposed. Proposed automating solutions were compared with estimated cycle time and required investment.

In the analysis phase of the design methodology attention was in tumbler packet assembly and product parts. Problems in automating assembly process were identified and the simplest problems were solved in the analysis phase. More demanding problems were solved in the synthesis phase of the design methodology by using 3D-modeling and by building prototypes of feeding devices. In the simulation phase assembly process was divided into work phases and the way in which automation could be used to perform each work phase was studied. Theoretical values of cycle time and investment cost were calculated for the found solutions. Based on the comparison made in the evaluation phase a structure for automated assembly machine was proposed.

In this thesis problems for automating tumbler packet assembly were discovered. Two different structures for automated assembly machine were proposed to Abloy Oy. One structure aims to optimize cycle time and the other aims for reasonable investment cost. Outcome of this thesis was a proposed design methodology for identifying and solving problems in automated tumbler packet assembly and results of its implementation.

Keywords: tumbler packet, design methodology for assembly machine, automatization of assembly

TIIVISTELMÄ

Tatu Tykkyläinen: Analyysi ja suunnittelu automaattiselle haittalevypaketin kasaukselle
Diplomityö
Tampereen yliopisto
Automaatiotekniikan diplomi-insinöörin tutkinto-ohjelma
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Suurin osa teollisten tuotteiden kokoonpanoprosesseista tehdään edelleen käsin, johtuen esimerkiksi tuotantosarjojen koosta, tuotteen elinkaaresta ja automatisoinnin vaatimasta investoinnista. Manuaalisessa kokoonpanossa kustannukset voivat olla jopa 50 % valmistuskustannuksista ja 40 % henkilöstökuluista. Yritykset tutkivat jatkuvasti erilaisia keinoja hyödyntää automaatiota tuotantokulujen vähentämiseksi.

Tuotteiden automaattisessa kokoonpanoprosessissa erityisesti kappaleiden syöttö sekä tuotteiden tarkistus ovat haasteellisia. Automaattisen kokoonpanon onnistumiseksi syötettävien kappaleiden laadun on pysyttävä tasaisena ja kappaleet on syötettävä aina samassa asennossa koneelle. Manuaalisessa kokoonpanossa ihminen pystyy mukautumaan tilanteeseen ja tarkastamaan kappaleen laadun kasatessaan. Automaattinen kokoonpano tuottaa tasaisempaa laatua, koska kone hylkää kaikki huonot kappaleet. Manuaalisessa kokoonpanossa huonotkin kappaleet voivat mennä läpi.

Abloy Oy halusi selvittää haittalevypaketin kokoonpanoprosessin automatisointia. Tällä hetkellä kyseinen kokoonpanoprosessi tehdään manuaalisesti. Diplomityössä perehdyttiin haittalevypaketin kasaukseen ja ehdotettiin vaihtoehtoja kuinka yleisiä automaatiokomponentteja, kuten teollisuusrobotteja, voitaisiin käyttää haittalevypaketin automaattiseen kokoonpanoon. Ehdotettuja automatisointi vaihtoehtoja vertailtiin arvioidun jaksonajan ja vaadittavan investoinnin avulla.

Suunnittelumetodologian analyysivaiheessa tutustuttiin haittalevypaketin kasaukseen ja tuotteen osiin. Analyysivaiheessa myös tunnistettiin mahdolliset esteet automatisoinnille ja ratkaistiin yksinkertaisimmat ongelmat. Vaativammat ongelmat ratkaistiin metodologian synteesivaiheessa käyttämällä 3D-mallinnusta ja rakentamalla prototyyppejä syöttölaitteista. Simulointivaiheessa kokoonpanoprosessi jaettiin työvaiheisiin ja tutkittiin kuinka automaatiota voitaisiin käyttää työvaiheiden suorittamiseen. Löydetyille ratkaisuille laskettiin teoreettinen arvio jaksonajasta ja investointikustannuksista. Arviointivaiheessa tehdyn vertailun perusteella suositeltiin rakennetta automaattiselle kokoonpanosolulle.

Diplomityössä löydettiin ongelmia, joita haittalevypaketin kasauksen automatisoinnissa on. Abloy Oy:lle ehdotettiin vertailujen perusteella kahta erilaista rakennetta automaattiselle kokoonpanosolulle. Toinen rakenne tähtää jaksonajan optimointiin ja toinen vaadittavan investoinnin kohtuullistamiseen. Diplomityön tulos on ehdotettu suunnittelumetodologia automaattisen haittalevypaketin kasauksen ongelmien löytämiseen ja ratkaisemiseen sekä sen käytännön tulokset

Avainsanat: haittalevypaketti, kokoonpanosolun suunnittelumetodologia, kokoonpanon automatisointi

PREFACE

This thesis was written for Abloy Oy. I want to thank Kimmo Kuusela and Marko Kokkonen from Abloy Oy. Their guidance and support were important for the success of this thesis. I must also thank Kaptas Oy and everybody who works there. They helped me to see things in different perspective and helped me to overcome difficult challenges.

This thesis took over a year to write. At the beginning I could not imagine how difficult it could be to answer such a simple question. During this thesis I realized that I should have approached many of the problems from a different angle. All of these mistakes have taught me something and I am sure that in my future projects those lessons are needed. This thesis required a lot of work and not all of that work made it in this thesis. But I am glad that I got the chance to work on this subject, because it has taught me so much about designing an automated production line.

I would like to thank professor Jose Luis Martinez Lastra and Luis Gonzales Moctezuma from Tampere University of Technology. My thesis progress was far from ideal and got very complicated. But thanks to their guidance I was able to complete this thesis.

My gratitude goes to my family and friends as well. Everybody in my family has been very supportive during this long process. I could not have done this without their support and encouragement. I want to especially thank my girlfriend for sacrificing her make-up brush to my feeder prototypes.

Joensuu, 20.10.2019

Tatu Tykkyläinen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating current
CAD	Computer aided design
CAM	Computer aided manufacturing
CNC	Computer numerical control
CO^2	Carbon dioxide
DC	Direct current
E_k	Kinetic energy
FMS	Flexible manufacturing system
Laser	Light amplification by stimulated emission of radiation
m	mass kg
MIT	Massachusetts Institute of Technology
MTBF	Mean time to failure
MTTR	Mean time to repair
Nd:YAG	Neodymium-doped yttrium aluminum garnet
Pcs	Pieces
RMS	Reconfigurable manufacturing system
SCARA	Selective Compliance Assembly Robot Arm
US	United states
v	Speed m/s

1. INTRODUCTION

1.1 Background

For most companies and corporations, the main purpose is to make money. A company needs to stay profitable in order to secure their continuing operations. This requires companies to constantly respond to changing demands from customers. Modern customers don’t just look at price. They want products that are of good quality, reasonable in prize and delivered on time. Companies that specialize in manufacturing of goods have to be able to meet customer expectations, attract new customers with desirable products and still be able to keep production costs and delivery times reasonable. This requires companies to use production systems that can handle increased demands while maintaining efficiency and quality. During the last century product quality has been improved and costs lowered because of mass production. Companies have built assembly lines where workers work together to assemble products. Each worker does one part of the assembly. These types of production lines are called manual assembly lines. A well known example of a manual assembly line is Ford’s assembly line for T-Model car. [16]

Use of automation has revolutionized manufacturing in various fields. While automation has had a great impact on part fabrication process, part assembly process has not changed as much. Even today most of the product assembly processes are done manually by workers with simple tools, like screwdrivers and hammers. In the manufacturing industry, assembly costs can be as high as 50 % of the manufacturing cost and assembly process can account for 40 % of the labor costs. Manufacturers should constantly study their own assembly processes and find chances to employ automation. There are multiple reasons as why a production system is developed or changed. For example, a new product is introduced, work environment needs improvement or there is a desire to increase efficiency of old systems. But the main reason for automating production has always been an attempt to reduce direct labor costs. [16, 18]

Efforts to reduce manual labor have been made since the beginning of the 20th century. Replacing solutions have been mechanical in nature, such as feeders, robots with trays and automatic screw feeding. In the last two decades, lowering of assembly costs have been tried by employing assembly robots and high-speed automation. Success has been rare. It is difficult to build an economical assembly system where only one robot handles all work phases. This is because one robot alone is not enough. A robot needs peripheral devices, e.g. grippers to pick parts and sensors or, machine vision, to see where a part is. If an assembly process consists of multiple parts, a robot might need a separate gripper for each part and several different sensors to locate each part. Peripheral system costs build up and make it hard to justify system costs when compared to a manual assembly. In a manual assembly, a worker only needs certain tools to complete an assembly. Human hands are capable of picking objects of different shapes and while assembling, a worker can inspect the part for any visual faults. A worker can also quickly respond to unexpected situations, such as parts being faulty and unable to go together. A worker simply puts faulty parts aside and picks new parts. If the same problem was encountered by an automated assembly line, it would cause an error and the entire production would stop until someone acknowledges it. In order to use automation efficiently in assembly, part quality must be constant. It is worth noting that product quality with automation is better than with manual labor. If parts are not a perfect fit, automation will not allow it to pass. The part is either rejected automatically or it causes the production to stop, because assembly process can't be continued. A human assembler could instead force parts together and send it forward. Automation ensures that product quality remains unchanged.[16, 18]

Manual assembly is often economic for small batches and products that require flexibility from a production system. Automated assembly is most useful if a product has been designed for it and the foreseeable production rate is high. Otherwise manual assembly is most likely the only option. When automation is applied in correct circumstances, it can bring the following advantages:

1. Reliable product with constant quality
2. Lowered costs with increased production
3. Increased operator safety
4. Chance to redesign product

Designing products with assembly in mind carries advantages to manual assembly and even more so to automatic assembly. The equipment used in assembly should be considered already in the design phase. Automated assembly is much more demanding on how parts are fed. During the design, special focus must be put on how easy parts are to orient with automatic feeders.[16, 18]

1.2 Problem definition

This thesis was made for Abloy Oy. Abloy is a Finnish lock company that specializes in rotating tumbler disc locks.

Abloy has a great interest on automation and how it could benefit their production, since most of their products are assembled manually. Abloy has defined tumbler packet assembly as one possible process where automation could be beneficial. Several studies by Abloy Oy had been performed to see if some more difficult parts could be fed with machine vision and an industrial robot. Results from these tests showed that it was possible. But these solutions would have been too expensive or they would have been too slow.

1.3 Objectives and scope

The purpose of this thesis is to investigate tumbler packet assembly process and suggest possible ways to automate it. Outcome is a proposed design methodology for identifying and solving problems in automated tumbler packet assembly and results of its implementation. The following research questions were chosen as the most suitable for this subject:

1. What automation equipment could be used to assemble a tumbler lock packet?
2. How do different solutions compare in investment and cycle time?

Aim of this thesis is not to make the decision of which automation solution is the best but to create and compare possible solutions. The final decision to invest requires accurate financial information and production data, neither of which are available publicly.

Measurements or 3D-models concerning products of Abloy Oy are not accurate. Their only purpose it to give the reader a general idea of object sizes and shapes.

1.4 Outline

The thesis structure is divided into 8 chapters. Chapter 1 is the introduction to the background of the problem and explaining of the research questions. Chapter 2 outlines the theoretical background of the used design methodology and introduces some general automation equipment. Chapter 3 explains the proposed design methodology to be used. Chapters 4,5,6 and 7 cover the implementation of the proposed methodology. Each phase of the methodology has their own chapter to improve thesis readability. In chapter 8 work done in this thesis and achieved results are discussed.

2. BACKGROUND

2.1 Automation equipment

This chapter explains briefly and generally the different automation and manufacturing equipment that are used in this thesis. Described components and systems are common in industrial applications.

2.1.1 Pneumatics

Using compressed gas to create movement is called pneumatics. Pneumatics is similar to hydraulics. They both work on same principles and actuators. The main difference is that hydraulics uses fluid and pneumatics uses gas. Compared to a hydraulic system, a pneumatic system provides less force, but its movements are softer and a hose breakage does not create dangerous situations. Pneumatics is well suited for hazardous environments where spark could cause a disaster.[19]

The gas in a pneumatic system is usually air. Pressure in the pneumatic system is created with an air compressor, that contains a pump, reservoir and air treatment functions. Air treatment is needed to remove water vapor from the air before it is fed to actuators. Filters are used to ensure clean air. Pneumatic systems are open loop systems. This means that used air doesn’t need to be circulated back to the compressor, but instead it can be released directly to atmosphere. Since the pneumatic system does not need to be a closed system, many factories distribute it from single source to an entire factory. The normal pressure for the pneumatic system is 10 bar. [19] Figure 1 demonstrates a basic pneumatic system with an air compressor, a valve and a cylinder actuator.

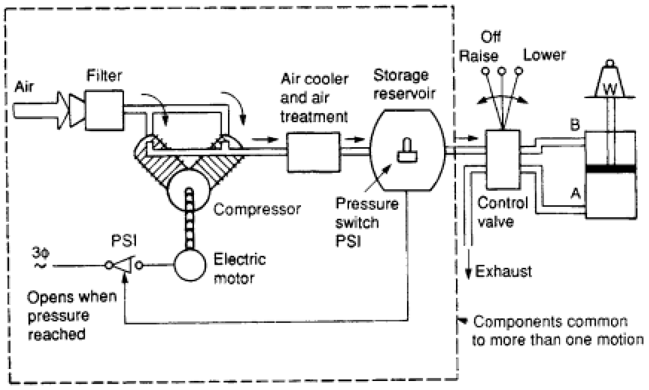


Figure 1 Example of pneumatic system [27].

With actuators, gas or fluid energy is converted to a linear movement and a rotary movement [19]. Pneumatic actuators are cheap and very simple actuators. Pneumatic actuators should be used when handled parts are light and fast speeds are needed. Pneumatic actuators are commonly used in grippers, since quick and reliable part picking and dropping is important to the utilization rate. [14] The simplest linear movement actuator is cylinder [19].

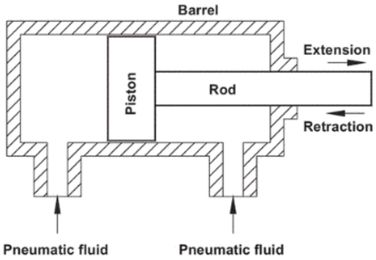


Figure 2 *Cylinder actuator for hydraulics or pneumatics [19].*

The cylinder actuator in Figure 2 consists of a rod with a piston inside a barrel. Compressed air is fed behind the piston and pressure then moves the piston forward. Pressure on the other side of the piston is released to open air.

A piston diameter is important when calculating cylinder force or speed. System pressure together with the piston diameter define the amount of force that a cylinder can apply. Speed is a function of the air flow rate and the piston diameter. System pressure has no effect on the speed of the cylinder, but it has an effect on acceleration. [19] The speed of a pneumatic cylinder is limited by how much kinetic energy the cylinder end can handle before breaking. Manufacturers usually provide information on how much kinetic energy an actuator can handle and how much force a cylinder provides with certain pressure [14].

2.1.2 Machine vision

Machine vision combines software and hardware solutions to automate visual inspections. It is used to verify part existence and to gain its current properties [15]. Part properties can be anything visually detectable, such as shape, position, orientation or surface quality. Machine vision is a important part of any manufacturing system, where part quality, documentation or traceability are desired. Common applications for machine vision are differentiating between parts, guiding robot to part, checking assembly for missing parts and detecting scratches or other impurities in the part surface. Figure 3 shows basic hardware and software parts of a machine vision system. [28]

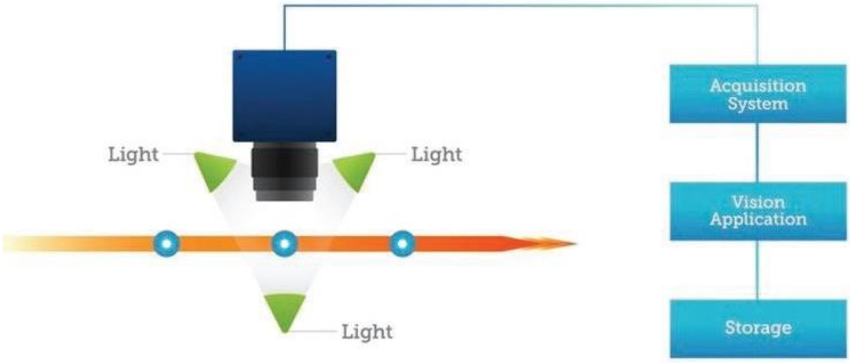


Figure 3 *Machine vision application hardware and software [1].*

When designing a machine vision application, an engineer selects suitable components. The main components are the vision application, camera, light source and lens. By selecting hardware components an engineer selects what aspects of a part are highlighted and what kind of an image vision the application receives for analysis. Vision application then uses algorithms to recognize shapes and objects from the image. The engineer must teach the vision application what features the image has to contain and what needs to be measured. Machine vision systems are not universal, but rather designed to perform certain inspections on a certain part. [15, 28] Figure 4 shows the difference that lighting alone creates. Both pictures have the same can, but the left picture uses bright ring light and the right one uses diffused light.

Figure 4 *Difference caused by light source [2].*

A human being might be able to read the code from both pictures, but visual inspection algorithms can not. Visual inspection software can make some basic image improvements on the digital level but it is always better if the received image is of good quality and the subjects of inspection are clearly visible. Designing a machine vision inspection solution requires the engineer to know something about illumination, optics, visual inspection software and part presentation. The engineer must consider both hardware and software side and combine them for the best possible solution. [15, 28]

2.1.3 Industrial robot

The first industrial robot was employed by General Motors in 1961. It was powered by hydraulics and it had 5 moving axes. That was the maximum number of axes that control technology of the time allowed to use. Since then industrial robots have evolved thanks to technological advances and creative robot designers. Changing hydraulic motors to electrical motors, allowed robots to be smaller and more accurate. At first DC (Direct current) and stepper motors were used. DC motors were fast but not powerful enough to handle big loads. Stepper motors were good for applications where high precision was needed. When AC (Alternating current) servo motors became available, they replaced DC and stepper motors in the majority of industrial applications. The performance of AC -motors has constantly improved with providing better precision, high load-carrying capacity, advanced control and good repeatability. [31] In 2018, 422 thousand industrial robots were shipped globally, and total global sales of industrial robots was 16.5 billion US (United states) dollars [23].

These days industrial robots are viewed as standard products by system integrators and automation providers. Industrial robots are used because of their low-price, speed and flexibility. With well-known systems, such as industrial robots, manufacturers can realistically estimate MTTR (Mean time to repair*)* and MTBF *(*Mean time to failure) for their products. This reduces the risk for the system integrator and to the end-user as well. Considering safety aspects is important with industrial robots. Robots can move quickly, and the biggest robots are able to carry over 1000 kg. Various international standards exist to define an industrial robot and to help integrating them safely into production. [31]

Industrial robots are usually classified by the form of the robot structure. The robot structure is comprised of prismatic and rotary joints that have been linked together. By moving joints together, a robot can position itself in a number of different configurations and reach any position inside a working area. A robot needs at least six joints to be able to reach any place in any angle. Industrial robots have been classified by the robot industry into five classes: SCARA, articulated, cartesian, parallel and cylindrical.

The robot name **SCARA** is an abbreviation of *Selective Compliance Assembly Robot Arm*. SCARA robot has four joints and it was designed to meet the needs of assembly applications. Figure 5 shows the SCARA robot configuration.

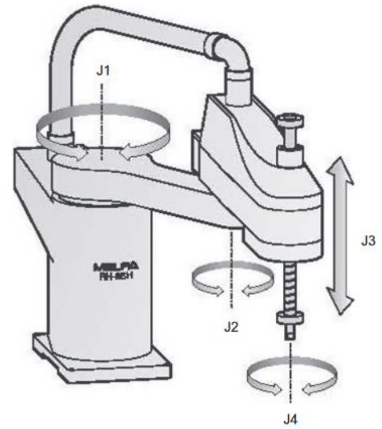


Figure 5 *SCARA robot [31].*

The SCARA robot has one rotating base axel, two rotating axels on the same vertical plane and one prismatic axel that moves vertically. Arm configuration is rigid and allows the robot to accomplish fast and precise movements. Acceleration is also very good. These robots are usually used in assembly tasks and possibly for palletizing some small items. The drawbacks of SCARA are its limited reach and small payload carrying capability, less than 2 kg. [31] SCARA robots are mainly used in applications where quick movements and short cycle times are required. [31]

Articulated arm robot is the most common industrial robot. It is comprised of two or more rotating joints. The most common configurations have four and six joints. A six joint structure of the robot allows it to reach any position in multiple different arm configurations.[31] Figure 6 shows an example of an articulated arm robot.

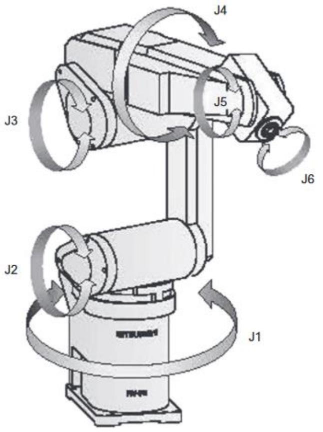


Figure 6 *Articulated six-axis robot [31].*

Each joint in the robot carries the weight of the following joints and the robot structure is not rigid. This has an effect on the robot’s carrying capacity, accuracy and repeatability. Despite this articulated arm robots are well suited for the majority of applications. They are used in welding and painting applications as well as in handling applications of objects of all sizes. A typical carrying capacity can be from 3 kg to 1000 kg and the largest robots can have a reach of over 3.5 m. [31]

The cartesian robot category includes robots that use linear drives for their major axes and their movement coincides with the cartesian coordinate system. It is common that these robots only have three axes. Sometimes they are equipped with rotating fourth axis. [31] Figure 7 illustrates a cartesian robot.

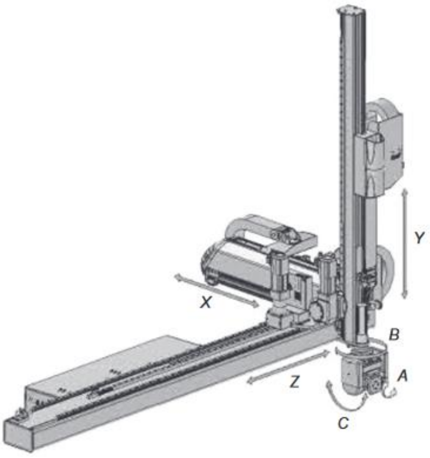


Figure 7 *Cartesian robot [31].*

A cartesian robot structure is variable and flexible. These robots can be freely constructed by using modular kits. This way the robot can be designed to suit the needs of the application. Cartesian robots are mainly used in part handling, palletizing, machine tending and plastic moulding. Heavy duty versions can move objects weighing up to 3000 kg. Despite their modular and simple design, an equivalent articulated robot is usually cheaper. [31]

Parallel robots are also called delta robots. This robot design is a recent one and it aims to achieve high acceleration and speed by reducing arm weight. This robot does achieve a performance similar to SCARA, but typically they are only able to carry loads under 8 kg. The robot structure consists of arms that have rotary or prismatic joints. Motors that control joints are in the base structure above the arms. The main applications for this robot are assembly operations and picking. They are often used in packaging lines in the food industry. [31] Figure 8 shows a parallel robot.

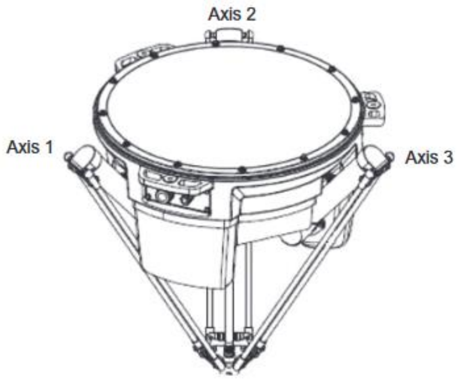


Figure 8 *Parallel robot [31].*

Cylindrical robots are a combination of rotary and linear axels. Typically, the base axis is rotating and attached to it are the horizontal and vertical axes. This robot has a rigid structure and it is able to access deep cavities. This makes them generally suitable for machine tending and part pick and place applications. They are mostly used in electronics industry for clean room applications. [31] The basic structure of a cylindrical robot is in Figure 9.

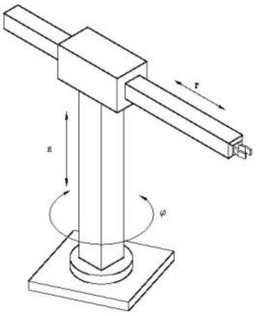


Figure 9 *Cylindrical robot [8].*

2.1.4 Metal laser cutting

The first laser was built in1960 and since then laser technology has been actively researched. Laser stands for *light amplification by stimulated emission of radiation*. Basically, a laser is a device that produces as well as amplifies powerful beams of directional and coherent light. A laser consists of three basic elements: a gain medium that amplifies light, an energy source that pumps energy to medium and two mirrors that trap light between them. [30] See Figure 10 for an illustration of this construct.

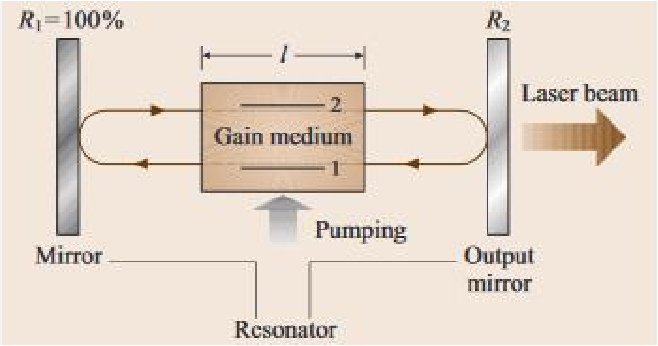


Figure 10 *Construction of a basic laser [30].*

The laser medium can be solid, semiconductor, gas or liquid. Lasers are classified based on the medium that they use. The Medium defines the output wavelength and almost every possible substance has been tried to use as active medium in a laser. The energy source can be a lamp, electrical current or another laser. The first laser was realized by using ruby as gain medium. Ruby was in form of a rod and both ends of the rod were polished. Excitation of the medium was done with a flash. [30]

Today, laser technology is present in multiple areas of science and industry. For example, lasers are used in medical science, communication and manufacturing. Even in everyday devices like laser printers and barcode scanners. Now days laser technology is actively used in manufacturing to replace many traditional fabrication processes. Laser can be easily and economically used to perform cutting, welding, coating, marking and metal hardening. Laser is also usually cleaner and more quiet than comparable mechanical process. [24] In 2018, the international revenue for industrial robots was 5058 million US dollars and for 2019 it is expected to grow up to 5161 million US dollars. [23]

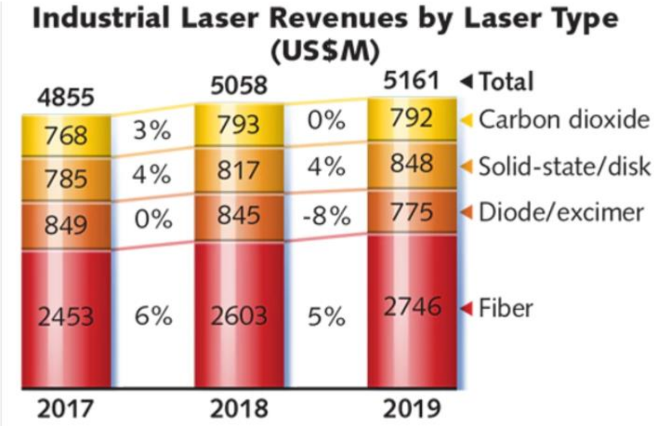


Figure 11 *Estimated industrial laser revenues by laser type [23].*

Figure 11 shows the revenues for industrial lasers in the past two years and an estimation for the year 2019. The same figure also shows revenues for the most common lasers used in industrial applications: CO_2(Carbon dioxide), solid-state/disk, diode/excimer and fiber. Gas laser CO_2 and solid-state laser Nd:YAG (Neodymium-doped yttrium aluminum garnet) are used in the majority of laser machining applications [21].

The carbon dioxide or CO_2 laser employs gas as its gain medium. CO_2 lasers are popular in the manufacturing sector because of their ability to deliver high output power, controlled power mode and high beam quality. This laser type is especially suitable for sheet metal cutting. With CO_2 laser, it is possible to achieve high cutting speeds, processing flexibility and superb cut quality. [21] The power in available solutions ranges from few watts to 10 kW. The beam guidance is done using moving mirrors. [30]

Solid-state lasers refer to lasers that use solid substances as medium. Fiber lasers are a sub-section of the solid-state lasers [24]. Nd:YAG is a good example of solid-state lasers and it is widely used in manufacturing. Interest to use Nd:YAG instead of CO_2 in cutting processes is growing. Unlike CO_2 laser Nd:YAG has a short wavelength, high peak power and it can be focused to even a smaller area. It also supports wider options in optical material and the beam can be delivered in a fiberoptic cable making the system more flexible. Because of this flexibility and high power, Nd:YAG is widely used in the field of robotic cutting. [24] Nd:YAG is suitable for cutting through a thick or highly reflective material, such as copper and gold. It is often used in applications where precision is wanted. [21]

Cutting material with a laser is a two-dimensional process. An intense laser beam is focused to achieve material removal from a workpiece. The material melts or vaporizes because of the heat that the laser beam creates. Melting happens through the thickness of the material. The molten material is pushed aside by a pressurized assist gas jet. Various types of assist gas may be used to achieve different kinds of reactions in the material. Assist gas could cause a melt expulsion, which would help the material removal, or enhance the material by oxidizing it. Cutting shapes is accomplished by moving the laser beam across the workpiece in a desired cut pattern. Figure 12 demonstrate how laser cuts metal. [24]

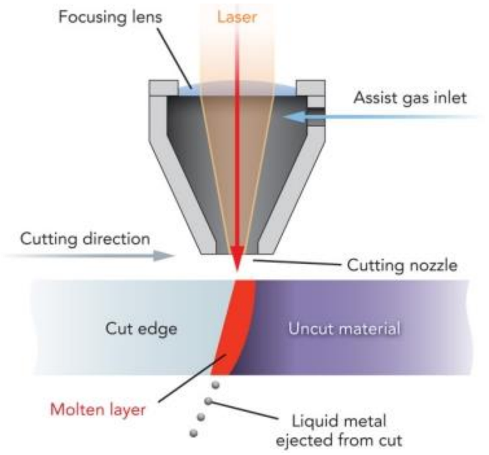


***Figure 12** How laser is used to cut metal [11].*

Cutting metal with laser has several advantages over the mechanical cutting techniques [21, 24]:

1. Easy to integrate with automation. The majority of laser applications allow detailed control of part dimension and cutting speed via CNC-control (Computer numerical control).
2. Laser doesn't touch the part. There is no need to clamp the part down or to have the part positioned exactly.
3. There is no tool wear or need to change tools between products.
4. Laser can be cost effectively used for prototyping production or for fully automated production.
5. Part dimensions are fine and precise.
6. High cutting speeds can be achieved.

7. Cut quality is better.
8. Laser can be used to cut many different materials. Even nonmetallic materials are possible.

Drawbacks of laser cutting are a high initial investment on equipment, maintenance costs and running costs. When considering laser instead of a traditional mechanical cutting, a cost analysis is recommended. Laser can't compete in costs or in cycle time with a punch press or a CNC turret when used to make standard products. Materials with high thermal conductivity and high reflectivity, like copper, aluminum and gold are difficult to cut with an infrared laser. The material thickness limit is defined by the beam penetration capability and incomplete cuts are hard to fabricate. [24]

2.1.5 Vibratory feeders

Maintaining the part order all the way through the manufacturing process is often expensive. In many cases, parts are delivered in boxes or bags instead of pallets. [17] Part feeding is a major problem for an automatic high-speed assembly. An automatic assembly requires parts to be presented in the same location and in the same orientation each time. Any problems in part feeding can have great effects on automation system performance. Part feeding needs a mechanism to sort incoming parts and to make them ready for assembly. [18]

A machine that is designed to orient and sort out parts before assembly phase is called a part feeder. The most common feeder used in the assembly industry is a vibratory bowl feeder. Nearly 80 % of the automated assembly systems are fed with them. For small parts that are required at frequent intervals, vibratory bowl feeders, vibratory tracks and different mechanical feeders can be used economically. Designing a functioning part feeding solution is essential in ensuring fault free performance of any automated assembly system. If feeders don't work reliably or they are too slow, the entire assembly process is affected and the production capability of the system is reduced. Because of this, part feeding is responsible for a large part of the assembly machine costs. [17]

A vibratory bowl is a very common part feeder that uses a vibrating bowl to move and orient parts. The feeder itself consists of a bowl that is supported by three springs. The bowl is also connected to an electromagnet that is used to create vibrating movement. When the bowl vibrates, parts rise along a spiral track inside the bowl. The spiral track moves parts out of the bowl. [18] Figure 13 shows a structure of bowl feeder.

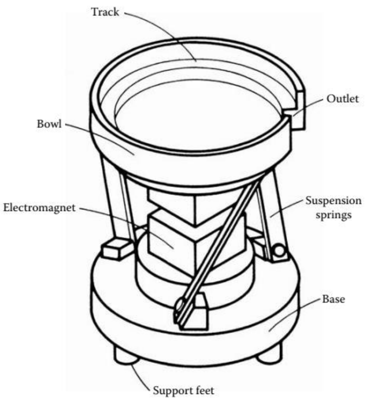


Figure 13 *Vibratory bowl feeder [18].*

The vibratory bowl feeder allows the greatest flexibility of all feeding systems when designing orientating devices. Orienting parts inside the bowl is done with mechanical features along the spiral track. Orienting features can be divided into two groups: passive and active. Passive orienting devices work on the principle of rejecting parts that are in a wrong orientation. In a bowl feeder, passive orienting devices would push parts off the spiral track and drop them at the bottom of the bowl. From there parts would start climbing the track again. [18]

Figure 14 shows how a bowl feeder can feed and orient screws. First a wiper blade rejects screws that are standing on their head or if there are multiple screws on top of each other. A screw can be tipped over or dropped back down to the bowl. The next orienting device is a pressure break. Screws can pass here only in a line and either their shank or head facing forward. Pressure break also prevents any congestion from forming if the delivery chute is full. Excess parts are dropped to the bowl. The final orienting device is a slot in the track. A screw drops down to the slot and is held there by its head. It doesn’t matter if a screw comes head or shank first. This device is an active orienting device whereas the two previous ones were passive. [18]

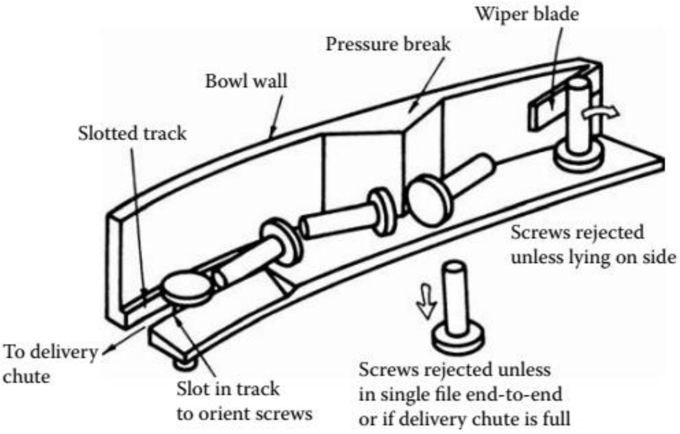


Figure 14 *Screw orienting in bowl feeder [18].*

Active orienting devices change the part orientation instead of rejecting it. Some parts can have number of different orientations in which they could come out of the feeder. For example, a part has eight different orientations, but only one orientation is accepted. Orienting with just passive devices, the actual feed rate of the feeder would be the unoriented feed rate divided by eight. By using active orienting devices, like the rail in Figure 14, the feed rate can be improved.

In Figure 15, there is an example of how active devices can be used to sort rectangular blocks. The first orientating device is a wiper blade that prevents parts lying on their side from passing. Then a rail lifts a block against the bowl wall and effectively changes its orientation. The rail is an active orientating device and the wiper blade is a passive one. [18]

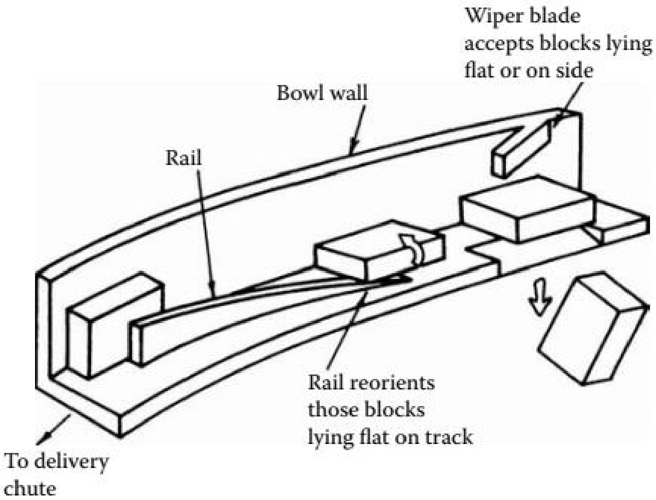


Figure 15 *Orientating rectangular block in bowl feeder [18].*

Each vibratory bowl is designed and manufactured to feed certain parts. Even today the majority of bowl feeder design and manufacturing is done by hand by skilled workers. These workers use their experience and examples from literature to come up with suitable orienting devices and fine tune them to feed certain parts. Bowl feeders can be designed to feed a wide array of parts. Figure 16 shows how a groove and sloped edge can be used to sort parts. Figure 17 illustrates how bottle caps could be fed with bowl feeders. Bowl feeders can’t be used for parts that could tangle, like springs, or with parts that can’t touch each other [18].

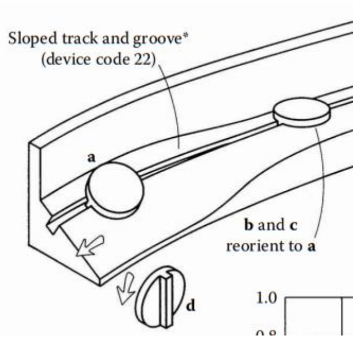


Figure 16 *Sloped track and groove sorting example [18].*

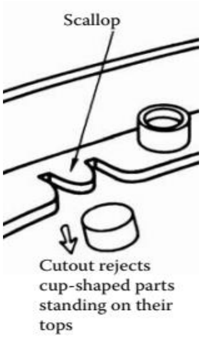


Figure 17 *Bottle cap sorting example [2].*

Vibratory bowl feeder performance depends on the amount of material in a bowl. As the bowl empties, performance of the bowl changes. Because a bowl is fed with constant power, reduction in mass of the bowl leads to an increase of the feed rate. This is one of the major disadvantages of vibratory bowl feeders. Assembly machines are usually designed to work with fixed cycle times and a feeding device must bring a new part available in a uniform time.

The effect of the vibratory bowl load sensitivity can be reduced by increasing stiffness of the springs, but at the same time the overall feed rate lowers considerably. Some more advanced and expensive bowls use accelerometer and silicon-controlled rectifier control systems to achieve controlled feed rates. Bowl acceleration changes as a function of the bowl mass. By measuring acceleration, a control system can keep the bowl vibration steady. A more simple and cheaper solution is to monitor the bowl fill level with a sensor and automatically add new parts from a secondary feeder. This keeps the bowl load constant and minimizes changes in the feed rate. [18, 31]

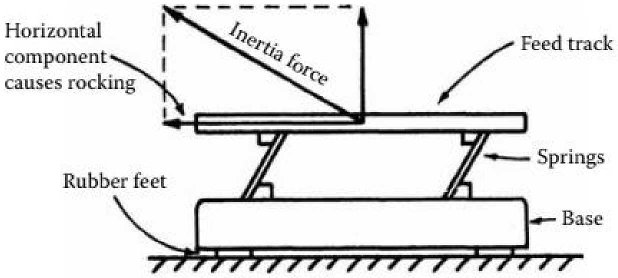


Figure 18 *Structure of linear feeder [18].*

A linear feeder works in same manner as the vibratory bowl, but the part movement is linear. A linear feeder structure is in Figure 18. Linear feeders don’t usually have any orienting features. They are mainly used for part transport and they are often paired up with bowl feeder. The bowl feeder orients parts and the linear feeder transports parts to the assembly machine. Linear feeders can also be used with more delicate and larger parts than a bowl feeder could handle.[18, 31]

2.2 Design methodology in manufacturing

When a manufacturer needs to make a change in their product or production, they start a design process. Reasons for starting a design process could be a need to update an existing system to meet market demands, a need to introduce a new product or improve working conditions. The final goal of a design process is to find a solution that fills all the manufacturing requirements. Needed solutions might be complex and at the start of the process it is impossible to account for every possible problem. It is normal that requirements might change or become more detailed as the design process progresses. Because not all problems can be foreseen, it is not unheard of that a design process is handled with less of a planned structure and with more dealing with problems as they arise. [16]

The responsibility for a design process falls on engineers and designers. During a design process designers are faced with problems that require a lot of thought and time. Solving these problems requires designers to have knowledge on multiple different application areas and readiness to seek out new information. From the psychological point of view, a design is a performance that requires comprehensive understanding of physics, mathematics, chemistry, mechanics, electrical engineering, hydrodynamics, design theory and machine elements. In addition to knowledge, characteristics of a good designer are resolution, initiative, tenacity, optimism and teamwork. These same qualities also apply to process managers. [16]

A design of a new system can be based on experiences and models of other similar systems. Then the design is already well tested and it just needs to be adapted to the current process. If there are no past experiences or previous solutions then designers have to create a brand new solution. In these situations, a common practice in the industry is to solve a problem by the trial-and-error method. In this method, designers use creativity and intuition to form a solution that they think will work. During the design process, all decisions are somewhat based on intuition and experience. These kinds of best guess decisions must be made because otherwise the process would cease progressing. But decisions made with intuition only might ignore some crucial bits of information and cause problems later. [16]

Design methodology is a list of actions that should be taken when designing a good system or solution. The design methodology is based on cognitive psychology, science of design and work experience from many different domains. Actions inside the design methodology are working steps that are linked together and phases of design separated by organization and content. A plan given in the design methodology is a general guide that needs to be adapted and modified to the needed task. Having a predetermined structure on a design process allows concentrating on important aspects and creating overall good solutions. Without a structure, time might be wasted on thinking of ways to work and leave designers with numerous possible approaches. The structure makes it easier for designers to concentrate on the entire process and not get distracted by smaller problems. [16] Figure 19 shows a flowchart of a general problem-solving sequence.

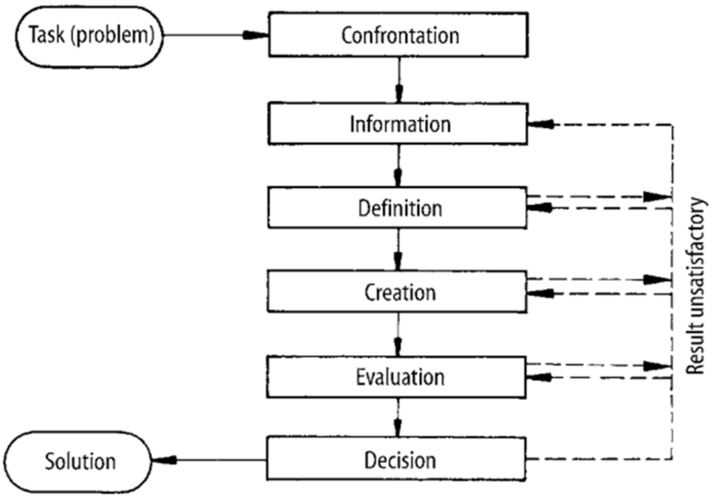


Figure 19 *Sequence for solving problems [26].*

Confrontation is the first phase and involves getting to know the problem, i.e. what is known and what is not known. The duration and importance of this step is highly affected by the designer’s experience, area of expertise, knowledge and ability. During the **information** phase, the designer studies the problem itself more deeply. What are the requirements and limitations? Are there existing solutions for this problem and could they be used here? The **Definition** phase involves detailing the main task in an abstract level to assist in deciding the main constraints and objectives. A neutral definition the task encourages the designer to look for solutions with an open-mind and to come up with more unconventional solutions. The found solutions are developed and combined in the **creation** phase and compared in the **evaluation** phase. All these steps lead to the **decision** phase where the best possible solution is picked. Each phase can be repeated until requirements for the next step are met. Sometimes problems or new information that was learned in the creation or evaluation phases might require designers to return to the information phase. This process of repeating phases is called iteration. By repeating phases designers can be sure that the found solution is satisfactory. [26]

The design methodology process can be and should be adapted to suit the needs of different industrial domains and therefore a lot of different variations of it are suggested in the literature. It is up to the designer to find right one for the current task. Although there are multiple different design methodologies available in literature, all of them follow a similar structure. Design and implementation are elementary phases in the development process. These elementary phases incorporate such activities as information gathering, defining goals, appraisal, decision and realizing solution. [16]

2.2.1 Systematic approach to variable manufacturing system

Francalanza et al. propose a design methodology for changeable manufacturing system [22]. In their methodology, the requirements for the design process come from external activities. These activities are process planning, investment planning and product design. Mentioned activities don’t stop when the design process is activated. They continue occurring continuously and in parallel with the design process. The visualization of the proposed methodology is in Figure 20. Phases of the proposed methodology are analysis, synthesis, simulation, evaluation and decision. [22]

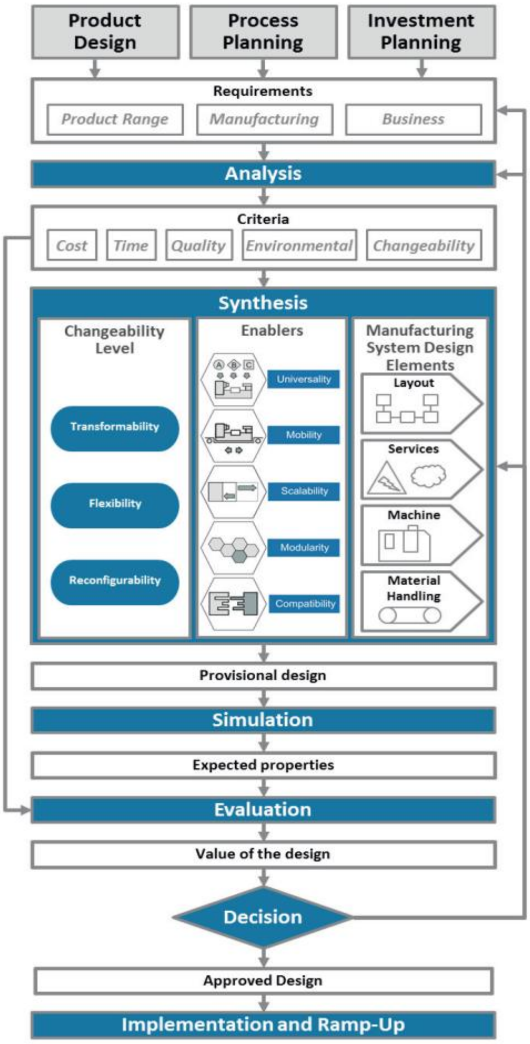


***Figure 20** Proposed design methodology for changeable manufacturing system [22].*

In **analysis**, requirements for system are introduced to the designer. From the requirements the designer forms goals that need to be met and understands problems behind the task. The result of the analysis is criteria that is used to evaluate the found solutions later in the design process. Common requirements for a changeable manufacturing system are product range, business and manufacturing requirements. The designer must understand what kinds of products the manufacturing system is used to make now and how a product can change in the future. Only by trying to estimate possible future products the design of an optimal changeable manufacturing system is doable. Business requirements deal with economic indicators, like price per part and investment cost. Manufacturing requirements encompass all manufacturing processes that must be performed to form a final product, manufacturing strategy and machine layout.

Synthesis is the next phase. Synthesis is a combination of elements or components to build the whole system. During this activity the designer creates solutions for problems in a manufacturing system. Francalanza et al. suggest that the designer should commit to domains of changeability, enabler and design element [22]. With the changeability domain the designer chooses on what level the system changeability is implemented. The designer can choose between factory level transformability, FMS(Flexible manufacturing system*)* or RMS (Reconfigurable manufacturing system*)*. This decision affects the designers' options in the changeability enablers domain and in the design elements domain.

Simulation involves the creation of an artificial history to a provisional design solution. The created history is observed. From these observations estimations for the technical performance of the real system are created. Output of this activity is the expected technical properties of the provisional design solution.

In **evaluation**, the provisional design solution is compared against the design criteria set in the analysis phase. A solution is given a value based on how well it meets the established requirements.

The **Decision** is made based on results from the evaluation activity. The designer can choose to continue with the current design or they can choose to try a different solution. When a satisfactory design is achieved, the project advances to implementation planning.

2.3 Computer-Aided Design

The first numerical control machine was built in Massachusetts Institute of Technology (MIT) in 1952. This was the first computer controlled milling machine and it was one of the first steps towards CAD (Computer Aided Design). Manufacturers and engineers saw CAD's potential even though computers of the time were not advanced enough to realize it. The problem with the computers was limited graphics, user interfaces and storage capacity. Many manufacturers and organizations invested a lot in developing CAD-systems. During 1950's and 1960's multiple companies developed their own commercial CAD software. These early CAD programs aimed to remove the need for hand-drawn documents and to create electrical technical drawings that could be created and modified quickly. In the 1970's cheaper computers allowed CAD to spread to every field of engineering. Until 1970's, CAD drawing had been limited to two dimensions, but the addition of the third dimension allowed engineers and designers to test their designs in a completely new way. They could build larger 3D assemblies and test their functionality virtually. Printing out technical drawings of 3D models for manufacturing was also quick. 3D models could also be used directly to generate code for milling machines with CAM (Computer Aided Manufacturing) software. CAD technology continued to advance and refine in 1990's thanks to increased computing power. [20] In the 21th century, CAD is still evolving and it continues gaining new uses in the world. It is widely employed in multiple fields of technology, such as computer games, 3D graphics design, architecture, structural engineering, electrical engineering and product development. [25, 32]

Modern CAD solutions can be categorized roughly into two different categories: mesh modeling and parametric modeling. Mesh modeling is generally used for artistic purposes since precise measurements are not important and the user simply pushes and pulls the shapes that are wanted. Mesh-modeling can be compared to sculpting and as such it is favored by digital artists and game designers. [20]

Parametric CAD software is used by drafters, mechanical engineers and engineers because they need their models to be realistic. With the parametric modeling software the user can define an object's place, height, width and thickness precisely. All values are entered as parameters for creating an object. Figure 21 shows a cube created with parametric modeling software and cube's parameters. [20]

Parameter	Name	Unit	Expression	Value
Favorites				
User Param				
User ...	Height	mm	10 mm	10.00
User ...	Width	mm	Height	10.00
User ...	Depth	mm	Height	10.00
Model Para...				

Figure 21 *Cube created with parametric modeling [20].*

All parameters can be saved and modified later if necessary. This allows engineers and designers to build accurate representations and even specify object's physical properties, such as material and thermal properties. A finished 3D model can be anything from a building to a spring or a screw. CAD also supports building assemblies from individual parts. Assemblies are built by defining relations between different parts. In assembly parts can move if defined relations allow it. Designers can build entire machines from parts or from smaller assemblies. Figure 22 shows a 3D model assembly of a robot arm. [20, 32]

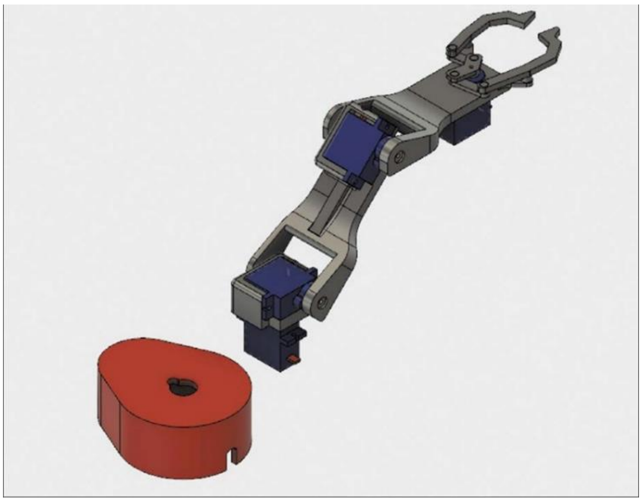
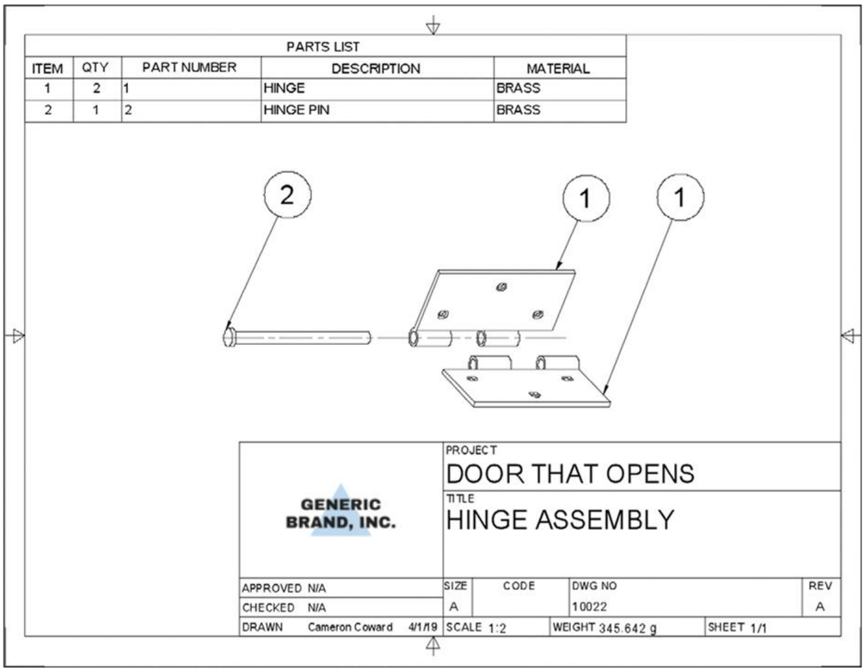


Figure 22 *Robot arm 3D model assembly [20].*

With CAD software, a model can be resized, tilted, rotated and moved in any direction. This lets engineers to see inside models, look for a same problem from different angles and consider all possible options. When a model is complete, the entire system can be tested in a simulated environment to make sure that everything fits together and there are no collisions during the actual movement. In addition, effects of environmental conditions can be tested and accounted for before anything is built. Once everybody is happy with the design, it can be transformed to manufacturing instructions with detailed information about manufacturing tolerances. Examples of manufacturing tolerances are surface quality and hole or axel machining tolerance. Figure 23 shows hinge assembly instructions drawing made from a 3D model with CAD. [20, 32]



PARTS LIST

ITEM	QTY	PART NUMBER	DESCRIPTION	MATERIAL
1	2	1	HINGE	BRASS
2	1	2	HINGE PIN	BRASS

GENERIC BRAND, INC.

PROJECT DOOR THAT OPENS

TITLE HINGE ASSEMBLY

APPROVED N/A

CHECKED N/A

DRAWN Cameron Coward 4/1/19

SIZE A

CODE

DWG NO 10022

REV A

SCALE 1:2

WEIGHT 345.642 g

SHEET 1/1

Figure 23 *Example technical drawing [20].*

CAD technology used in a right way can improve design quality, decrease time in designing and reduce the complexity of a geometric design. Proper designing tools makes it easier for engineers and designers to go through multiple iterations and evaluate their performance. Building production lines with CAD makes it possible to build entire production lines virtually and test functionality with 3D representation of the product. This way multiple different options can be tested without the actual product. [20, 25, 32]

2.4 Tumbler lock manufacturing

Rotating tumbler disc locks were invented by Emil Henriksson in 1907. In 1919 Ab Lukko Oy was founded to manufacture these locks. Later, Ab Lukko Oy became Abloy Oy. Rotating tumblers are a unique locking solution and it has many benefits over traditional pin and spring locks. Rotating tumblers are harder to manipulate and mechanically they are more reliable. Lock to open all discs must be in a correct orientation. When a key is inserted in a lock, grooves in the key guide discs to correct the orientation. Picking tumbler disc lock is difficult since you cannot detect when the disc is in correct orientation. [3-5]

Over the years there has been several updates to the lock design, but the basic function is still the same. The current product family is called Protect2. Protect2 has 1.97 billion different key combinations and it has been patented to year 2030. [3]

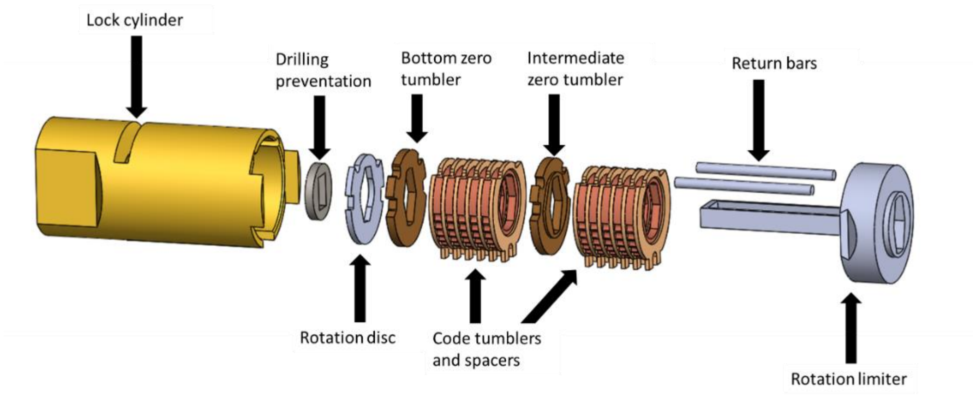


***Figure 24** Tumbler packet parts.*

The tumbler packet consists of multiple different parts. The main parts of a tumbler packet are lock cylinder, drilling preventation, rotation disc, bottom zero tumbler, intermediate zero tumbler, code tumblers, spacers, return bars and rotation limiter. Parts are named in Figure 24. Parts are machined and manufactured by Abloy Oy. Figure 25 further illustrates the manufacturing and storage process that happens before assembly.

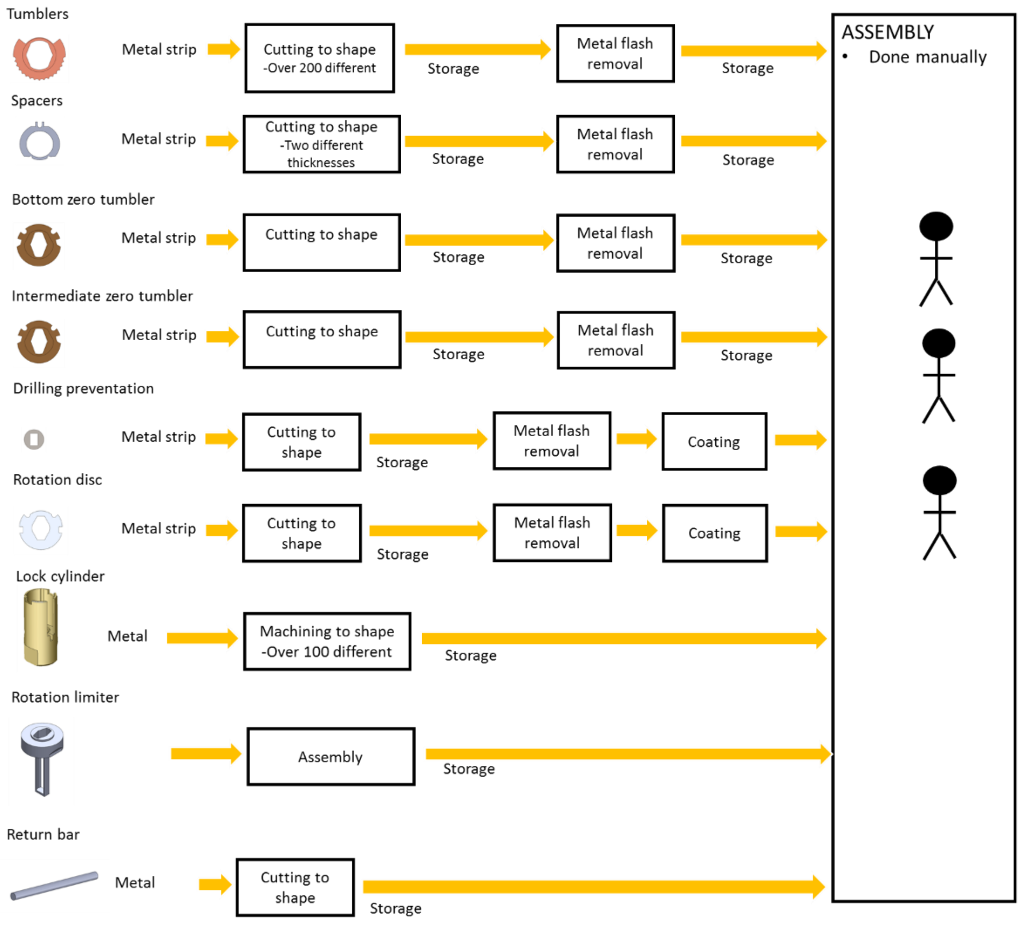


***Figure 25** Manufacturing process for tumbler packet parts.*

Code tumblers, intermediate/bottom zero tumblers and rotation discs are shaped and cut with line punching machines. Remaining metal flash is then removed and some parts are coated when needed. After that, discs are stored to wait for assembly. Lock cylinders are machined individually from single a piece of metal. Lock cylinder measurements can vary slightly after manufacturing. Rotation limiters have moving parts so they are assembled separately before they are used in a tumbler packet assembly.

2.4.1 Assembly steps

There are several steps to packet assembly. Currently a packet is manually assembled inside the lock cylinder. Assembly is carried out by a single person and all necessary parts are placed so that they can be reached with ease. Parts come in boxes and not in any order. Each lock is unique and requires its own combination of code tumblers. Assembler is responsible for picking the correct parts from boxes, orienting them and placing them inside the lock cylinder in the correct order. The steps for a manual packet assembly inside the lock cylinder are demonstrated in the flowchart in Figure 26.

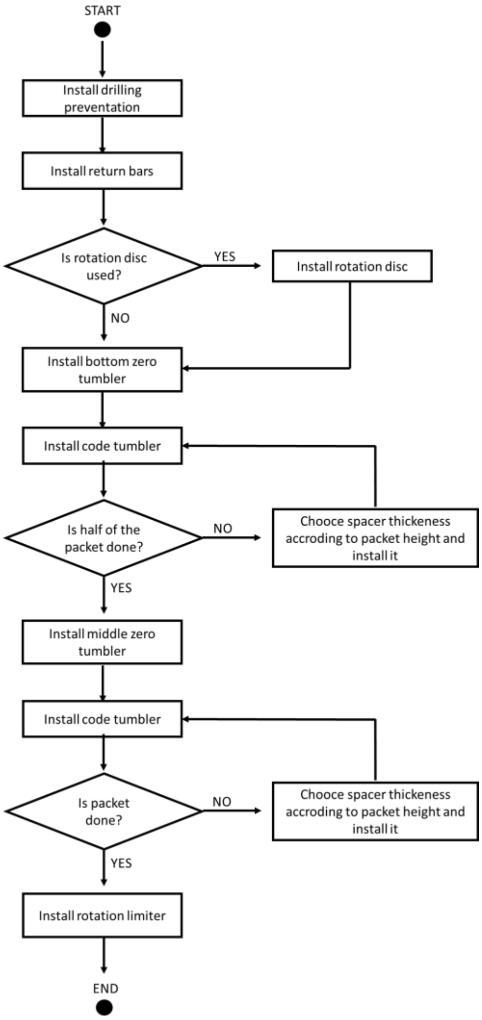


Figure 26 *Flowchart for packet assembly*

Packet assembly starts with placing a drilling prevention disc at the bottom of the lock cylinder. Next return bars are installed against the wall of the lock cylinder. Return bars are held in place by grease or special tool that can be removed after rest of the parts are in place. Rotation disc is next, if it is used with current product. Then comes bottom zero tumbler, first tumbler that starts the actual tumbler packet. On top of the bottom zero tumbler is placed all code tumblers with spacers between. The intermediate zero tumbler goes in the middle of the packet. A rotation limiter is inserted last and it is locked together with lock cylinder to keep parts from falling out.

3. PROPOSED METHODOLOGY

This thesis approaches the design process for a tumbler packet assembly by employing the methodology suggested by Francalanza et al. [22]. It needs to be adapted to suit the needs of this thesis.

In this thesis, only four phases are going to be used: analysis, synthesis, simulation and evaluation. The aim of this thesis is to go through the different alternative solutions and find a way to compare them, but not to make a decision for single best option. Because of this, the decision phase of the methodology can be left out and the design process can be ended in the evaluation phase. Figure 27 shows the proposed methodology.

For improved readability, each phase of the proposed methodology is described in their own chapter. The following chapters 4, 5, 6 and 7 each explain the actions and results of one phase.

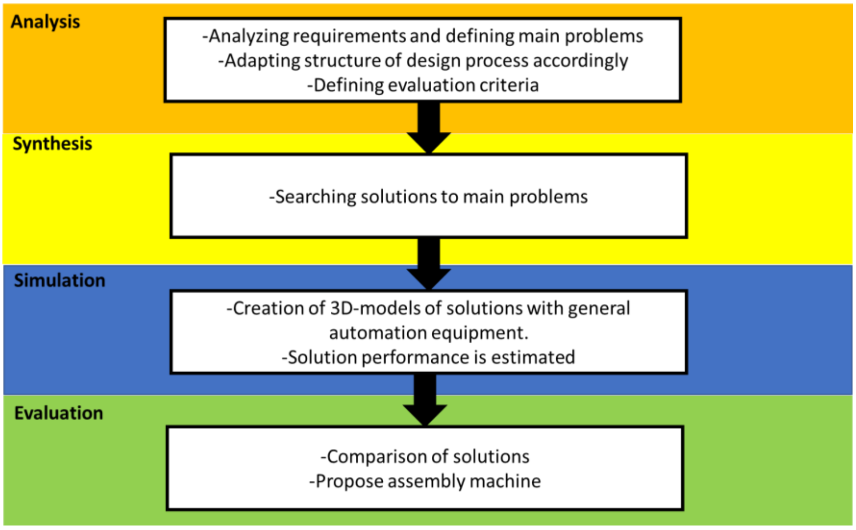


Figure 27 Proposed design methodology.

3.1 Analysis

In the analysis phase, all requirements are collected. Gathered requirements include the needs of assembly process and part feeding as well as the requirements for performance. Once all requirements are collected, they are analyzed. Based on the analysis, problems are identified.

If a problem can be solved with common sensors or a suitable solution can be found from the literature, it is considered solved. A problem that can't be solved with previously mentioned methods is marked as a main problem. The structure of the of design process is then adapted so that the identified main problems can be solved efficiently in the synthesis phase.

In the evaluation phase, the found solutions are compared against the defined criteria. The criteria is chosen and defined in the analysis phase.

3.1.1 Performance requirements

The target speed for the packet assembly was defined to be 30 seconds by Abloy Oy. The maximum amount of parts for a tumbler packet is 22 parts. Let's assume that packet assembly and installation to lock cylinder can run parallel. With a 30 second target speed and 22 parts to handle, it leaves 1.4 seconds for the picking and placing of one part.

3.1.2 Part feeding requirements

An assembly machine has to pick correct parts from feeders and place them together in a correct order. A tumbler packet assembly process doesn't change between product variations, only parts that are used in a tumbler packet can change. All necessary parts must be fed to the machine by feeders and this requires finding a suitable feeding solution for all of them.

The amount of needed parts for the assembly is a problem for machine design. An assembly machine needs to have access to about 60 different code tumblers since that is the amount of code tumblers one lock batch uses. The price per a fed part needs to be kept low. Additionally, feeders can't be much slower than the part cycle of 1.4 seconds. Although not all parts are needed constantly.

Machine vision in orientation detection

A tumbler packet has multiple different parts. Some parts have only 2D features. These parts are easy to feed with machine vision. There are a lot of cheap, compact machine vision cameras with integrated software and vision tools available commercially. The camera resolution does not need be high since the field-of-view only needs to be 15 mm x 15 mm.

Shannon's sampling theorem states that the sampling rate must be at least twice the original signal [29]. If the smallest detectable feature is 0.05 mm, then maximum pixel size is 0.025 mm. With this information the camera needs on one side

$$\frac{15\,mm}{0.0025\,mm} = 600\,pixels. \tag{1}$$

The minimum camera resolution is 600 x 600 pixels. All tumbler packet parts have clear 2D features that allow part orientation to be detected with machine vision.

Code tumbler

Code tumblers are a difficult part to feed and the most crucial to the assembly. Their edge contains a lock coding, and thus the edges are irregular. In the middle of the tumbler, there is a small bulge and a hole for a key. The bulge is much less than a millimeter in height. The tumbler is not completely round either. Its edge has a large opening for return bars. Figure 28 shows a 3D model of an example code tumbler.

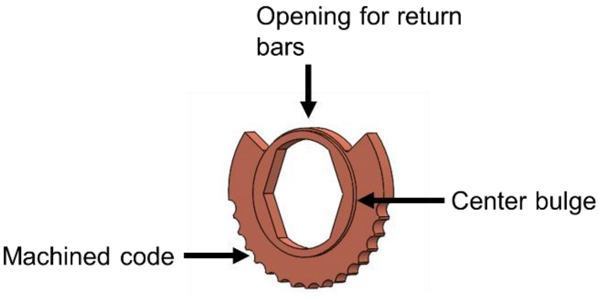


Figure 28 *Code tumbler.*

A bulge in the center of the part is a suitable feature for sorting parts according to the upward facing side. Sorting devices like this have been used in the literature. See Figure 16 in chapter 2. Since code tumblers are a high volume part, their successful feeding is critical for an automated assembly. Because of this code, the tumbler feeding have to be considered as one of the major obstacles for automating assembly.

Bottom zero tumbler

Bottom zero tumbler is the first tumbler in a packet. It does not have any coding in its edges. It has small holes for return bars and a hole for the key. It is worth noting that the key hole in a zero tumbler is considerably smaller and of different shape than in the code tumblers. A bottom zero tumbler can be flat and only have 2D-shapes, but some products require it to have a center bulge, just like in the code tumblers. Figure 29 shows a bottom zero tumbler with a bulge and Figure 30 shows it without a bulge. In Figure 30 illustrates that bulge in bottom zero tumbler is not completely round.

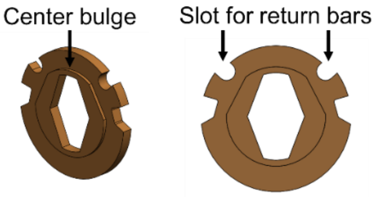


Figure 29 *Bottom zero tumbler with bulge.*

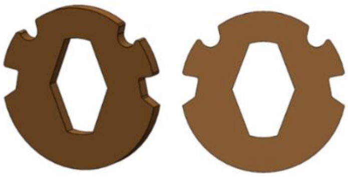


Figure 30 *Bottom zero tumbler without bulge*

A bottom zero tumbler has multiple variations. Between variations a tumbler's outer edge shape changes and so does the shape of the center hole. A bottom zero tumbler changes between production batches, but not during them. A bottom zero tumbler is difficult to install to a lock cylinder since it must be perfectly in line with the return bars. Part orientation and position is best to confirm with machine vision. Part features are easily recognizable from the picture and only one is required for each tumbler packet. When a bottom zero tumbler has the bulge, a sorting solution similar to the one that works with code tumblers can be used to separate tumbler right face up before machine vision inspection.

Intermediate zero tumbler

An intermediate zero tumbler is installed in the middle of the packet after the packet already has several code tumblers and spacers. It has a small hole for the key and places for return bars. Like bottom zero tumbler its installation is precise work since it has to align perfectly with return bars. An intermediate zero tumbler has no variations and it is installed in every tumbler packet. It has a bulge in the middle, but the shape of the bulge is not round. The bulge shape is the same as in a bottom zero tumbler. Figure 31 shows an intermediate zero tumbler.

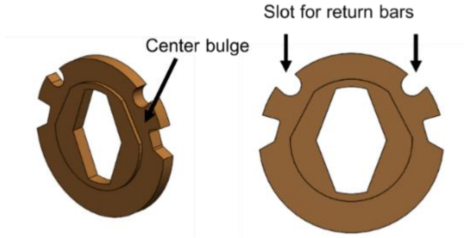


Figure 31 *Intermediate zero tumbler.*

Similarly to the code tumblers, the bulge could be used to sort the intermediate zero tumbler correct face up. The tumbler's outer edge has an extrusion that is coincident with the bulge's flat side. Together these features might make it possible to orient parts in a feeder. If the sorting would be successful it would limit the part orientation to two options. The exact orientation could be detected by several small optical or inductive sensors.

It could be to feed these parts with a mechanical feeder, but it is not worth studying further. The same feeding technique with a bottom zero tumbler is the best option. A simple mechanical feeder can make sure that parts are facing right way up and then machine vision can detect the precise part orientation. Since the intermediate zero tumbler and bottom zero tumbler are never needed at the same time, the same machine vision equipment could be used for both of them to reduce costs.

Spacer

Spacers only have 2D features and only their orientation needs to be known for the assembly. There are two different thicknesses of spacers. Spacers have a hole in the middle and they are almost completely round. Roundness is broken up by a place for the locking pin. This is a critical feature when considering a tumbler packet assembly. There is a small width difference on the locking pin side. Figure 32 shows a spacer and its dimensions.

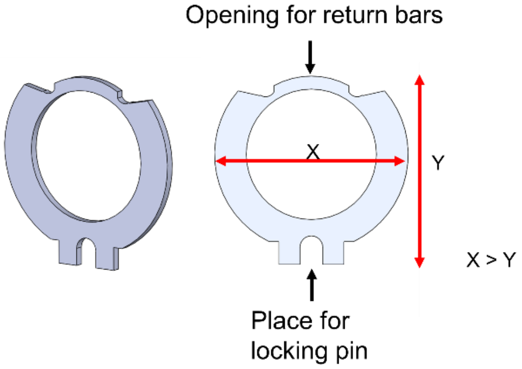


Figure 32 *Spacer features and dimensions.*

Spacers are placed between every tumbler in the packet and this makes them high volume part. Because of this, spacer feeding must be reliable and fast. Spacer’s orientation can easily be detected with machine vision. But since spacers have to be fed inside 1.4 seconds in order to meet the predetermined cycle time, studying other ways for their feeding is beneficial. Ensuring fast and reliable spacer feeding is critical for the assembly cycle time. Spacer feeding requires further study in the synthesis phase.

Rotation disc

A rotation disc is used with products that do not use a bulge in the bottom zero tumbler. A rotation disc is of a different material than tumblers. Its shape is similar to a bottom zero tumbler, but it only has 2D shapes. Figure 33 shows a rotation disc.

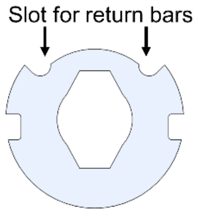


Figure 33 *Rotation disc.*

A rotation disc also has places for return bars and a hole for the key. The key hole is bigger than in a bottom zero tumbler, but smaller than code tumbler. Since a part does not have any 3D features or other features that could be used in a mechanical sorting, machine vision is the most suitable solution for the part orientation detection.

Lock cylinder

A lock cylinder has over 100 different variations. A lock cylinder's outer shape changes between variations, but the dimensions that concern the tumbler packet assembly do not. Differences between variations are at the end of the lock cylinder. Figure 34 illustrates a lock cylinder and which parts of the lock cylinder change between variations.

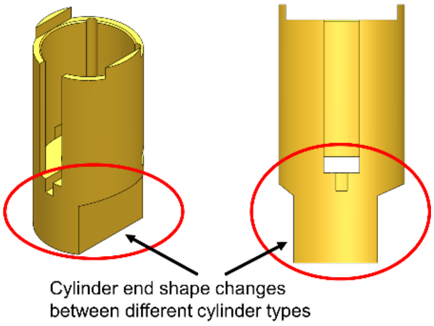


Figure 34 *Lock cylinder and changes between variations.*

The lock cylinder position and orientation must be known exactly before anything can be installed in it. The lock cylinder dimension must also be verified before it is used in an assembly. The cylinder opening and inner height must be measured before a tumbler packet assembly is started.

Each packet is constructed to fit into a specific lock cylinder. Lock cylinder dimensions might vary after machining and some residual burr might remain in the tumblers, thus causing changes to packet height in the assembly. To minimize problems and to a ensure successful assembly, the lock cylinder's inner height has to be measured before the packet assembly and during the assembly, the packet height must be measured constantly.

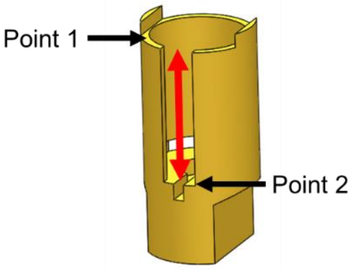


Figure 35 *Lock cylinder inner height is the difference between point 1 and point 2.*

Figure 35 illustrates what is a lock cylinder's inner height. The difference between points 1 and 2 is the lock cylinder's inner height. A tumbler packet is assembled to match that height. This measurement could be done with a laser distance sensor or a mechanical measurement probe combined with a low force pneumatical cylinder.

Verifying the lock cylinder opening before assembly is important. Lock cylinders and spacers are designed to be a tight fit. In an optimal situation, the difference between a spacer diameter and a locking cylinder opening diameter is less than 0.15 mm. If both parts are manufactured to the exactly right measurements, the space between parts is less than 0.05 mm. If a lock cylinder experiences shrinkage after machining or it was machined incorrectly, spacers can't be installed in it and the lock cylinder can not be used.

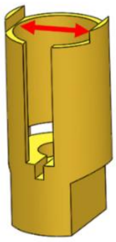


Figure 36 *Lock cylinder opening diameter.*

Figure 36 specifies what is meant by a lock cylinder opening. Simple solution for measurement is to use a mechanical tool that is machined to exact dimensions of the cylinder. An example of proposed tool is shown in Figure 37.

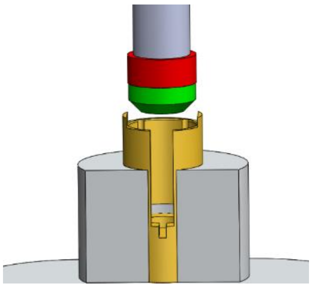


Figure 37 *Two stage tool for measuring lock cylinder opening.*

A tool would have to have two stages. The first stage is machined to the cylinder opening's minimum tolerance and the second stage is machined to maximum tolerance. In

Figure 37, the tool's first stage is shown in green and the seconds stage in red. When a tool is inserted in the lock cylinder, its position is monitored with a measurement probe. The tool's stopping point will tell if the cylinder opening is too small or too large. Figure 38 shows how the tool would behave when the cylinder opening is acceptable and Figure 39 shows when it is not.

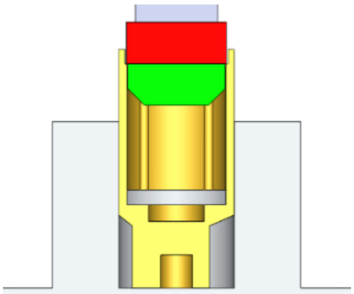


Figure 38 *Tool has stopped at right height and cylinder is OK.*

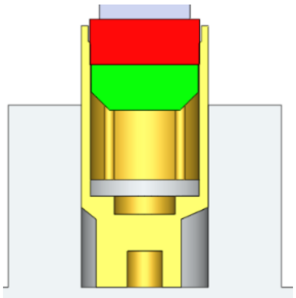


Figure 39 *Tool has gone too far and cylinder is not OK.*

System for moving lock cylinder

While a cylinder is moving between the work stations, its orientation must remain constant and parts already inside the cylinder remain correctly positioned. The finished lock cylinder must then move out of the machine in a controlled fashion, because each assembled lock cylinder is unique and its identification data must move with it to the following assembly process.

A pallet system is suitable to handle a lock cylinder transfer. Pallet feeding is easily extendable and the pallet position and transfer speed are easily controlled. A pallet system also has advantages when considering future applications. This thesis concentrates only on one phase of the entire product assembly. If Abloy decides later that they want to automate other product assembly phases as well, they can easily extend pallet track to those machines.

A pallet could have just a hole that has exactly the same radius as the lock cylinder. Figure 40 shows an example of this kind of a pallet. The problem with this solution is that it does not lock the cylinder orientation. If the lock cylinder moves during any of the assembly phases it will cause problems later in the assembly.

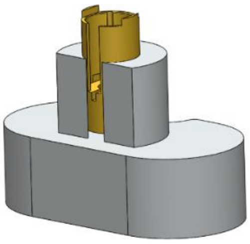


Figure 40 *Lock cylinder pallet without orientation lock.*

It is preferable to have a pallet that locks the cylinder orientation and prevents it from moving during transport and assembly. The orientation lock could be achieved by adding a separate guide part at the pallet. This part would be removable and it could be changed according to used lock cylinder.

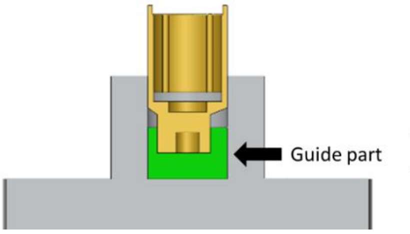


Figure 41 *Cross section of a pallet with guide part. Guide part is shown in green.*

Figure 41 shows a cross section of a pallet in which the lock cylinder orientation is kept constant with the help of a separate guide part. The guide part is shown in green color. This part is specifically designed for this lock cylinder variation. When the cylinder type changes, the guide part must also be changed.

Return bars

A return bar is a rod that is cut to a certain length. Feeding them with a linear feeder or a bowl feeder in a correct orientation is easy. Only their position needs be known before the assembly. Figure 42 shows a return bar.

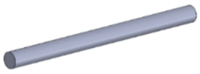


Figure 42 *Return bar.*

Return bars are installed in the lock cylinder before tumbler packet. Successfully placing return bars in a correct position and keeping them in place is crucial when a tumbler packet is brought to the lock cylinder. The tumbler packet and return bars must be exactly aligned with each other. To help keeping the return bars in a correct position, the lock cylinder has small guiding grooves.

Return bars are made of magnetic a material so a magnet outside of lock the cylinder can hold them in place. The lock cylinder itself is not magnetic, but some other components are. The rotation disc and the drilling preventation disc are drawn to magnets. The magnets holding the return bars can’t be too strong or they will pull these parts from their position. Magnets could be integrated on lock cylinder pallets. Figure 43 shows magnets position in a pallet.

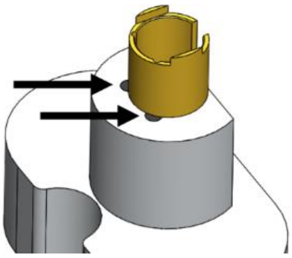


Figure 43 *Lock cylinder pallet with magnets. Arrow point to magnets.*

Drilling preventation disc

A drilling preventation disc is at the bottom of a lock cylinder. It is a round disc that has a rectangular hole in the middle. The lock cylinder has a machined place for it. Figure 44 shows a drilling preventation disc. A small mechanical feeder would be ideal for this part. The part can be installed without knowing the part orientation. Only its position needs to be known so that it can be picked. The part could also be oriented in the feeder if the part shape was modified. Figure 45 shows a modified drilling preventation disc.

Figure 44 *Drilling preventation disc.*

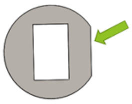


Figure 45 *Modified drilling preventation disc.*

A modified disc could be easily oriented in the feeder since it is not completely round. The width difference in part could be used to orient it. The shape change would have no effect on the function of the part. This modification is not critical for a successful assembly and was only mentioned for future considerations.

Rotation limiter

A rotation limiter is the final piece in the assembly. It is lowered inside the lock cylinder that already has the tumbler packet and all other parts as well. The rotation limiter then locks together with the lock cylinder. For installation, the rotation limiter position and orientation need to be known. It has distinctive 3D features. Figure 46 shows a rotation limiter.

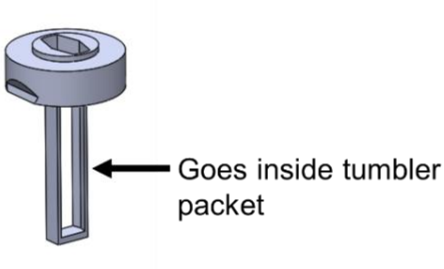


Figure 46 *Rotation limiter.*

A rotation limiters shape is comparable to a screw. Similar feeding solutions should work for both. A rotation limiter feeding device needs to have a straight line that has a gap just wide enough for the rotation limiter to fit there in a certain angle. Figure 47 shows an example of how a rotation limiter could be oriented mechanically.

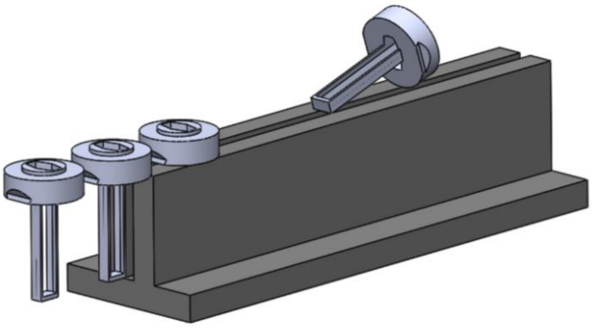


Figure 47 *Rotation limiter sorting.*

The proposed sorting method limits the part orientation to two options. A rotation limiter can be installed in both of these orientations. Abloy Oy has guidelines on which orientation a rotation limiter should be installed. Machine vision is required to find out the part orientation if these guidelines are followed.

3.1.3 Flow of design process

After studying all parts and collecting all requirements, used design methodology needs to be adapted. Figure 48 shows the structure of an adapted design methodology. For the synthesis phase, the design process is divided into separate tasks to solve the main problems found in the analysis. Three main obstacles for automating a tumbler packet assembly were identified: code tumbler feeding, spacer feeding and packet assembly to a lock cylinder.

Code tumbler feeding needs to be economical and ensure that parts are right way up for the assembly. A mechanical feeder with a groove seems suitable for this task, but it needs to be tested. If tests are successful small low-cost mechanical feeders can be used.

Spacer feeding could be accomplished with machine vision. Mechanical feeding solutions should still be researched, since spacers are high volume parts and any problems in their feeding has a great impact on the assembly machine's cycle time. A good mechanical feeder makes part picking easier and quicker than feeding with just machine vision.

Packet assembly to lock cylinder studies how a tumbler packet assembly should be handled. A tumbler packet has many parts that all need to kept in a constant orientation during the packet assembly. When a code tumbler or spacer is inserted into the lock cylinder, it must be done in a correct orientation and position. The lock cylinder and spacers have been designed to be a close fit. Part won't go inside lock cylinder or it will push the return bars from their position, if part is in a wrong orientation.

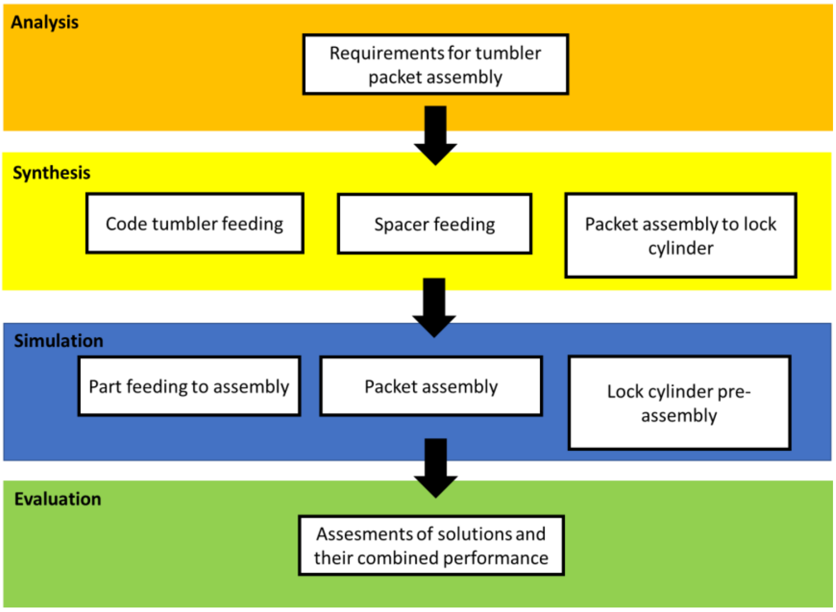


Figure 48 *Adapted design process structure after analysis.*

A tumbler packet assembly process consists of three work tasks that can be performed at the same time. The simulation phase is structured according to these tasks. Tasks are part feeding to assembly, packet assembly and lock cylinder pre-assembly.

Part feeding to assembly concentrates on how parts that are needed in a packet assembly can be fed to the machine. The needed parts include all tumblers and a rotation disc. Resulting 3D models show how the needed parts can be collected efficiently and brought to the assembly phase.

Packet assembly handles assembling a tumbler packet and installing it inside lock cylinder. To complete the assembly, all necessary parts must be accessible by the assembly equipment. Part feeding delivers most of the parts to the assembly. Spacers are fed directly to the assembly.

Lock cylinder pre-assembly is responsible for preparing the lock cylinder for tumbler packet and finishing it with a rotation limiter. Preparing the lock cylinder includes installing drilling preventation disc and return bars. Once the tumbler packet is inside the lock cylinder, a rotation limiter must be installed to finish the entire assembly.

3.1.4 Common criteria for evaluating design

To compare all proposed systems, some common criteria must be set. Estimated cycle time and relative investment were chosen to be the most suitable ones. Cycle time and investment cost can be estimated when there is knowledge of what kinds of actuators and standard industrial equipment could be used.

Epson offers very comprehensive technical information and 3D models of their robots. Prices for Epson robots were available in Wisematic Oy website [9, 10]. For these reasons Epson robots were chosen to be used as examples in this thesis.

Estimating cycle time

Cycle time consists of actuators moving each on their own turn. Tumbler packet assembly requires actuators that can accomplish picking and placing a part and moving it between two points. The movement between points is done with an electrical actuator, such as an industrial robot or a linear servo. Part picking or placing is done with small pneumatical cylinders.

To make it easier to compare robots of different manufacturers, a common cycle time test has been defined in the robotics industry. This test involves a robot performing a typical assembly application movement, where the robot picks a part, delivers it somewhere and then returns to the picking point. The defined test cycle consists of three movements. First, 25 mm upwards after which the robot moves horizontally 300 mm and finally 25 mm downwards. Then the robot moves back to the starting position by executing the same movements in reverse order. In a robot’s technical data, manufacturers tell how long it took for their robot to complete the movement in question. [31]

Epson gives an articulated robot C4 a standard cycle time of 0.37 seconds. The time that manufacturers give is for an optimal situation. In cycle time estimations, given time value is used as time that it takes from the robot to move between two points. Table 1 has standard cycle time for all the robots that are used.

***Table 1** Picking and placing time for robots according to manufacturer.*

Robot	Test movement	Time (s)
6-axis robot C4	25 mm vertical 300 mm horizontal 1 kg payload	0.37
SCARA robot G1	25 mm vertical 100 mm horizontal 0.5 kg payload	0.3
SCARA robot G6	25 mm vertical 300 mm horizontal 1 kg payload	0.38

In a tumbler packet assembly, the needed pneumatical movements are short and don't require much force. In most cases, 20 mm stroke distance is enough. Pneumatical movement times are estimated by using a small pneumatical cylinder with 20 mm stroke length and 6 mm bore diameter as an example. This corresponds to SMC cylinder MXS6. For this cylinder the manufacturer gives a kinetic energy limit of 0.018 J. [13] The equation 2 below is used to calculate kinetic energy E_k for an object.

$$E_k = \frac{1}{2}mv^2, \tag{2}$$

where v is speed and m is mass of an object. Equation 3 can be used to find out theoretical maximum speed v of the cylinder.

$$v = \sqrt{\frac{2E_k}{m}} \tag{3}$$

If cylinder is used to move a 500 g weighing object, its theoretical maximum speed is

$$v = \sqrt{\frac{2*0.018\,J}{0.5\,kg}} = 0.268\ldots\frac{m}{s} \approx 0.3\,\frac{m}{s}. \tag{4}$$

And movement time for 20 mm with the speed of 0.3 m/s is about 0.07 seconds. In reality a cylinder never achieves this speed with short strokes since acceleration and deacceleration takes time [14]. Most part gripping actions only need a stroke of few millimeters and the movable mass is small. For these reasons, in cycle time calculations all pneumatical movements are assumed to be 0.3 seconds. For the smallest movements, this time could be too long but with communication delays between sensors and actuators this time is a suitable average [14].

Assembly cycle time is determined by how long it takes for a robot to pick all parts and place them to an indexing table. Cycle time consist of the time used to move between the points and the time it takes a pneumatical gripper to pick or place a part. In performance estimations, the flowchart shown in Figure 49 is used to calculate how many times a robot or some other actuator needs to move and a gripper needs to act to complete one cycle.

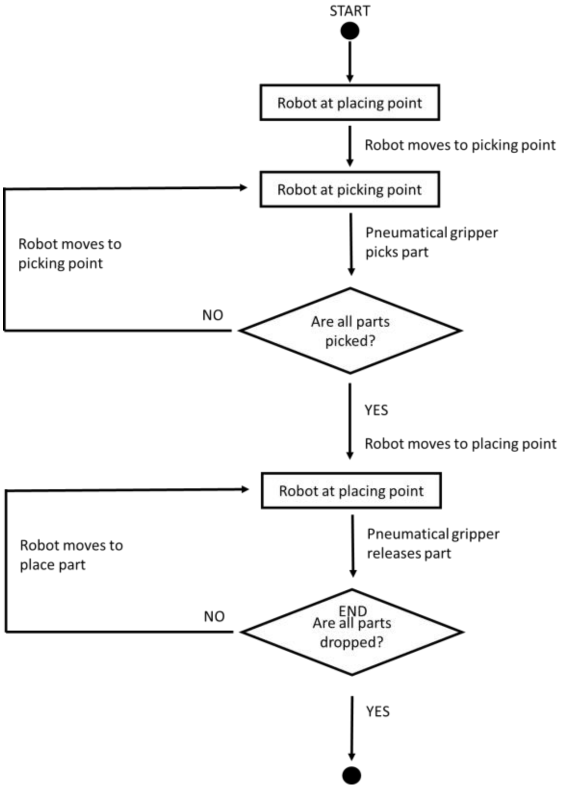


Figure 49 *Robot cycle flowchart.*

In all cycle time calculations, a tumbler packet with 11 tumblers, 10 spacers and a rotation disc is used. This packet configuration has most parts and hence is the most time consuming.

Estimating investment costs

The main investment cost goes to buying actuators. Unfortunately, actuator prices are not predictable. Many manufacturers have similar products, but their prices are different. This makes estimating realistic costs difficult.

To calculate a comparable investment cost required a more general approach. It was chosen that only the cost of main actuators is considered and all used components must be standard industrial equipment. Price values used in the investment estimation were either found on the Internet or were estimates from people who have extensive experience in the part handling automation. Estimated investment costs were rounded up to nearest 500 €.

Industrial robots are common in the part handling automation. Table 2 lists the prices for Epson industrial robots that were used.

***Table 2** Epson industrial robot prices [9, 10].*

Robot	Price (€)
6-axis robot C4	21 100
SCARA robot G1	14 100
SCARA robot G6	20 400

Prices for the other general automation equipment are estimates from professionals in Kaptas Oy. They have several decades worth of experience in automation. Other automation equipment includes machine vision, servo motors and different kinds of feeders. Table 3 lists estimated part prices.

***Table 3** Estimated prices of general automation equipment.*

Actuator	Price (€)
Linear servo	3000
Rotary servo	3000
Machine vision for part orientation	3500
Vibratory bowl feeder	4000
Commercial screw feeder	500

Some cases might require the use of more custom automation equipment. A price for custom equipment is not readily available and would require asking detailed offers from suppliers. In this thesis, price for custom equipment is not commented or included in estimations.

3.2 Synthesis

The main problems found in the analysis phase are attempted to solve in the synthesis phase. Commitment to the flexibility domain is followed, i.e. the machine is to be designed to work with multiple different products without the need for changing the machine parts.

CAD is used to create models of the proposed solutions and to aid in the problem-solving process. Some more important and difficult designs are tested by building prototypes and their functionality is then tested. The results of these tests are recorded. The phase is completed when all problems have at least one proposed solution.

3.2.1 Code tumbler feeding

The minimum requirement for the mechanical code tumbler feeder is to orient a tumbler right way up for the assembly. A small bulge in the center of the tumblers is an ideal feature for sorting. The bulges height is small, but it locks on easily to a groove with the same depth and width. Similar sorting solutions have been used in the industry before.

Two feeders were designed to test sorting the tumblers using the bulge. The first feeder prototype uses a tilted surface to sort the tumblers. This design could easily be used in bowl feeders. The second prototype uses a brush to swipe parts in a wrong orientation away. This type of sorting machines are commercially available for a small screw feeding. These screw feeding devices would only require a small changes to work with tumblers.

Test equipment

To test the code tumbler feeder design, a test equipment was built. The testing equipment included two linear feeders, one of which had the protype sorting surface mounted on and the other one had a buffer for the parts. Figure 50 has a picture of the testing equipment.

Figure 50 *Testing equipment.*

During the test, the buffer feeds tumblers to the sorting surface. As the sorting surface vibrates, tumblers move across it. This test setup is not perfect for a sorting test because some parts will drop before they get to the sorting devices. To compensate for this, test was repeated multiple times and parts that dropped too soon were counted. The following formula was used to calculate the sorting percentage.

$$Sorting\ percentage = \frac{Passed\ parts}{100 - Parts\ dropped} \tag{5}$$

In one test, 100 tumblers were run through the sorting surface. The parts were counted after all the parts had either passed the sorting or had dropped from the sorting surface. Same test was performed multiple times. A few test runs were performed to see how changing the power of vibration in the feeder would affect the sorting percentage. The used linear feeder power was documented in each test.

Sloped groove feeder prototype

The feeder prototype uses a tilted feeding surface that has a groove suitable for the tumbler bulge to lock on. The tumblers are fed to a ledge that allows tumblers to settle to a line. Once the ledge ends the tumbler that has bulge up falls off from the sorting surface. If tumbler bulge is facing down, the tumbler locks onto the groove and moves along it. This design could easily be adapted to the vibratory bowl feeders. Figure 51 shows a 3D model of the sorting surface design.

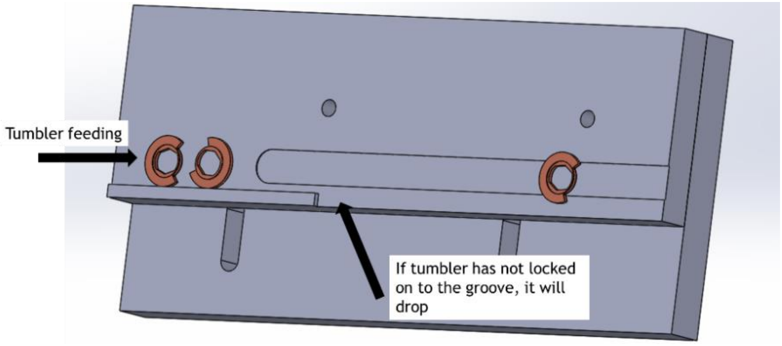


Figure 51 *Sorting surface example.*

Some right way up tumblers are also going to fall off. The bulge in the middle is round and perfectly in the center of the tumbler, but the tumbler’s outer shape is not round. The tumbler’s radius is less when measured from the return bar opening. Figure 52 the outer dimension differences of a tumbler.

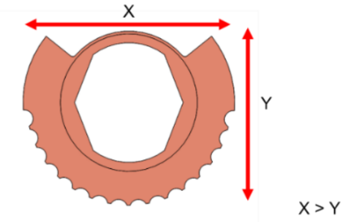


Figure 52 *Tumbler outer dimensions difference.*

When the tumbler rotates, the bulge position changes. The groove had to be placed according to the bulge’s highest possible location. If the groove is too low, the tumbler’s outer edge can get caught in it. That is why a tumbler with the opening facing down will fall off, because the bulge is too low to lock on to the groove. Figure 53 shows how the bulge and the groove fit together when the tumbler is in a suitable orientation. Figure 54 shows how the bulge is too low to lock on to the groove if the return bar opening is down.

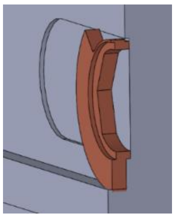


Figure 53 *Bulge at right level.*

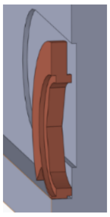


Figure 54 *Bulge too low.*

The feeding tests showed that sorting with the groove works. Tumblers move in the groove without a problem. The passing percentage was also good. In tests 1 - 6 on average 20.3 % of the fed parts came out sorted correctly. The results of the tests are in Table 4.

Table 4 *Results of test for sloped groove feeder.*

Test	**Feeder power (%)**	**Passed parts (pcs)**	**Dropped parts before sorting (pcs)**	**Passing percentage (%)**
1	44	20	6	21
2	44	20	5	21
3	44	19	5	20
4	44	18	6	19
5	44	21	7	22
6	44	18	6	19
7	47	5	7	5
8	50	1	10	1

In tests 7 and 8 an increased feeder power led to the tumblers moving faster but they also started vibrating excessively. Most of the tumblers fell off because they were bouncing on the sorting surface.

Brush feeder prototype

The brush feeder uses a moving brush and a groove to organize tumblers the right way up. The tumblers are fed to a horizontal surface with the groove. If the tumbler bulge does not lock onto the groove, the brush will push it to the side. These types of sorting machines are commercially available for a small screw feeding. These already available screw feeding devices would only require small changes to work with the tumblers. Figure 55 shows a 3D representation of the brush feeder.

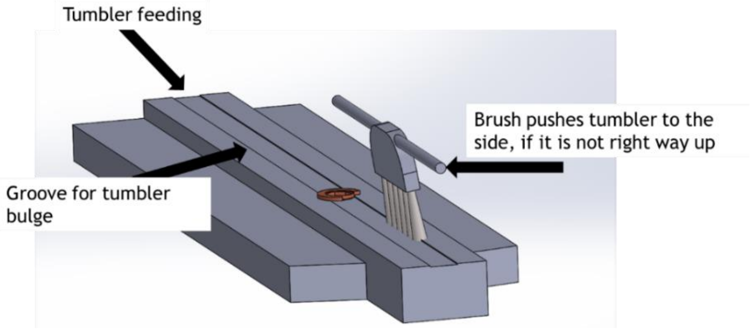


Figure 55 *Brush feeder example.*

This feeding system is quite reliable. Since the brush moves back and forth, the tumbler in wrong orientation is always pushed to the side. The tumbler's outer shape is not a problem either. The brush used for sorting needs to be soft. Tumblers are light so a hard brush can easily push even the tumblers with correct orientation to the side.

The brush feeder has the better passing percentage than the sloped track feeder. An average of 40.6 % parts came out right face up in tests 1-6. Results can be seen in Table 5.

Table 5 *Results of test for brush feeder.*

Test	**Feeder power (%)**	**Passed parts (pcs)**	**Dropped parts before sorting (pcs)**	**Passing percentage (%)**
1	75	34	10	37
2	75	36	13	41
3	75	35	9	38
4	75	39	6	41
5	75	40	11	44
6	75	40	8	43
7	85	26	7	27
8	100	2	4	2

In tests 7 and 8 increasing feeding power led to tumblers moving faster but since they were bouncing in the groove the brush could easily swipe them away. The test results show that an increased feeder power drastically lowered the passing percentage.

Making tumblers with laser cutter

The tumbler material is challenging for laser cutting. It would be greatly beneficial, if laser cutting of the material is possible. There are about 200 different tumbler types and currently each tumbler type is manufactured and stored individually. If the assembly machine could make a tumbler when it is needed, it would remove unnecessary work phases and save storage space. To make needed tumblers a laser would need as input material blank template -disc or material strip. The laser cutting of the tumbler material was tested in 3 different companies.

Company 1 was unable to cut the tumbler material, because the material contains high percentage of copper. Copper reflects the laser beam. Cutting it without a special reflective lens could damage the cutting equipment.

Company 2 cut the material successfully, but the cutting result was bad. The cutting time was between 23 – 58 seconds. Company 2 performed 3 tests. In test 1, the cutting time was 23 seconds. Figure 56 shows the results of test 1. In test 2, cutting time was 24.8 seconds and Figure 57 illustrates the result. The cutting time in test 3 was 58 seconds. The result of test 3 is in Figure 58. The tests were performed using 300 W laser and cutting distance was 25 mm.

Figure 56 *Company 2 test 1.*

Figure 57 *Company 2 test 2.*

Figure 58 *Company 2 test 3.*

Company 3 was also able to cut the material. They were able to improve the cut quality. Some small burr still remained in the edges. Figure 59 shows the cut result from their test. They used a 2000 W laser and the feed rate was 83.3 mm/s. The average cutting time was 0.5 seconds.

Figure 59 *Company 3 cutting results.*

The cutting results from company 3 are promising. The edge quality was sufficient for the making of tumblers and the cutting speed was suitable. The only downside was the remaining burr in the corners and in the sides. Figure 60 points the locations where the amount of burr was greatest.

Figure 60 *Residual burr in cut.*

The biggest burr was in the corners. The maximum burr height was about 0.15 mm. At average burr height was 0.06 mm. Company 3 said that with further testing they could finetune the laser parameters and minimize the amount of burr. The residual burr can also be reduced by designing the laser cutting path to start and end outside of the tumbler. This way burr born in the start or at the end of cutting would remain outside.

3.2.2 Spacer feeding

Spacers and the lock cylinder are a tight fit. During spacer installation the lock cylinder already has the return bars inside, which increases difficulty of spacer installation even more. The feeder for spacers must be able to orient parts with high accuracy.

Two options were found for spacer orienting. The first option is to use a mechanical feeder that is designed for sorting spacers according to the width difference. The second option relies on the gravity assisted sorting. Since a spacer’s center of mass is not in the center of the part, gravity should pull spacers to the same orientation.

Mechanical sorting

The small width difference in a spacer can be used to sort them according to their orientation. As Figure 32 in chapter 4 shows, the spacer width is less in the return bar opening. This feature allows to limit the spacer orientation to two possibilities. Sorting could be done with the brush feeder prototype that was tested in the code tumbler feeding. For a spacer the groove in the sorting surface has to be machined to match the spacers width in the return bar opening. Figure 61 illustrates how the spacer sorting would work. The first two spacers are in the right orientation and the brush can’t push them away since they are inside the groove. The third one in the back is sideways and can be pushed away by the brush.

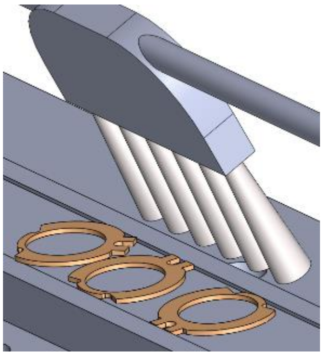


Figure 61 *Three spacers in a brush feeder. First two spacers are in right orientation. Third spacer is in wrong orientation.*

Part feeding was tested by using the same testing equipment as with the code tumblers. Only the sorting surface was changed. The new sorting surface had a larger groove for the spacers. In one test 100 spacers were driven through the feeder. Table 6 has all the results of different tests.

Table 6 *Results of spacer feeding tests.*

Test	Feeder power (%)	Passed parts (pcs)	Passing percentage (%)
1	80	36	37
2	80	30	41
3	80	33	38
4	80	32	41
5	80	29	44
6	100	34	43

The sorting by the width difference had an average of 31 % as the passing percentage. Spacers came out in either of the two orientations. During the tests, it was noticed that the spacer shape won’t allow for a perfect orientating in the feeder. Spacers came out of feeder in a slight angle as shown in Figure 62. This problem could be minimized by manufacturing the sorting surface with high tolerances. Still to recognize in which of the two orientations a spacer comes out, some sensor is required.

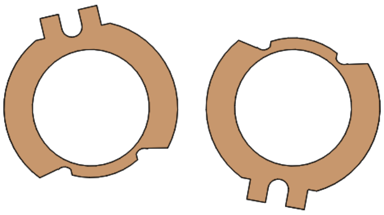


Figure 62 *Achieved spacer orientation in feeder tests.*

Gravity assisted feeding device

The spacer’s center of the mass is slightly towards the locking pin extrusion. When a spacer is placed on a horizontal stick that vibrates or rotates, gravity pulls the locking pin side of the spacer down. Figure 63 below illustrates the orientation in which gravity pulls spacer.

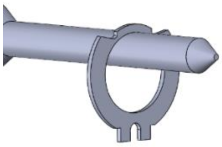


Figure 63 *Spacer end position when pulled by gravity.*

To use gravity for orienting, spacers have to be fed to the stick and then the oriented spacers must be somehow fed to the machine. An example of a machine for spacer feeding with this method is proposed in Figure 64.

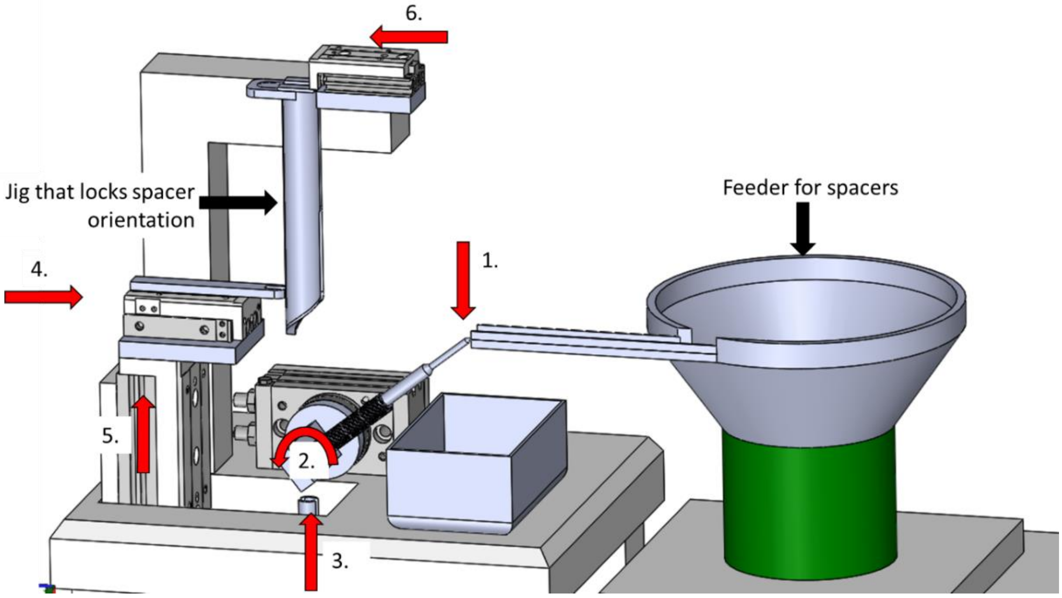


Figure 64 *Proposed machine for spacer feeding.*

The proposed spacer feeding method requires several actions before spacers are oriented. Steps needed for spacer orientation are:

1. The spacers are fed to the stick and gravity orients the spacers.
2. When the stick is full, it turns from the feeder to the jig.
3. A support from below lifts spacers to the jig. The jig has orientating features that guides the spacers to the right orientation while they are lifted.
4. Once the support has lifted the spacers out of the stick, a second support comes from the side.
5. The second support presses parts against the jig top. Now the stick is free to turn back and get new parts.
6. During the assembly, a small cylinder pushes the spacers out of the jig one at a time from the top.

If the stick length is 100 millimeters, it can hold about 200 spacers. If a tumbler packet has 10 spacers and the packet assembly time is 30 seconds, 200 spacers take about 10 minutes. Gravity alone can’t orient spacers perfectly. The jig also needs to have some guiding features to orient the spacers. The locking pin extrusion can be used to orient spacers while they are lifted inside the jig.

3.2.3 Packet assembly to lock cylinder

In packet assembly, the main purpose is to place all needed parts inside a lock cylinder. The lock cylinder already has the return bars and the drilling preventation disc inside. Placing of new parts needs to be done carefully, because if the return bars move from their place the assembly fails. The return bars are only held in place by magnets.

Assembling the tumbler packet first in a jig and moving it from there to the lock cylinder seems to be the best option. By assembling the complete tumbler packet in the jig first allows the jig to have guiding features that the lock cylinder doesn’t have. Then the entire packet could be lowered to the lock cylinder with one movement, which minimizes the risk of the return bars moving.

Packet assembly in a jig

The packet assembly in the jig is more reliable and quicker than assembling the packet directly into the lock cylinder. If each part was installed one by one to the lock cylinder it would take more time and there would be a higher chance for something to go wrong. The return bars have to be installed to the lock cylinder before the packet assembly and they are held in place by magnets. If the return bars are not in a correct position or move during the assembly, spacers or tumblers can’t be inserted in the lock cylinder and the packet assembly has to be stopped. If the whole tumbler packet can be installed to the lock cylinder, chances for the return bars moving is lower since the packet will guide the return bars to their place.

The jig itself needs to have the same features as the lock cylinder has. The jig opening dimension must be the same as the lock cylinder’s and it has to have a feature that mimics return bars since the return bars lock the part orientation in the tumbler packet. The jig also must have an opening for the spacer’s locking pin extrusion. Figure 65 shows one possible design for the packet jig and its crucial features.

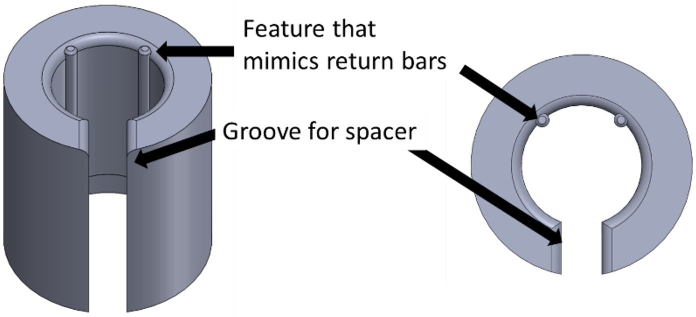


***Figure 65** Packet jig and important features.*

To make the packet assembly faster and more controlled, a support from below is needed. This support prevents the parts from turning inside the jig. The support should be position controlled. This can be achieved by using a linear servo or a stepper motor. Between every part, the support moves down so that the packet top is always at level with the jig top. Figure 66 describes the steps needed to install a part in the packet jig.

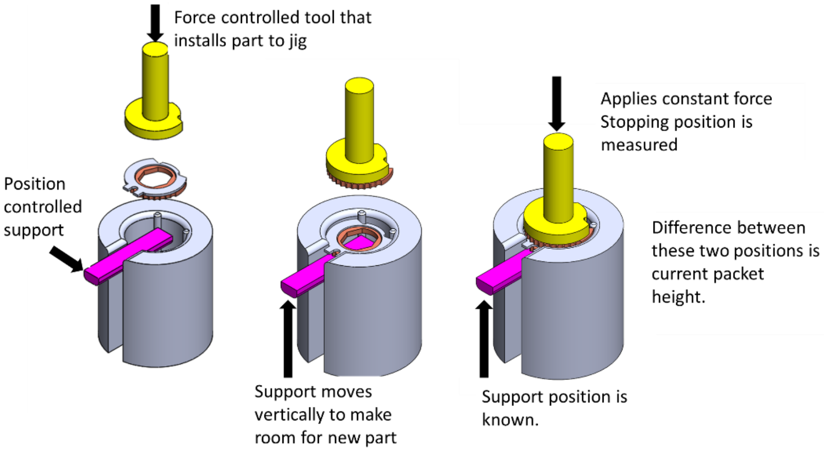


***Figure 66** Steps to install new part to packet jig.*

The packet height can be measured from the difference between the lower support position and the upper support position. The packet height should be measured simultaneously with placing new part on the jig. Part placement should be performed by applying a constant force on the part and measuring where the part’s movement stops. This measurement combined with known position of the lower support results in the packet height. If a part is placed by an industrial robot or by some other manipulator that can move vertically, the manipulator position must also be known. With modern industrial robot’s accuracy this is not a problem.

With the measurements and the actuators described, a tumbler packet can be assembled in the jig. The tumbler packet assembly steps on software level are illustrated in the flowchart shown in Figure 67.

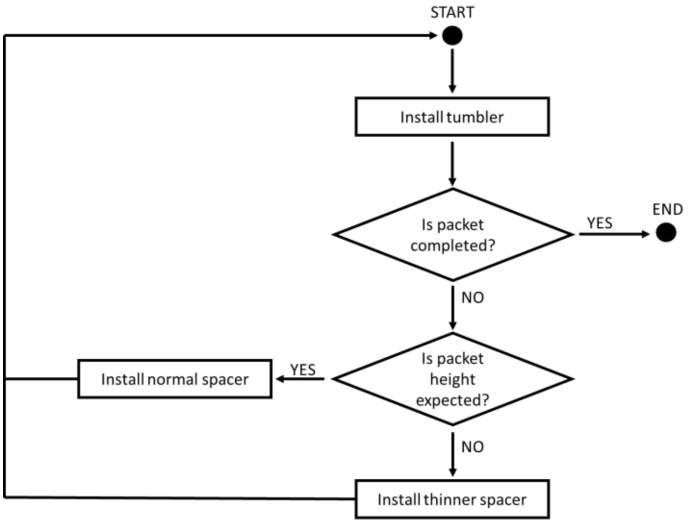


Figure 67 *Flowchart for packet assembly in jig.*

When a new tumbler is placed in the jig, the machine checks if that was the last tumbler in the packet. If it was, the packet assembly is completed. If it was not, then the packet height is measured and the received value is then compared to the expected packet height. If the packet height is acceptable then a normal spacer is installed. if the packet height is not inside the expected values, a thinner spacer is used. This cycle continues until the packet assembly is completed.

Packet transfer from jig to lock cylinder

The tumbler packet needs to be moved from the jig to the lock cylinder. At this point the lock cylinder already has a drilling preventation disc and return bars in place. The drilling preventation disc is at the bottom of the lock cylinder. The return bars are inside the lock cylinder and against the wall. They are held in place by magnets. It is important that the packet is lowered into the lock cylinder in a precise and controlled fashion. A similar position-controlled support that was used in the packet assembly can be used here as well. Packet lowering should also have an upper support that makes sure that the packet stays tight during movement and that it is pressed all the way down. Figure 68 below shows the steps that are needed to move the packet to the lock cylinder.

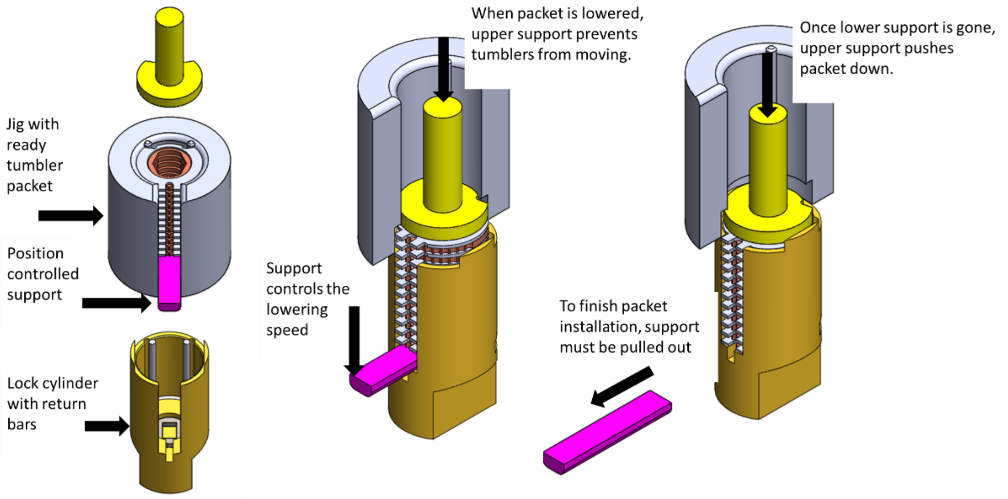


Figure 68 *Steps to move packet from jig to lock cylinder.*

The lower support is position controlled and upper support applies a constant force on the tumbler packet from above. This way the packet is pressed tightly between two supports and can’t move around. The lower support moves downward inside the lock cylinder and the packet follows. Once the lower support has reached the lock cylinder bottom, it must retract to the side to allow the packet to come all the way down. The upper support makes sure that the packet goes inside the lock cylinder.

3.3 Simulation

The simulation phase aims to answer which combination of equipment is the most suitable for the assembly, as different automation equipment could be used to achieve the same result. CAD software is used to illustrate how general automation equipment like industrial robots and pneumatic cylinders could be used to perform the necessary actions. The use of well-known and standard industrial parts makes it possible to create an estimation of the machines technical performance.

An assembly machine can be seen as a combination of several independent tasks that need be completed for the final product. These tasks can be performed at the same time and only parts need to move between them. Each of these tasks is designed separately to simplify the design process.

3.3.1 3D models of the part feeding equipment

In the simulation phase, two types of mechanical feeders are used: a vibratory bowl and a commercially available screw feeder. Machine vision can be used in combination with the both feeders to achieve a higher part orientation and position accuracy.

The vibratory bowl feeder is a very common feeder and it can be adapted to feed multiple parts. The vibratory bowl feeder can also support fast cycle times. The downside of the vibratory bowl feeder is its price. Figure 69 shows a 3D model of how a vibratory bowl feeder can be combined with a machine vision.

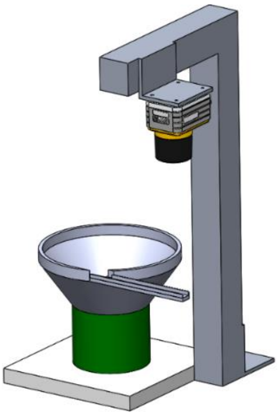


Figure 69 *3D model of vibratory feeder combined with a machine vision.*

The commercially available screw feeders could be adapted to feed tumblers and other parts. Automatic screw feeders have a mechanical design that lifts parts constantly to a vibrating sorting surface. A moving brush then removes the parts that are in a wrong orientation. The sorting surface is changeable and can be switched between part changes. The screw feeder OM-26 from OHTAKE is one of many suitable feeders [6]. Figure 70 has a picture of an actual OM-26 screw feeder. Figure 71 shows a 3D model that is used to represent the OM-26 feeder.

Figure 70 *OM-26 automatic screw feeder [6].*

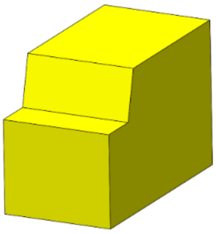


Figure 71 *3D-model representing OM-26 screw feeder.*

3.3.2 Part feeding

An assembly machine requires access to over 60 parts and each part requires its own feeder. All solutions require feeders to be concentrated around some automation equipment that is used to collect and transfer parts when the assembly requires parts. Grouping the feeders assures that all parts can be accessed quickly enough for the packet assembly.

Instead of mechanical feeders, laser cutting could be used to create the needed parts in an assembly machine. Laser cutting has many advantages over mechanical feeders. Laser cutting simplifies the machine operation and, in addition, reduces the need for storage and other manufacturing phases. If mechanical feeders are used instead, during batch change the parts inside the feeders must be checked and replaced manually. With a laser cutter, the assembly machine can make all the needed parts and only software changes are needed.

Mechanical feeders on shelves

Mechanical feeders are placed on shelves and the feeders are arranged so that a 6-axis robot has access to all of them. The feeders orient parts right face up and the robot picks parts in its gripper. The final part orientation is detected by a machine vision just before the assembly. The shelves hold all the necessary code tumblers, an intermediate zero tumbler, a bottom zero tumbler and a rotation disc. Figure 72 shows how the shelves are arranged around the robot.

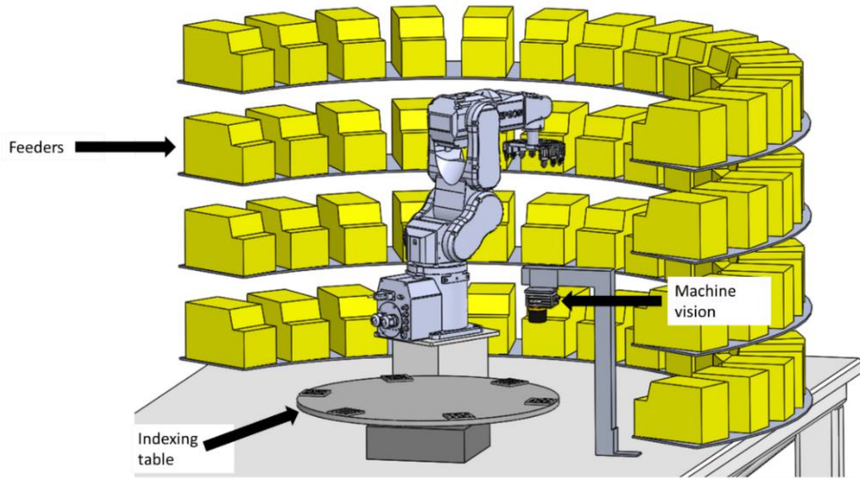


Figure 72 *Feeders layout on shelves.*

The robot has a gripper that can hold all parts for one packet. The robot picks all needed parts in its gripper and then places them on an indexing table. Figure 73 shows an example of such a robot gripper. The indexing table has a jig with a slot for each part. These slots keep parts from moving while the indexing table rotates. Figure 74 has picture of the indexing table with the jigs. Each jig has places for each part of the tumbler packet.

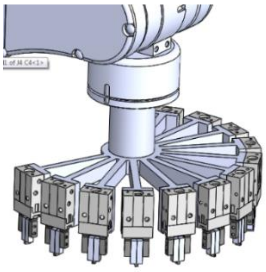


Figure 73 *Proposed robot gripper.*

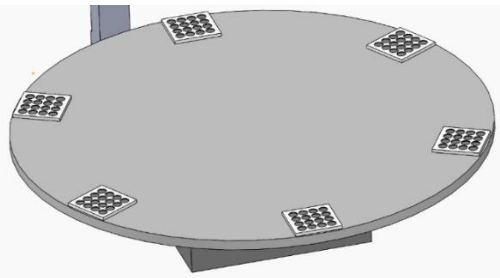


Figure 74 *Indexing table with jigs.*

Once all parts are in the indexing table jig, the table rotates and the parts move under the machine vision. The machine vision takes a picture and from that one picture every part's orientation is found out. After this, the table rotates again and now the parts are available for the assembly. The part position and orientation are known so the assembly can begin.

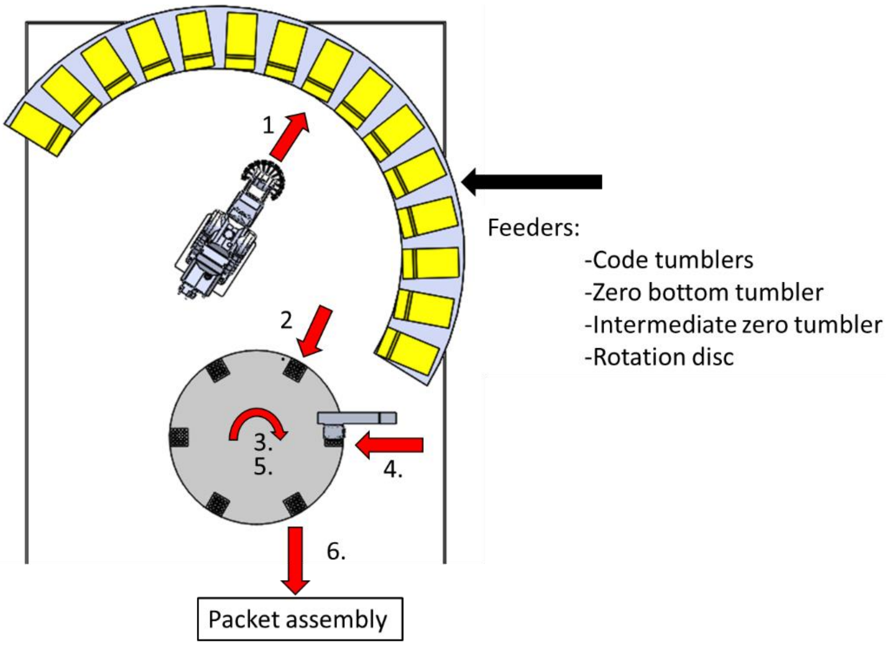


Figure 75 *Steps to picking parts from shelves and making them ready for assembly.*

Figure 75 shows the part feeding steps that a part goes through before it is ready for assembly. The steps are:

1. The robot picks parts from feeders.
2. The robot places parts in the jig on the indexing table.
3. The table rotates and moves parts under the machine vision.
4. The machine vision detects the part orientation.
5. The table rotates again and moves parts to the assembly.
6. Parts are ready for the assembly.

During one work cycle the robot has to pick 11 tumblers and 1 rotation disc. With this packet configuration the robot would have to move 13 times during one cycle. The pneumatical gripper needs to move 24 times. The first 12 times to pick a part and then another 12 to place the part. The gripper action time is 0.3 seconds and the Epson C4 robot movement time is 0.37 seconds. With this information, the cycle time would be

$$24 \cdot 0.3\ s + 13 \cdot 0.37\ s = 12.01\ s.$$

The investment for this machine includes an Epson C4 robot, 60 feeders and a machine vision. An estimated investment cost of the actuators is

$$21\ 100\ € + 60 \cdot 500\ € + 3\ 500\ € = 54\ 600\ € \approx 55\ 000\ €$$

Mechanical feeders along conveyor

Mechanical feeders are placed along a conveyor. The feeders drop parts directly on the conveyor and the conveyor moves parts to a robot. This reduces the distance that the robot needs to move while picking parts. Figure 76 shows the feeder layout.

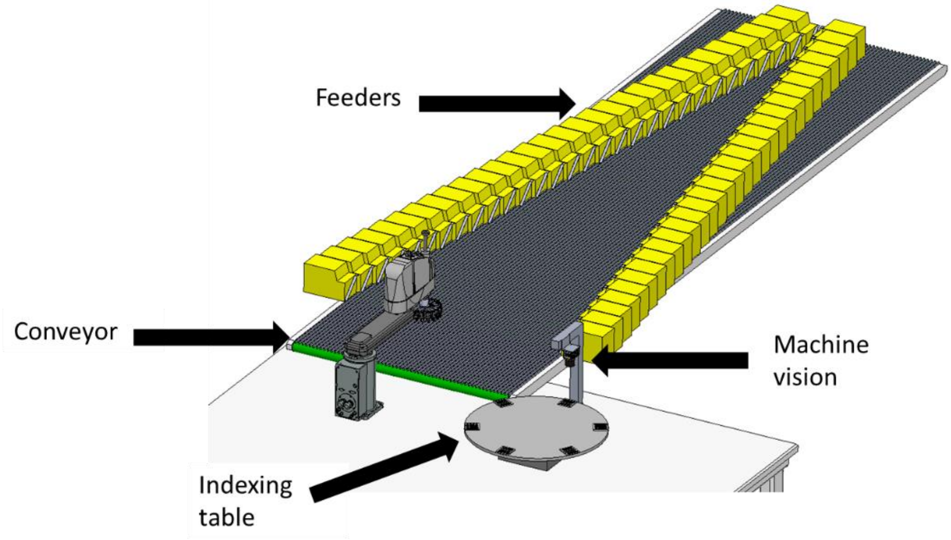


Figure 76 *Feeders along a conveyor.*

The conveyor has own track for each part. This allows the conveyor act as a buffer and concentrate parts to smaller area. The robot can easily pick needed parts from the end of the conveyor. The robot gripper can hold all necessary parts for the assembly of one packet.

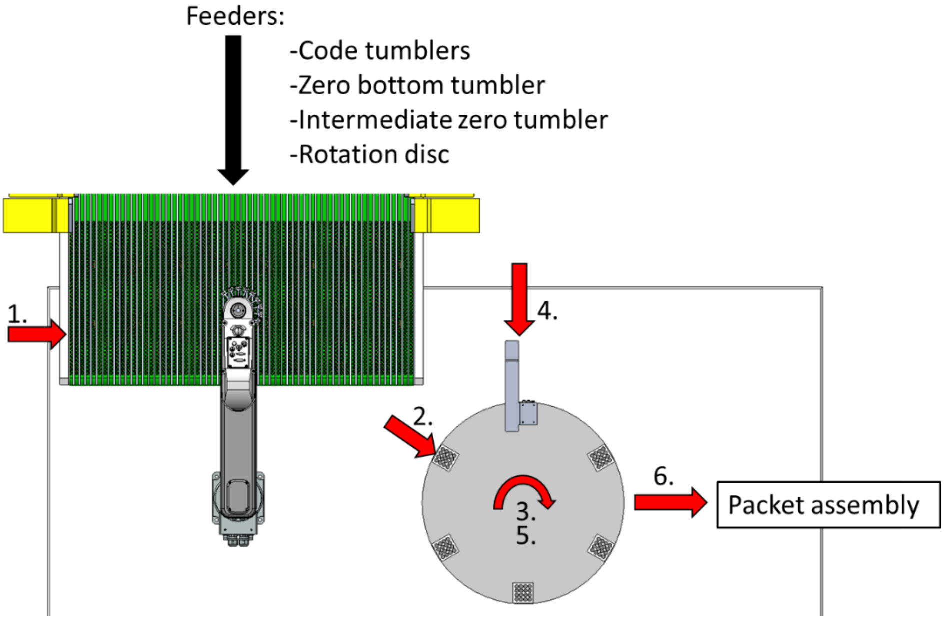


***Figure 77** Steps for picking parts from conveyor and making them ready for assembly.*

Figure 77 shows the entire work cycle of part feeding:

1. The robot picks parts from the conveyor.
2. Parts are placed on the jig.
3. The table rotates and moves parts to the machine vision.
4. The machine vision detects the part orientation.
5. The table rotates again, delivering parts to the assembly.
6. Parts are ready for the assembly.

During the work cycle the robot picks and drops 12 parts and moves 13 times. The robot moving distance is much shorter than with the feeders on shelves solution. This distance difference could have an effect on the robot moving time, but it is not commented on this thesis. The robot movement time is still assumed to be one that the manufacturer gives for pick and place action. For the Epson SCARA robot G6 that movement time is 0.38 seconds. The gripper movement time is 0.3 seconds. The estimated cycle time is

$$24 \cdot 0.3\ s + 13 \cdot 0.38\ s = 12.14\ s.$$

Machine actuator investment cost includes the Epson SCARA robot G6, a machine vision and 60 feeders. The conveyor is not included in the investment estimation, because it is a custom automation part. Actuator investment cost is

$$20\,400\ € + 60 \cdot 500\ € + 3\,500\ € = 53\,900\ € \approx 54\,000\ €$$

Mechanical feeders along puck track

The design is similar to the conveyor feeding, but now the tumblers are fed to small pallets called pucks. The pucks move around a track. Each puck has room for one tumbler. When a puck comes to the right feeder, a tumbler is dropped on it. Then that puck will move along the track to a machine vision and finally to the assembly. Figure 78 shows how feeders can be placed along the puck track and in reach of pneumatic manipulators.

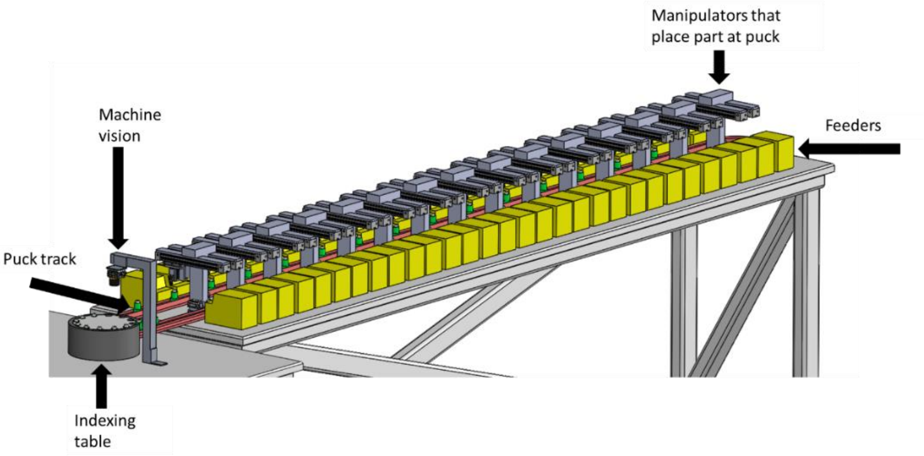


Figure 78 *Feeders along a puck track concept machine.*

At assembly, the puck position is controlled by an indexing table. One position of the indexing table has also the machine vision that senses the part orientation before a part goes to the assembly. Figure 79 demonstrates how the machine vision can be combined with the indexing table.

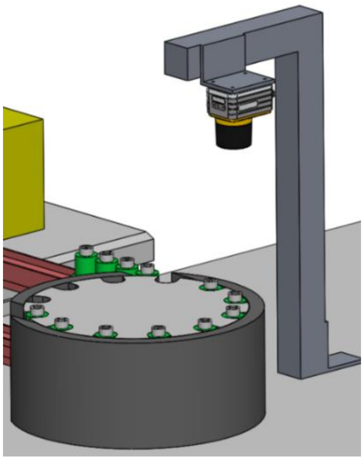


Figure 79 *Indexing table at assembly station.*

A manipulator required for getting parts from the feeders to the pucks. This manipulator needs to have both vertical and horizontal movement. The example of a manipulator in

Figure 80 is designed so that it can pick from two feeders, one on each side of the puck track.

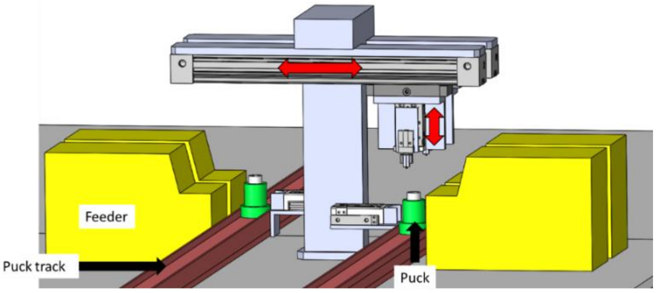


Figure 80 *Example manipulator for moving parts from feeders to pucks.*

Figure 81 shows part feeders and the necessary steps to feed a part to the assembly. These steps are:

1. The manipulators place right parts at the pucks.
2. The puck moves along the track to the indexing table.
3. The table rotates when a new part is needed in the assembly.
4. The machine vision detects the part orientation.
5. The table rotates again.
6. Parts are ready for the assembly.

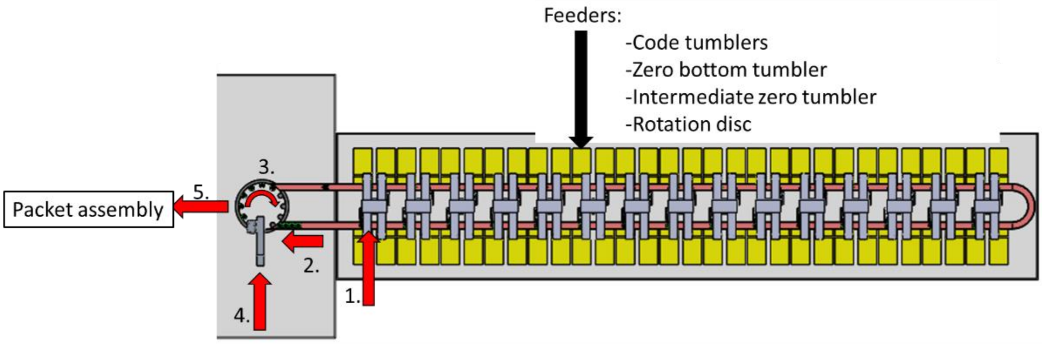


Figure 81 *Puck feeding steps to picking parts and making them ready for assembly.*

The cycle time estimation is challenging. The FlexLink puck track can move 5 m/s – 20 m/s [7]. The needed puck track length is almost 10 m so in the lowest speed it would take about 2 seconds for a puck to move through it. The part manipulator would need to stop the puck and place a part on it before releasing puck. To accomplish this about five pneumatical movements are required, which would take 1.5 seconds. The total time for a puck to pass the track is about 3.5 seconds. However, multiple pucks move on track at the same time, and they can have parts placed to them simultaneously. Because of this, the time between two pucks arriving at the indexing table should be the same as the slowest manipulator along the puck track.

The target time for the packet assembly is 30 seconds. When 30 seconds is divided for the 12 parts, the resulting time is 2.5 seconds per part. This means that as long as the part placing to the puck is faster than 2.5 seconds, the part feeding can meet the time requirement. If the indexing table is as fast as part manipulators, the time between pucks arriving at the indexing table should be about 1.5 seconds. And this gives the cycle time of

$$12 \cdot 1.5\ s = 18\ s.$$

The investment includes a puck track, feeders and a machine vision. The price for the puck track cannot be estimated since it is a custom part. Feeders and the machine vision alone would cost

$$60 \cdot 500\ € + 3\ 500\ € = 33\ 500\ €.$$

Laser cutting using templates

Using a laser cutter to make the tumblers at the assembly machine reduces the need for code tumbler feeding devices to just one. Some parts cannot be made from the template, so those have to be fed separately. Figure 82 shows an example of a machine where a puck track is used to move tumbler templates to a laser cutter and from there to the assembly.

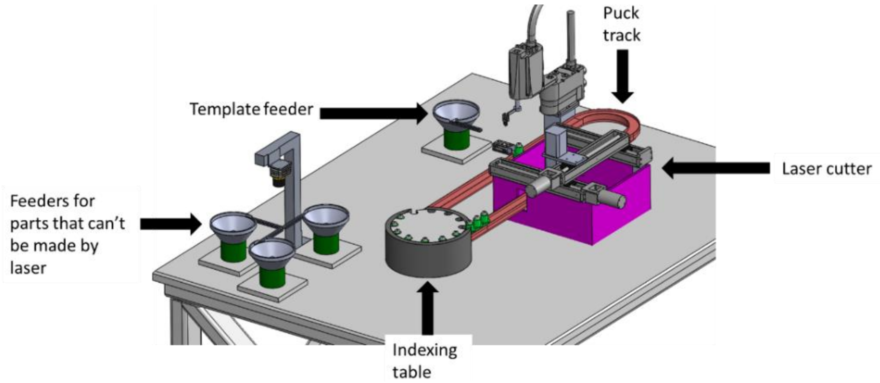


Figure 82 *Laser cutting parts from templates.*

A basic code tumbler template only needs to have the bulge and the hole for the key in the center. All outer edge features can be cut with laser. Figure 83 shows what the template tumbler could look like.

Figure 83 *Template tumbler.*

Since not all parts are made from the same material or there are big differences in shapes, some parts still have to be fed with their own feeder. The rotation disc is made of a different material and it is only used with certain products. The bottom - and intermediate zero tumblers are of the same material as the code tumblers but the hole for the key in the middle is much smaller and the center bulge is also different. The intermediate zero tumbler has no variations but the bottom zero tumbler has multiple variations. Changes in the bottom zero tumbler variations do not only limit to the outer edge but also the center hole shape changes. If the bottom zero tumbler would be made with laser cutting, each variation would require their own template. There would not be any savings in the storage space and with the same effort, a line punching machine can make the entire part.

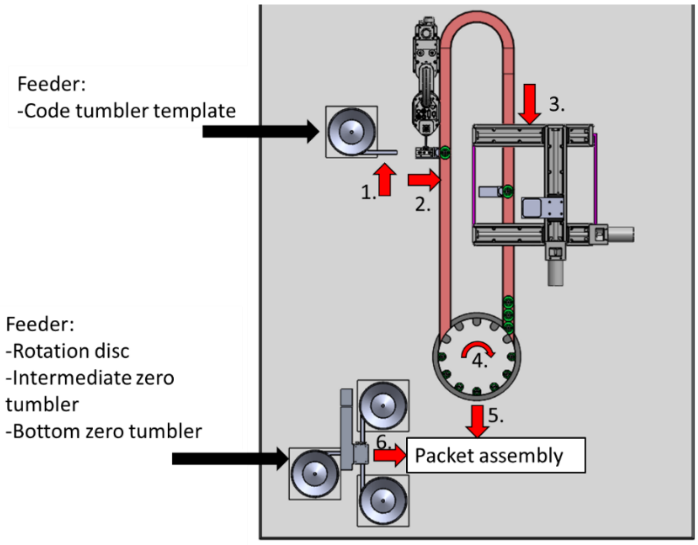


Figure 84 *Laser cutting from templates working principle.*

Figure 84 demonstrates that only the templates are fed to the laser cutter and other parts are fed directly to the packet assembly phase. The same figure also explains required the steps to feed a part to the assembly:

1. The manipulator places the tumbler templates at the pucks.
2. The puck moves along the track to the laser cutter.
3. In the laser cutter key coding is cut to the disc’s outer edge.
4. When the puck arrives at the indexing table, it is rotated to the assembly.
5. Parts are ready for the assembly
6. The rotation disc, the Intermediate- and the bottom zero tumbler are fed directly to the assembly

The template tumblers are fed to the puck track with a machine vision and a robot. See Figure 85 for a 3D presentation of a template tumbler feeding. The robot is Epson G1, which has pick and place time of 0.3 seconds. For the cycle time estimation, it is assumed that it takes about 0.5 seconds for the machine vision to find out the part orientation and to send that information to the robot. The robot has a pneumatic gripper that handles the part picking and placing.

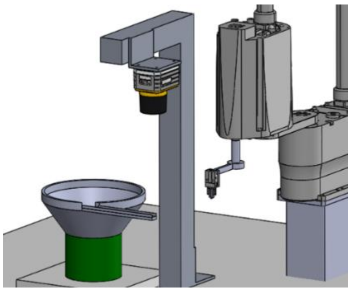


Figure 85 *Template tumbler feeding to puck track.*

The puck stopping and releasing can be done at the same time with the robot movement so it has no effect on the cycle time. The template tumbler to puck feeding needs the machine vision to detect the part's orientation before it can be picked. The robot picks part and places it on a puck that is already waiting. Finally, the robot moves back to its starting position. During the described work cycle machine vision detects the part orientation, the robot moves 2 times and the gripper acts 2 times. Duration of the work cycle is

$$0.5\ s + 2 \cdot 0.3\ s + 2 \cdot 0.3\ s = 1.7\ s.$$

Estimating the time for laser cutting is challenging. None of the laser cutting tests included cutting an entire code tumbler. Only smaller test parts were cut. The results of the laser cutting tests are in chapter 5.1.4. The tumbler cutting time can be estimated mathematically to be about 0.5 seconds. This time estimate is a calculated cutting time of a circle with a diameter of 12 mm with the cutting speed of 83.3 mm/s. The real duration for the tumbler cutting must be tested. Minimizing the residual burr might make the cutting process slower.

The bottom zero tumbler, the intermediate zero tumbler and the rotation disc all are fed separately. Because of this, a tumbler packet only needs nine tumblers from the laser cutter. When the 30 second time requirement is divided by 9, the resulting time is 3.33 seconds. The laser cutting process needs to be faster than that.

The slowest station along the puck track defines the part feeding cycle time. In the cycle time estimation, it is assumed that the template feeding is the slowest station along the puck track and the laser cutter achieves the calculated cutting times. The cycle time for the part feeding is estimated by calculating how long it takes for the template feeding to process 9 parts. The estimated cycle time is

$$9 \cdot 1.7\ s = 15.3\ s.$$

The investment includes a puck track, an Epson SCARA robot G1, four bowl feeders, two machine vision cameras and a laser cutter. The puck track is a custom part and its cost is not available. The laser cutter is also a custom component, but a price estimate for it was received with the laser cutting test results. Company 3 estimated investment costs for a laser cutting system to be 150 000 €. The estimate includes a 2 kW laser, optics and a cooling system. Total investment cost is

$$14\ 100\ € + 4 \cdot 4\ 000\ € + 2 \cdot 3\ 500\ € + 150\ 000\ € = 187\ 100\ € \approx 187\ 500\ €.$$

Laser cutting with punching machines

Joining a laser cutter with a punching machine removes the need for template manufacturing and allows a perfect tumbler positioning. Currently all tumblers are made by the line punching machines in large batches and then stored until they are used. If an assembly machine could make the needed tumblers from a metal strip, it would reduce or remove need for the external manufacturing processes. Figure 86 shows how all needed equipment could be arranged along a metal strip.

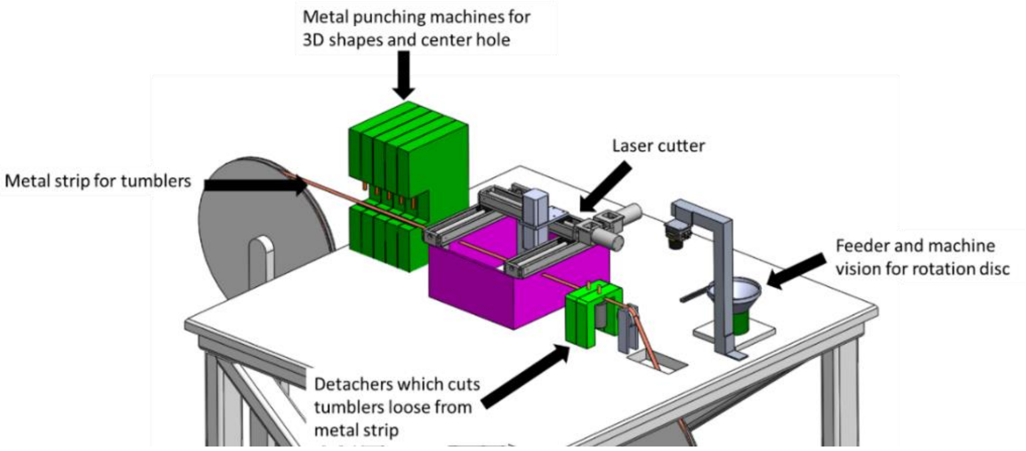


Figure 86 *Laser cutting with punching machines.*

The punching machines can make the necessary 3D shapes. It is more sensible to make a tumbler center hole with a punching tool than with a laser cutter. The center hole could be made with the laser cutter but the risk of the residual burr is greater. Cutting the outer edge of the tumbler with laser allows cut path to be flexible. For example, residual burr could be reduced by starting and ending the cut outside of the tumbler. The punching tools are needed for the following shapes:

1. Bulge in the code tumblers
2. Bulge in the intermediate- and the bottom zero tumblers
3. Hole for the key in the code tumblers
4. Hole for the key in the intermediate zero tumbler
5. Hole for the key in the bottom zero tumbler

Altogether five punching tools are required. Laser cutter won't separate part completely from the metal strip, but leaves it attached by small metal strips. Detacher is the tool that separates the finished part from the metal strip. The bottom- and the intermediate zero tumbler requires their own detacher tool and the code tumblers their own. This is because the zero tumbler's diameter is slightly different than the code tumbler's diameter.

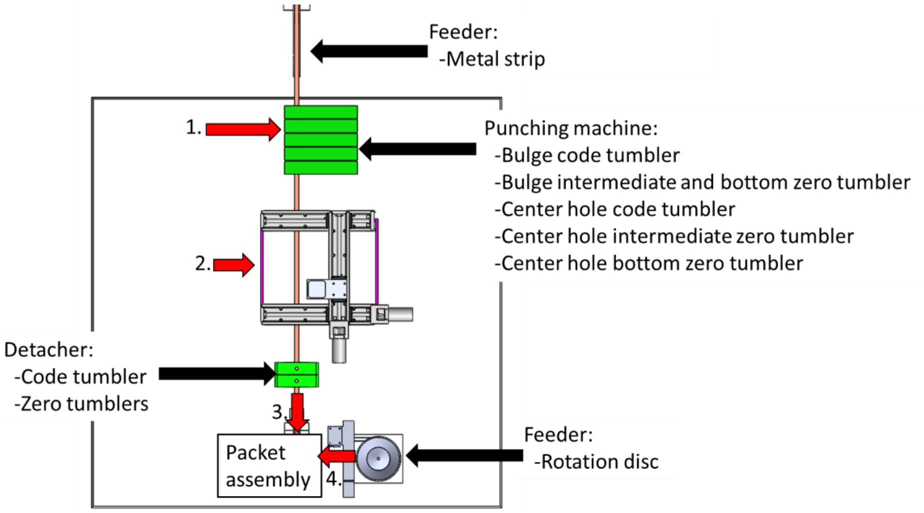


Figure 87 *Laser cutting with punching machines working principle.*

Figure 87 shows how different work phases have been arranged along the metal strip. The metal strip moves through all these stations and each station performs work on the part if they need to. To create the needed parts for a tumbler packet, the following steps are needed:

1. The punching machines create a center bulge and cut a key hole in parts that need them.
2. The laser cutter cuts the outer edge of tumblers, but leaves part attached to the metal strip.
3. The detacher separates the part from the metal strip. Now the part is ready for the assembly.
4. The rotation disc is fed separately to the assembly phase. A machine vision is used to detect the part orientation.

The cycle time of this solution is short. The metal strip can be moved very quickly from one station to another. The laser cutter, the detacher and the punching tools work simultaneously. The punching tools simply strike the needed shapes to the metal strip when the right part is at their position. The laser cutting takes about 0.5 seconds and in the cycle time estimation it is assumed to be the slowest work phase. The laser cutting time was calculated in chapter 6.2.4. The metal strip movement is quick but in the cycle time estimations it is assumed that it takes the same time as the pneumatical movement, which is 0.3 seconds. Now all 11 tumblers come from the laser cutter. The laser cutter has to cut 11 parts and the metal strip needs to move 11 times to create parts for one packet. The cycle time is estimated to be

$$11 \cdot 0.5\,s + 11 \cdot 0.3\,s = \ 8.8\,s.$$

The investment includes a bowl feeder, a machine vision, a laser cutter and five punching tools. Price for a punching tool is not known. Punching tools need to be custom made. The laser cutter price estimation was given in chapter 6.2.4. The investment cost for this solution is

$$4\ 000\ € + 3\ 500\ € + 150\ 000€ = 157\ 500\ €$$

3.3.3 Packet assembly

A packet assembly can be completed with different types of automation actuators. How the actuators are employed depends on where the packet jig is situated. The packet jig can be attached to a robot gripper or it can be attached to a table and the actuators bring the parts to it.

Part availability is important for the fast assembly. The part feeding must bring parts so that assembly can use them efficiently. Some important parts are fed directly to the assembly.

Part feeding to the assembly

The spacers are fed directly to the assembly since they are actively needed to adjust the packet height. The lock cylinder is also fed to the assembly. The other parts come from the part feeding systems conceived in chapter 6.2. These systems can have one or two outputs to the packet assembly. One output is for the tumblers and other to the parts that could not be fed through the same system. Figure 88 illustrates how parts are fed to the packet assembly phase.

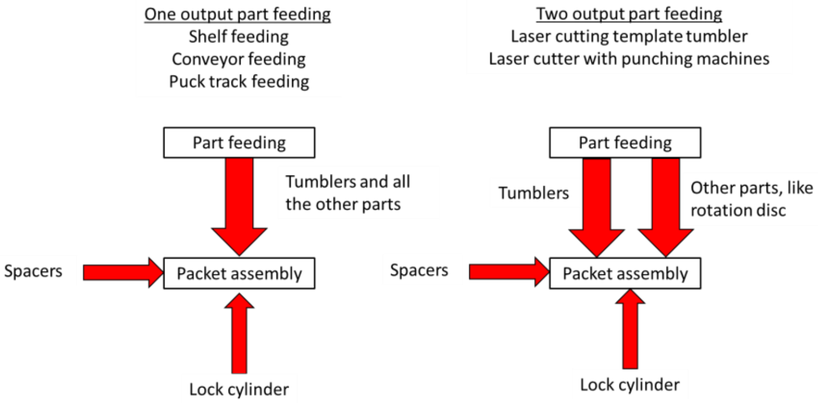


Figure 88 *Part feeding to packet assembly.*

For example, the shelf feeding and the conveyor feeding solutions have only one input to the assembly phase. The laser cutting with the metal strip has two inputs, one for the tumblers and another for the rotation disc.

One robot and a packet jig in a gripper

One robot handling the entire packet assembly keeps the design and machine layout simple, but slow. The robot moves to a part, picks it up and then moves to next one. The robot movement takes time and picking and placing parts requires the robot to stop and wait for a pneumatical gripper to act. There is always a delay between the robot ordering the gripper to close and the information that the gripper has closed to come back to the robot. This delay is minimal, but if the delay is 0.1 second and the robot repeats this process for every part, the delay will add up. For example, a tumbler packet has 11 tumblers and 10 spacers and each part requires picking and placing. One part has a 0.2 second delay and this delay is repeated 21 times. During one work cycle the robot waits for the gripper for 4.2 seconds.

To minimize these delays, part picking should not require a separate order from the robot. This can be achieved by designing a robot gripper so that parts are picked with a mechanical action. The robot can assemble an entire tumbler packet in its gripper and once the packet is finished, the robot installs it directly to the lock cylinder. Figure 89 shows an example of a robot with a packet jig in the gripper.

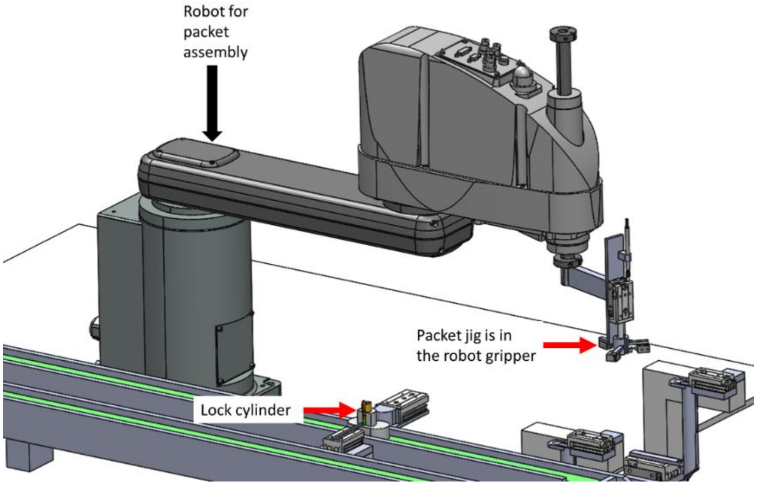


Figure 89 *One robot and a packet in the gripper.*

All needed parts have to be fed so that they are inside the robot's working area. This ensures that the robot can reach all the needed parts. Figure 90 shows an example of a layout for part feeding to a robot.

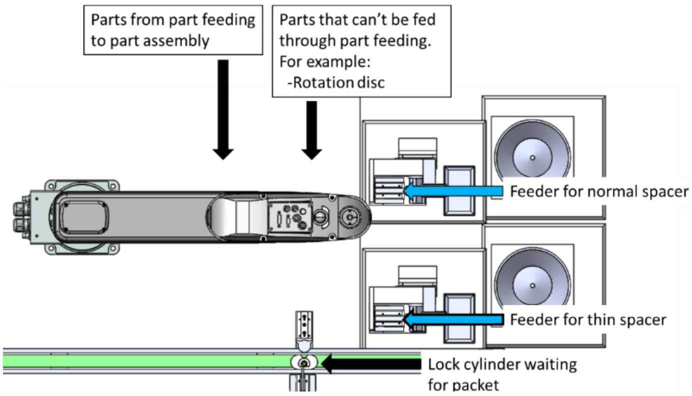


Figure 90 *Example of part feeding to robot.*

In Figure 91 there is a proposed gripper for packet assembly that uses pneumatic spring force and mechanical contact to move locking pins. The mechanical contact with the part pushes the locking pins open and, once the part has passed, the locking pins return by spring force. The packet is supported by the locking pins from below and another support applies a constant force from above. The packet height measuring is done by tracking the position of the upper support. The same measurement is used to determine if the part picking was successful. With this gripper, the robot can move constantly and check if the picking was successful during the movement. If it was, the robot can continue to the next part without stopping.

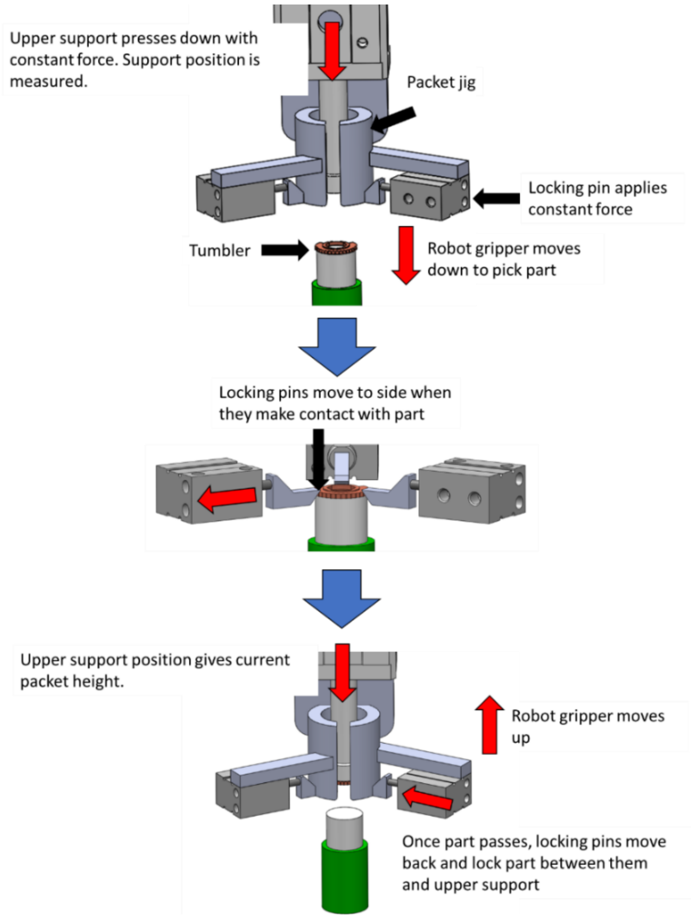


Figure 91 *Proposed gripper for quick part picking.*

The proposed robot gripper and lifting parts on a pedestal makes it possible for the robot to pick parts without stopping. The robot can collect the entire packet in its gripper with a constant movement. In the defined cycle time estimation scenario, a tumbler packet has 11 tumblers, 10 spacers and a rotation disc. Since pneumatical movements are not needed in the part picking, only the robot movement time is left. An Epson SCARA robot G6 has a 0.38 second pick and place cycle. The cycle time for part picking is

$$22 \cdot 0.38\, s = \ 8.36\, s.$$

It takes 8.36 seconds to collect a packet to the robot gripper. After that, the robot still needs to install it to the lock cylinder. The robot drives over lock cylinder and lowers the packet jig against the lock cylinder opening. The jig has features that will guide and lock it into the lock cylinder. The locking pins move aside and the upper support pushes the packet into the lock cylinder. Once the packet is down, the lower support moves out of way and the packet is in the lock cylinder. After this, the robot can pull out of the lock cylinder and during movement set all the pneumatical movements to the correct positions. To install tumbler packet to the lock cylinder requires the robot to drive over the lock cylinder and 3 pneumatical movements. The entire work cycle for the packet assembly and installation is

$$8.36\,s + 0.38\,s + 3 \cdot 0.3\,s = 9.6\,s.$$

The entire assembly cycle time is 9.6 seconds. Achieving this cycle puts a lot of demand on the spacer and code tumbler feeding. The part feeding must be able to keep up with the assembly. The investment includes only an Epson G6-robot, which costs 20 100 €. The total investment cost is rounded up to 20 500 €.

Two robots

Using two robots for the packet assembly leaves more time for the part picking and placing. When one robot is working on the jig, the other robot can pick a new part. One robot is responsible for handling parts from the part feeding system, like the tumblers and the rotation discs. The other robot handles the spacers. Figure 92 shows how two robots could be arranged together and Figure 93 shows how parts are distributed among the two robots.

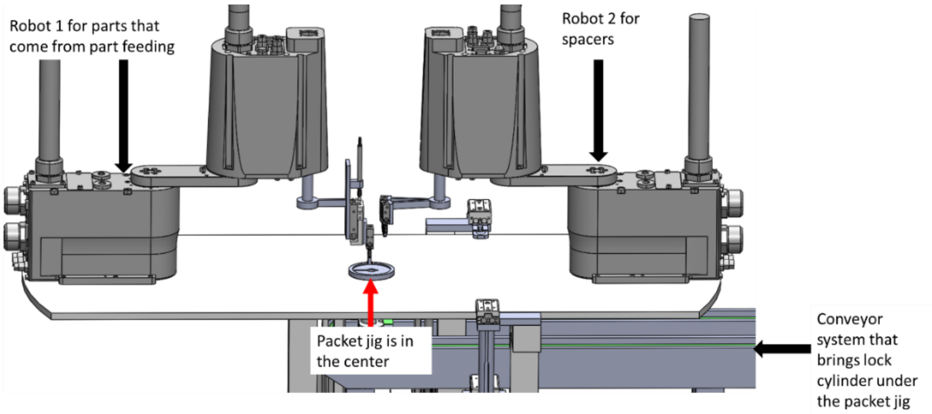


Figure 92 *Two robots working together.*

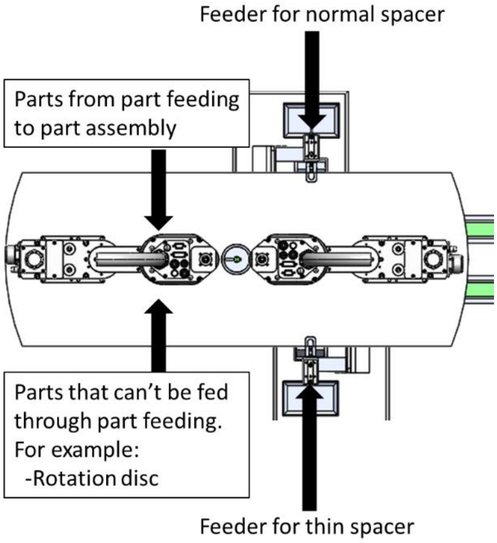


Figure 93 *Part feeding to two robots.*

The robot responsible for the tumblers should have a gripper with a small vertical movement. The position of this vertical movement is measured. This position measurement is needed for the packet height measurement. When the robot is placing new part on the jig, the packet height can be calculated by knowing the robot's z-axis coordinate, the vertical movement position of the gripper and the position of the support below packet. The robot that handles only the spacers should have a gripper that can hold two spacers at the same time, one of each spacer type. This ensures that the robot can quickly place the needed spacer after the packet height is measured. Figure 94 and Figure 95 show what kinds of grippers the robots could use.

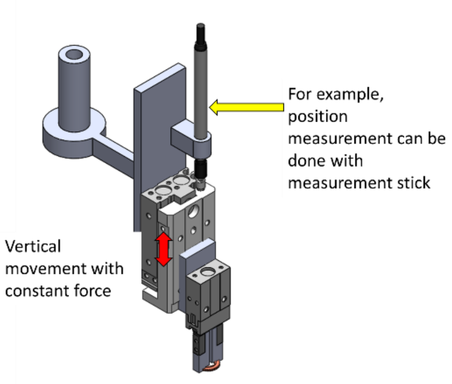


Figure 94 *Robot gripper with vertical position measurement.*

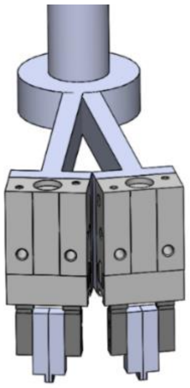
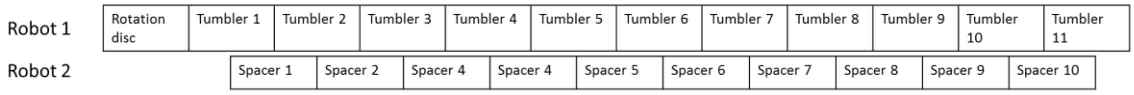


Figure 95 *Robot gripper that can hold two spacers.*

During the assembly cycle, the robots work and move at the same time. When one of the robots is moving away from the jig, the other robot moves to the jig. Robot 1 is responsible for the tumblers and other parts from the part feeding. It has 12 parts to place in the jig. Robot 2 has 10 spacers to place. The work cycle begins when the Robot 1 picks a rotation disc from the part feeding and places it in the jig. Then Robot 1 continues by picking the first tumbler and placing it in the jig. When Robot 1 pulls away from the jig, the Robot 2 comes to the jig in order to place a spacer. Figure 96 below illustrates how robots can work at the same time to bring parts to the jig.



Robot 1	Rotation disc	Tumbler 1	Tumbler 2	Tumbler 3	Tumbler 4	Tumbler 5	Tumbler 6	Tumbler 7	Tumbler 8	Tumbler 9	Tumbler 10	Tumbler 11
Robot 2		Spacer 1	Spacer 2	Spacer 4	Spacer 4	Spacer 5	Spacer 6	Spacer 7	Spacer 8	Spacer 9	Spacer 10	

Figure 96 *How robots can work together to bring parts.*

In Figure 96, one block represents one work cycle of a robot. The robot work cycle includes a movement to pick a part, picking the part with the pneumatic gripper, moving to the jig and dropping the part in the jig. During this cycle, the robot moves two times and the gripper acts twice. The duration of one robot cycle with the Epson G1-robot is

$$2 \cdot 0.3\,s + 2 \cdot 0.3\,s = 1.2\,s.$$

The Robot 1 defines the packet assembly cycle time as Figure 96 shows. The packet installation to the lock cylinder does not need to be considered here because the robots are not used in lowering the tumbler packet to the lock cylinder. The cycle time is the same as the Robot 1 movement time, which is

$$12 \cdot 1.2\,s = 14.4\,s.$$

The investment includes two small Epson SCARA robots G1 with a cost of

$$2 \cdot 14\,100\,€ = 28\,200\,€ \approx 28\,500\,€$$

Linear servos

Using linear servos that all communicate with the same motion controller minimizes the communication delays between the actuators. Linear servo motor axels are fast and precise. Instead of an industrial robot, a single linear servo could be used to move a part to the packet jig. Each servo would be responsible for moving a certain part. Figure 97 illustrates how the linear servos could be arranged around the packet jig.

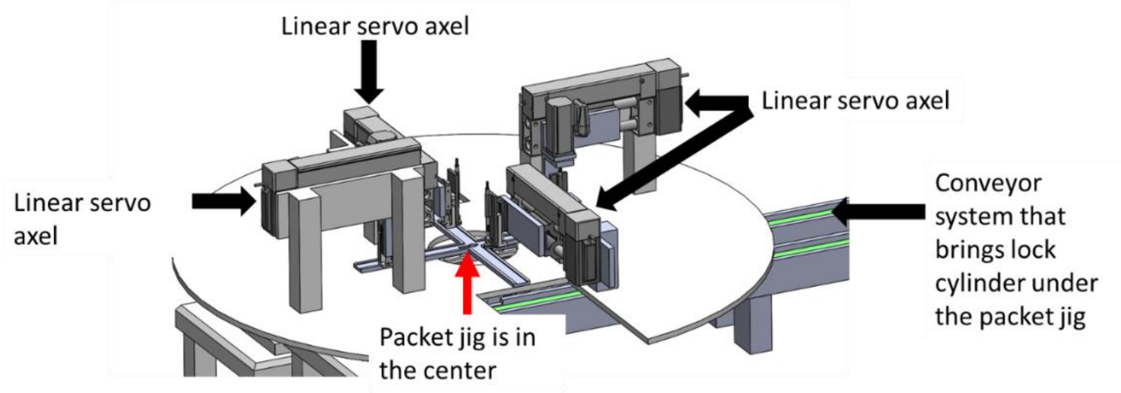


Figure 97 *Linear servos in packet assembly.*

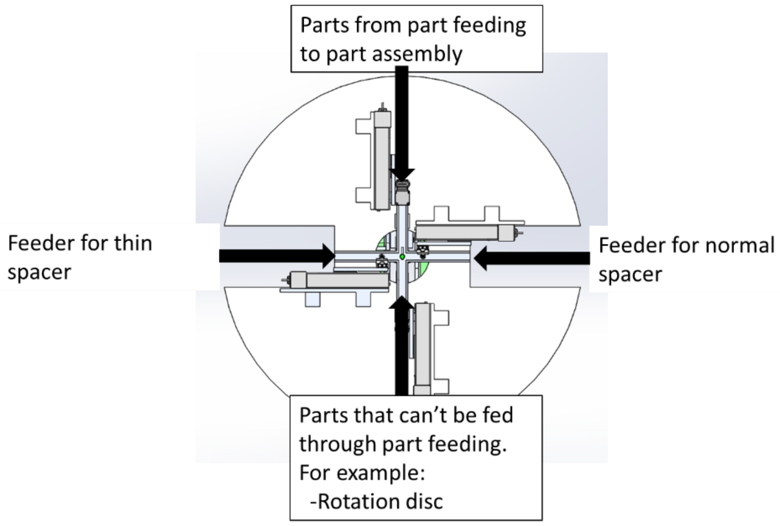


Figure 98 *Part feeding to linear servos.*

Figure 98 shows how parts could be divided among the linear servos. Both of the spacers have their own linear servos. This way a linear servo can have a spacer in its grip before the spacer is even needed. One servo handles parts from the part feeding and the other one those that are fed separately.

Servos move parts by sliding them against a surface. There is no need for the picking action and the part manipulator only needs to have a horizontal movement and a small vertical movement. Some part's orientation has to be adjusted before installed to the packet jig. The rotation disc is an example of such a part. The manipulator for parts like these must also have a rotating movement. An example manipulator is shown in Figure 99.

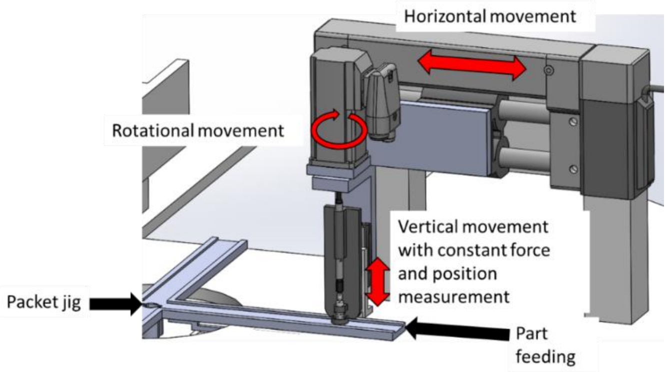


Figure 99 *Linear servo with tool that can correct part orientation.*

A tool for sliding the parts consists of a force controlled vertical movement and a position measurement. The vertical movement presses the parts against the surface and prevents them from moving. The position measurement is used to check if the part insertion to the packet jig was done successfully. The tool end itself needs to have some features that lock the part orientation during the movement. The same features that were used with the packet jig can be used to achieve this.

The packet assembly cycle time consists of the linear servos delivering parts in their own turn. When one servo has finished placing a part in the jig, the other servo can start moving towards the jig. When all the servos are controlled by the same controller, the next servo in turn can be driven close to the jig before it is free. Figure 100 below shows the order in which the servos deliver parts to the jig.

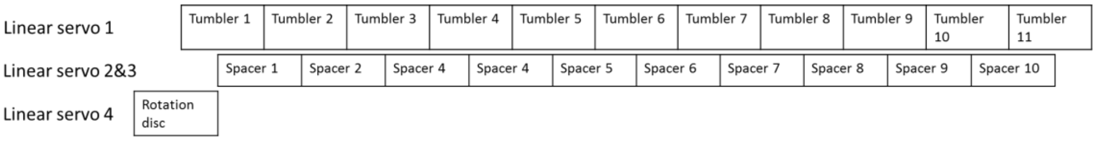


Figure 100 *Part delivery order with linear servos.*

One block in Figure 100 represents a work cycle for one servo picking a part and dropping it to the jig. In the 3D model, the SMC LEL25L-linear servo axels with a stroke of 300 mm were used. These axels have the maximum speed of 1000 mm/s [12]. The weight that servo is moving has an effect on the servo’s maximum speed. With 2 kg of weight, the linear servos maximum speed drops down to 700 mm/s [12]. With that speed, the servo can move objects 300 mm in 0.42 seconds. The stroke distance of 300 mm was chosen as an example. With a more accurate design, the stroke distance can be less. In one work cycle, the servo moves back and forth while pressing the part against the surface with a pneumatical actuator. In placing part to the jig, the controller checks that part has gone inside the packet jig with the gripper’s vertical position measurement. The cycle time for one linear servo is

$$2 \cdot 0.42\ s + 0.3\ s = \ 1.14\ s.$$

It takes 11 work cycles worth of time to complete the packet assembly. The packet installation in the lock cylinder is not done with linear servos but rather with separate pneumatic cylinders so it does not have an effect on the cycle time. The packet assembly cycle time with linear servos is

$$11 * 1.14\ s = \ 12.54\ s.$$

The investment consists of four linear servos and two rotational servos. The cost of investment is

$$4 \cdot 3\ 000\ € + 2 \cdot 3\ 000\ € = \ 18\ 000\ €$$

3.3.4 Lock cylinder pre-assembly

The lock cylinder feeding to the assembly machine is done by placing the lock cylinders on pallets. The pallets move the lock cylinders inside the machine and between the different workstations. Before the tumbler packet can inserted, the lock cylinder must be prepared by installing return bars and a drilling preventation disc. Once the tumbler packet is inserted into the lock cylinder, a rotation limiter must be installed to finish the assembly process.

Lock cylinder feeding

Feeding the lock cylinders to the pallets from a box or a bag by using a mechanical sorting device is problematic since the outer dimensions of the cylinder can vary. This makes designing a mechanical sorting device difficult. A mechanical feeding device would need a machine vision to check the lock cylinder orientation on pallet and a separate actuator to correct the lock cylinder orientation. Since a new lock cylinder is needed on 30 second intervals, designing and building a separate feeder for the lock cylinder does not seem necessary.

A machine operator can make sure that the lock cylinder is in correct orientation, if the lock cylinders are fed manually. Of course, there is no point for the operator to be constantly feeding the lock cylinders to the machine. That is why the lock cylinder feeding would require a buffer. If time between the buffer fillings is 20 minutes, the machine needs to have a buffer capacity of 40 cylinders. One way to build the buffer is to have multiple pallets in the system and a machine operator can place the lock cylinders directly on the pallets. But then the machine has to have over 40 pallets available. Using pallets as the buffer is problematic since the buffer size is limited by the size of the pallet track. In addition, placing the lock cylinder to a pallet manually requires the operator to release the pallet and wait for a new pallet to arrive.

It is more beneficial to build a simple linear feeder that acts as a buffer from which the lock cylinders are moved to the pallets. The operator places the lock cylinders in the correct orientation to the linear feeder buffer. If the cylinder diameter is about 15 mm, 40 cylinders need to have a 600 mm long linear feeder. In Figure 101 there is an example of what the lock cylinder buffer could look like. The lock cylinder orientation in the buffer could be locked by the shape of the lock cylinder end, similarly to what was done with the pallets.

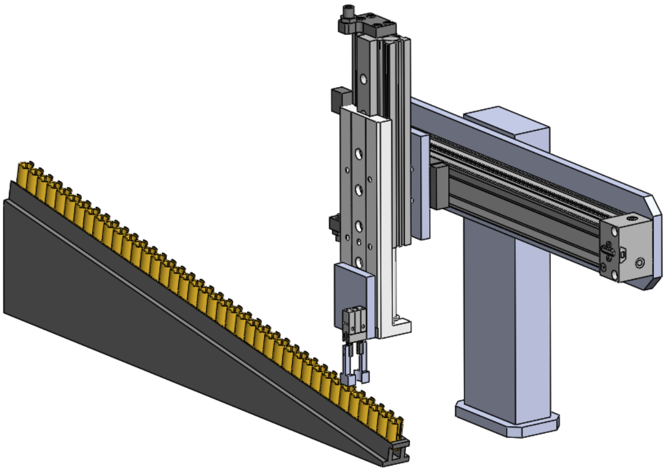


Figure 101 *Lock cylinder buffer example.*

The linear feeder needs some manipulator for moving the lock cylinder to the pallet. Used manipulator can be pneumatic with horizontal and vertical movements. The manipulator picks the lock cylinder from the buffer and places it in the pallet. The investment is considerably smaller than with the operator constantly feeding cylinders to the pallets.

A working cycle for the manipulator consists of pneumatical movements only. The manipulator needs to perform the same actions when picking the lock cylinder and when placing it to a waiting pallet. Between the picking and placing, the manipulator needs to move from the buffer to the pallet and back to the buffer after the lock cylinder has been placed. The actions for part picking and placing involve the gripper going down, acting and coming back up. Altogether 3 movements are needed for the part picking or placing and another 2 for the horizontal movement of the manipulator. The cycle time for the lock cylinder manipulator consists of eight pneumatical movements. The estimated cycle time is

$$8 \cdot 0.3\ s = \ 2.4\ s.$$

Installing drilling preventation, return bars and rotation limiter.

Drilling preventation and return bars must be installed before the tumbler packet and the rotation limiter after the packet is in the lock cylinder. One robot can be used to handle all of these parts. The robot needs to be placed so that it has access to the lock cylinder pallet moving to and from the packet assembly. In Figure 102, there is a 3D model of an automatic work station that could handle all these parts. The station layout can be viewed in more detail in Figure 103.

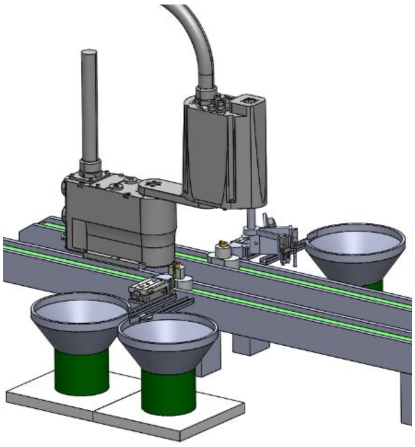


Figure 102 *3D representation of lock cylinder pre-assembly station.*

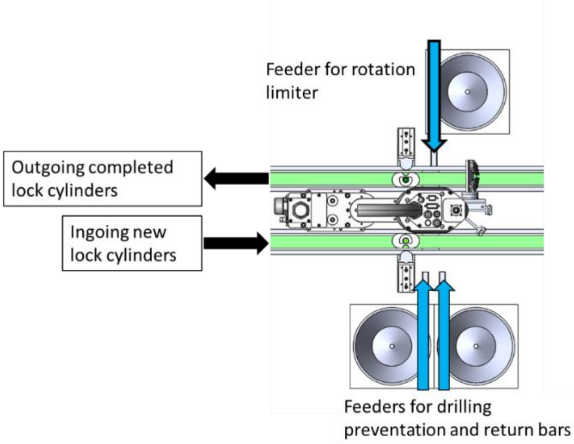


Figure 103 *Feeder and actuator arrangement for lock cylinder pre-assembly.*

The robot needs to have a gripper that works with all three parts. If necessary, the robot can hold the part in its gripper while waiting for the lock cylinder. Figure 104 shows an example of a robot gripper that has own actuator for each part.

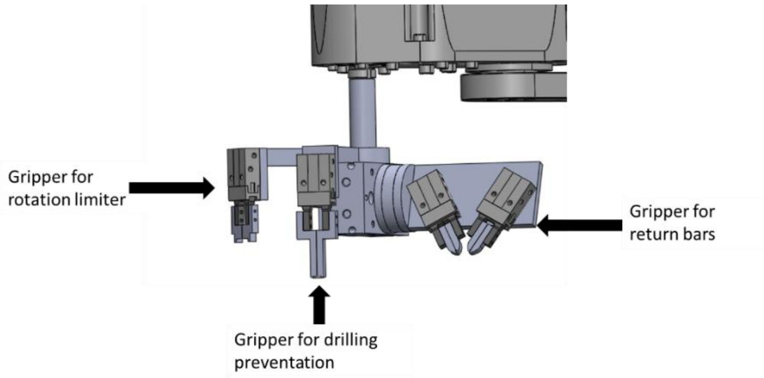


Figure 104 *Robot gripper for the rotation limiter, the drilling preventation and the return bars.*

During the work cycle, the robot has to move to pick the drilling preventation disc and then move to pick the return bars. Both parts can be fed with a vibratory bowl feeder. Assuming that the return bars come from the feeder one at a time, the robot needs pick twice to have both the return bars in the gripper. Installing of the return bars to the lock cylinder can be done with one robot movement. Placing the drilling preventation disc into the lock cylinder requires the robot to move once more. Altogether picking and placing of the drilling preventation disc and the return bars requires the robot to move 6 times and the pneumatic grippers need to act 5 times. The used robot is the Epson SCARA robot G1. This gives the return bars and the drilling preventation disc installation cycle time of

$$6 \cdot 0.3\,s + 5 \cdot 0.3\,s = \; 3.3\,s.$$

The rotation limiter is fed with a vibratory bowl and the final part orientation is found out with a machine vision. The rotation limiter installation requires the robot to move to the feeder, pick the rotation limiter and return to install it into the lock cylinder with a tumbler packet. This action requires the robot to move 3 times and the gripper to act 2 times. The cycle time for the rotation limiter installation is

$$3 \cdot 0.3\ s + 2 \cdot 0.3\ s = \ 1.5\ s.$$

If the robot does both actions in sequence, the robot cycle time is

$$3.3\ s + 1.5\ s = \ 4.8\ s.$$

The investment includes a Epson SCARA robot G1, three vibratory bowls and a single machine vision application. The cost for this equipment would be

$$14\ 100\ € + 3 \cdot 4\ 000€ + 3\ 500€ = 29\ 600\ € \approx 30\ 000\ €.$$

4. EVALUATION

4.1 Results from the simulation

In the simulation phase, all of the solutions had their cycle time and investment costs estimated according to the criteria set in the analysis phase. Table 7 has the estimated cycle time and investment collected for the part feeding solutions. Table 8 has the estimated cycle times and investment costs collected for the packet assembly into the lock cylinder.

Table 7 *Part feeding solutions cycle time and investment costs.*

Solution	**Cycle time (s)**	**Investment (€)**	**Comment**
Mechanical feeders on shelves	12.01	55 000	
Mechanical feeders along conveyor	12.14	54 000	
Mechanical feeders along puck track	18	33 500	Puck track not included in investment
Laser cutting using templates	15.3	187 500	Puck track not included in investment
Laser cutting with punching machines	8.8	157 500	Punching tools not included in investment

Table 8 *Packet assembly to lock cylinder solutions cycle times and investment costs.*

Solution	**Cycle time (S)**	**Investment (€)**	**Comment**
One robot and a packet jig in a gripper	9.64	20 500	
Two robots	14.14	28 500	
Linear servos	12.54	18 000	

The lock cylinder pre-assembly did not have a variety of solutions that could be compared. The investment cost for the only solution found is 30 000 € and the estimated cycle time was 4.8 seconds. As can be seen from Table 7 and Table 8, the lock cylinder pre-assembly is much faster than the other work phases. Thus, it will not limit the total machine performance.

Table 7 shows that the chosen part feeding system has a great effect on the machine's performance. The slowest solution for the part feeding was the puck track feeding that has a cycle time of 18 seconds. The fastest solution is the laser cutting with punching machines with its 8.8 second cycle time. There is almost a 10 second difference between the slowest and the fastest solution. It has to be noted that the laser cutting solution is also much more expensive. The mechanical feeder solutions with the industrial robots were a bit slower, but their price is more reasonable. The mechanical feeders on shelves is the fastest from non-laser cutting solutions.

The cycle times of the packet assembly to a lock cylinder are close to each other. The investment costs are also close to each other and nowhere as large as with the part feeding. The fastest solution was the one robot with a packet jig in the gripper that could do one cycle in 9.64 seconds. The slowest was a solution with two robots with 14.14 seconds' cycle time. It seems that using one robot with a packet jig gripper is the best option for the packet assembly. It has the best cycle time and the investment cost is only slightly higher than with the linear servo solution.

4.2 Proposed assembly machines

When choosing the part feeding system for an automated assembly machine, it is important to consider how the number of feeders affects the machine utilization rate. Part feeders are fine-tuned to work with parts that are of a certain quality. If the part quality changes or parts have abnormalities, the feeder might not function properly. If part feeding is comprised of 10 feeders, then the possibility for part feeding problems is 10 times greater than with just a single feeder. And any problems in the part feeding have a decreasing effect on the machine utilization rate.

A laser cutter makes the part feeding faster but it increases the investments costs considerably. To counter the increased costs, the laser cutter has other possible advantages. Making a tumbler on demand could reduce the need for other manufacturing processes, reduce the storage space and simplify the product changes. Also employing a laser cutter in the part feeding reduces the need for the feeding devices significantly.

Another option is to use mechanical feeders for the part feeding. The investments costs are lower and cycle times are only a few seconds longer. However, it provides no other advantages and a product change requires that the parts in the feeders are changed manually. Multiple feeders for the code tumblers increase the possibility of problems in the part feeding.

The laser cutter with punching machines solution is the best option for the part feeding, if the cycle time is the deciding factor. If the deciding factor is the investment cost, then the mechanical feeders on shelves option offers best compromise between the cycle time and the investment cost. The two proposed assembly machines are based on these part feeding solutions.

4.2.1 Investment cost

The best compromise between investment cost and cycle time would be the mechanical feeders on shelves for part feeding and the one robot with a packet jig in its gripper for handling the packet assembly. The cycle time of part feeding is 12.01seconds and the investment cost is 55 000 €. The packet assembly cycle time is 9.64 seconds and the cost of investment is 20 500 €. The lock cylinder pre-assembly is faster than the packet assembly or the part feeding. It has a cycle time of 4.8 seconds and the cost of investment is 30 000 €.

The assembly machine cycle time is the same as with the part feeding since the packet assembly cycle time is shorter. The part feeding cycle time is 12.01 seconds. The combined investment cost is

$$54\ 000\ € + 20\ 500\ € + 30\ 000\ € = \ 104\ 500\ €$$

This assembly machine's estimated cycle time would be 12.01 seconds and the actuator investment cost is about 104 500 €. The assembly machine would produce 2 398 parts in 8 hours. Figure 105 indicates what the proposed assembly machine could look like. Figure 106 explains how the different work stations are placed in relation to one another.

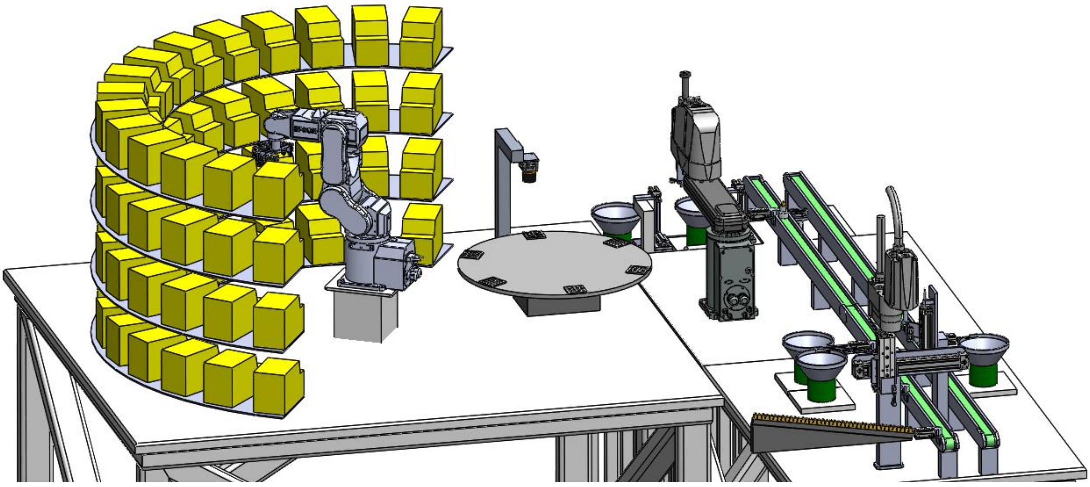


***Figure 105** Proposed assembly machine combination of "mechanical feeders on shelves" and "one robot with a packet jig in gripper."*

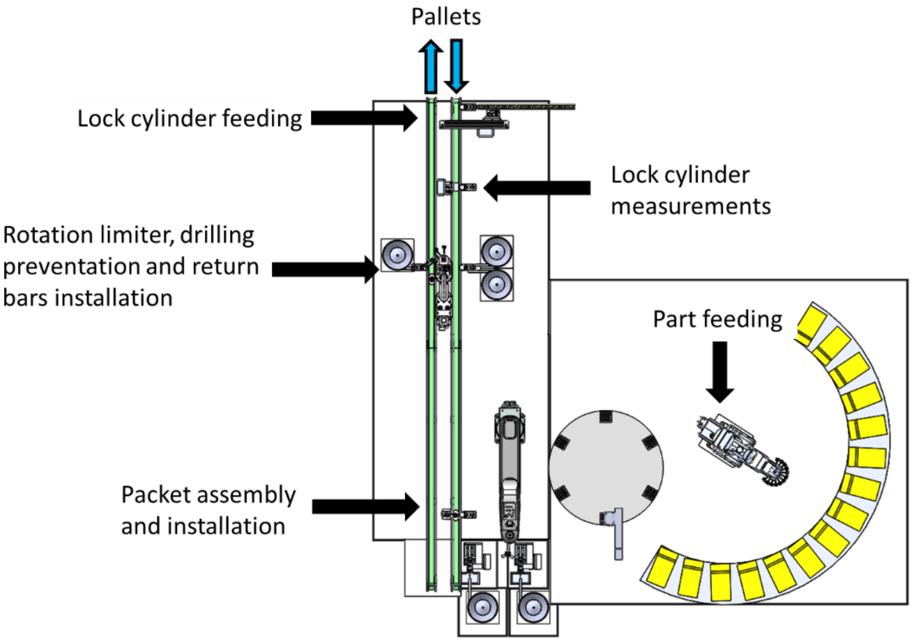


***Figure 106** Position of different work phases in proposed assembly machine with mechanical feeders.*

4.2.2 Cycle time

The assembly machine with the shortest cycle time would be a combination of the laser cutting with punching machines and the one robot with a packet jig in the gripper. The part feeding investment estimation for the laser cutting with punching machines is 157 500 € and it does not include the punching tool expenses. The cost of using the one robot with a packet jig in the gripper solution in the packet assembly is 20 500 €. The packet assembly cycle time of 9.64 seconds is longer than the part feeding's 8.8 seconds. The lock cylinder pre-assembly is the fastest of the three work stations, with its cycle time of 4.8 seconds. Its investment costs are 30 000 €.

The machine cycle time is the same as with the packet assembly, which is 9.64 seconds. The combined investment cost is

$$157\ 500\ € + 20\ 500\ € + 30\ 000\ € = \ 208\ 000\ €$$

Estimated cycle time for this assembly machine would be 9.64 seconds and the actuator investment cost about 208 000 €. With this cycle time, the assembly machine would produce 2 987 parts in 8 hours. In Figure 107, there is a representation of what an assembly machine could look like. The more detailed explanation of the station places is in Figure 108.

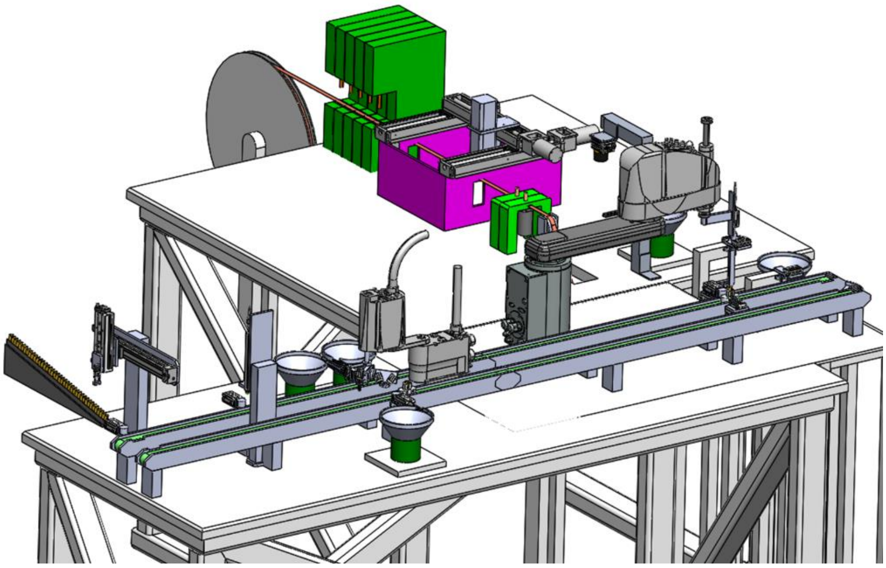


Figure 107 *Proposed assembly machine configuration of "laser cutting with punching machines" and one robot and jig in gripper".*

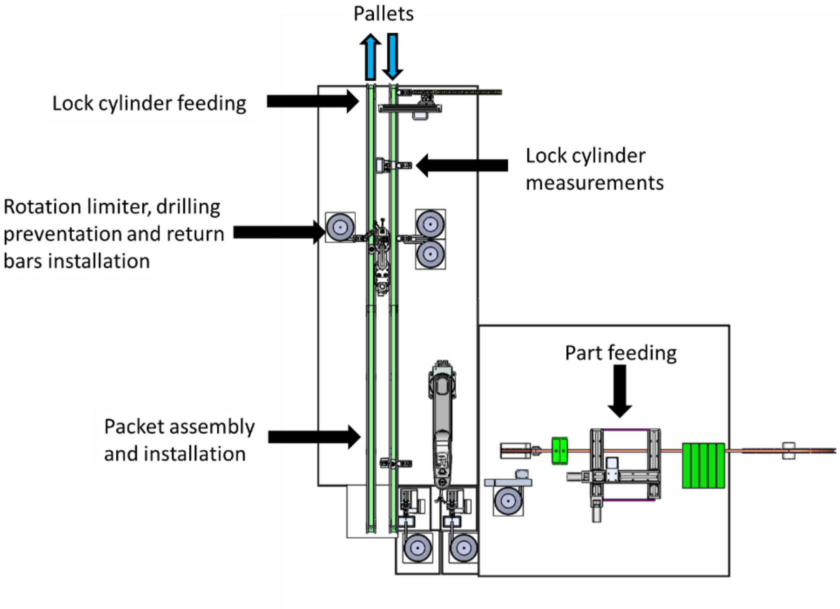


Figure 108 *Position of different work phase in the proposed assembly machine with a laser cutter.*

Although this combination would be considerably more expensive, it has some advantages that should be considered. With this machine, the entire tumbler manufacturing process would be handled by the laser cutter and a few punching machines. There would be no need to manufacture large batches of the tumblers to storage waiting for assembly. The proposed assembly machine would reduce the number of needed manufacturing processes, reduce need for storage space and lower manufacturing costs.

Before making the decision to use laser cutting in part feeding, a further study of the laser cutting and the tumbler manufacturing process is required. During this thesis, the possibility to cut tumbler material with a laser has been confirmed. But cutting of the entire tumbler has not been tested. The test needs to be conducted, so that a realistic cycle time for laser cutting can be used in the evaluations. For justifying the machine investment cost, the impact to the tumbler packet part manufacturing and storing needs to be considered and studied much more closely.

5. CONCLUSIONS

In this thesis, a design process methodology for solving the problems facing an automated tumbler packet assembly was created. The created methodology was based on examples from the literature. In this methodology, the design process for a tumbler packet assembly was divided into four phases: analysis, synthesis, simulation and evaluation. CAD software and 3D modeling were extensively used to aid in the problem solving and in the visualization of the proposed solutions.

In the analysis phase, the requirements were gathered and the problems with the automatic part feeding studied. Some of the identified part feeding problems could be solved easily, e.g. if a part could be fed with a combination of a vibratory bowl and a machine vision. The more demanding and crucial problems of the code tumbler feeding, spacer feeding and a packet assembly to the lock cylinder were left to be solved in the synthesis phase. The criteria for evaluating the results of the methodology was defined to be estimated cycle time and investment cost.

During the synthesis phase, solutions to the bigger problems were proposed. Some solutions were tested by creating prototype feeders to ensure their functionality. Tests with actual parts were carried out to see how they would perform. The code tumbler feeding was tested with feeders that used a groove and the bulge in the code tumbler to orient them. The code tumbler orienting was successful with this method. Another way of feeding the code tumblers was to make the needed tumblers in an assembly machine with a laser cutter. The laser cutting of the tumbler material was deemed possible after it was tested in three different companies. Orienting spacers with a groove that locks the spacer orientation was tested, but the feeder orienting accuracy was not satisfactory. As an option, a spacer feeder that uses gravity and a rotating stick was proposed and visualized. The solution for the reliable packet assembly to the lock cylinder was assembling packet first in a special jig that mimics the lock cylinder features. Once the entire packet is assembled, it is moved to the lock cylinder with a single movement. This minimizes the risk of parts moving when a tumbler packet is installed to a lock cylinder.

The simulation phase of the methodology answers to the first research question of this thesis, namely how general automation equipment can be used in tumbler packet assembly. To simplify the design process, the tumbler packet assembly was divided into three separate tasks: part feeding, packet assembly and lock cylinder pre-assembly. Each task was solved individually, by employing well-known and general automation equipment such as SCARA and articulated arm industrial robots as well as linear servo motors. Each solution was constructed using a CAD software and the estimations of their performance were made. The criteria set in the analysis phase defined how the performance of the solutions was evaluated.

In the evaluation phase, the results from the simulation are collected and discussed. The research question of how different solutions compare on cycle time and investment costs with each other is answered. When using a laser cutter with punching machines in the part feeding, the shortest cycle times are achieved. But the laser equipment rises investment costs considerably and the price for the punching tool is not known, so this is probably the most expensive solution. If the part feeding is realized with mechanical feeders, the investment cost is lower. When the mechanical feeders are placed on shelves where a robot can reach all of them, the cycle times are only a few seconds longer and the investment cost is much lower than with a laser cutter. For the packet assembly to the lock cylinder, the shortest cycle time was achieved by using one robot with a custom gripper. Its investment cost is also reasonable. The solution for the lock cylinder pre-assembly used a SCARA robot to install all the needed parts into the lock cylinder and a pneumatic manipulator for the lock cylinder feeding.

When deciding on the final solution for the tumbler packet assembly machine, the main deciding factor has to be chosen. The assembly machine design can aim to optimize either the cycle time or the investment cost. For this reason, two assembly machines were proposed in this thesis. One that aims to achieve the shortest cycle time and another aims to minimize the investment cost. The proposed machines are otherwise identical, but their part feeding methods are different. A laser cutter with punching machines is ideal for minimizing the cycle time of the assembly process. If lower investment costs are desired, then the part feeding should be handled by placing the mechanical feeders on shelves and using an articulated arm robot to pick parts from there. Decision of which is better for their need is left to Abloy Oy.

At the beginning of this thesis, the research questions seemed to be straightforward. During the analysis phase, the problematic nature of automating the tumbler packet assembly started to emerge. There were lots of problems of different sizes and all of them needed to be addressed and solved. For the purposes of this thesis, problems were handled on a general level, without going into detail. Hopefully in the future Abloy Oy can use the information provided in this thesis to further study automating their tumbler packet assembly. Recommended targets for further study are the laser cutting of tumblers, the spacer feeding, the testing of packet assembly to a jig and moving packet from a jig to a lock cylinder in the proposed fashion.

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