Martin Neumayr, BSc

Productivity Increase of Flexible Manufacturing Systems by Externalisation of Measurement Procedures

MASTER´S THESIS

for the Purpose of Obtaining the Academic Degree

Diplom-Ingenieur (Dipl.-Ing.)

Master´s degree programme: Production Science and Management

submitted to

Graz University of Technology

Faculty of Mechanical Engineering and Economic Sciences

Institute of Production Engineering

Supervisor: Univ.-Prof. Dipl.-Ing. Dr.techn. Rudolf Pichler

Head of Institute: Univ.-Prof. Dipl.-Ing. Dr.techn. Franz Haas

Graz, December 2019

AFFIDAVIT

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly indicated all material which has been quoted either literally or by content from the sources used. The text document uploaded to TUGRAZonline is identical to the present master‘s thesis.

Date   Signature

Acknowledgement

At first, I would like to thank the initiators of this thesis Mr. Josef Büchsenmeister, Production Manager of ENGEL Austria for offering me this interesting chance and my supervisor Professor Rudolf Pichler. The patient guidance, ongoing support and constructive criticism during the cooperation was essential to overcome arising challenges.

Many thanks go to Mr. Roman Naderer, team leader of flexible manufacturing systems and various other stuff members at the shop floor. Their advice and detailed knowledge have contributed significantly to the success of this project.

My beloved parents deserve special thanks for their support and encouragement throughout my entire time of studies.

Finally, I also would like to thank my girlfriend for accomplishing all ups and downs and her patient support during the last years.

Abstract

In cooperation with ENGEL Austria GmbH, this master thesis deals with the issue of non-value-generating process steps in flexible manufacturing systems. In particular, it considers the measuring cycle of radio transmission probes in CNC-machine centres.

During the current measurement cycle there is no value added to the workpiece, resulting in a loss of productivity and efficiency of the machine. It is therefore essential that an exact quantification of this process is obtained. The suitability of different measurement methods for an automated process sequence outside the machine is investigated and an economical solution is presented.

The thesis begins with an explanation of the initial situation and provides an overview of the components, machines and the respective systems to be used in a theoretical chapter. Then, the industrial metrology as well as advantages and disadvantages of different methods are explained. A market study provides information on current measuring instruments and their suitability for an outsourced measuring process.

In a follow-up step, the measuring cycle in the manufacturing machine is evaluated and analysed on the basis of data acquired from the machine. Based on this evaluation, the design of a feasible externalised measurement process is developed. A cost comparison shows the possible savings and takes them into account in an investment calculation. Finally, a comparative calculation illustrates the increase in productivity of the manufacturing system.

Kurzfassung

In Zusammenarbeit mit der Fa. ENGEL Austria GmbH beschäftigt sich die vorliegende Arbeit mit der Thematik von nicht wertgenerierenden Prozessschritten in flexiblen Bearbeitungssystemen. Im Speziellen wird der Messzyklus von Funkmesstastern in CNC-Bearbeitungszentren behandelt. Da während eines Messzyklus keine Wertschöpfung am Bauteil erzielt wird und die Maschine dadurch an Produktivität einbüßt, ist eine genaue Quantifizierung dieses Prozesses unumgänglich. Des Weiteren wird die Tauglichkeit von verschiedenen Messmethoden für eine automatisierte Prozessabfolge außerhalb der Maschine untersucht, sowie eine ökonomische Lösung dargelegt.

Die Arbeit beginnt mit einer Erläuterung der Ausgangssituation und gibt einen Überblick über die verwendeten Bauteile, Maschinen und deren Systeme in einem theoretischen Kapitel. Anschließend werden die industrielle Messtechnik sowie Vor- und Nachteile verschiedener Methoden erklärt. Eine Marktstudie gibt Aufschluss über aktuelle Messgeräte und deren Eignung für einen ausgelagerten Messprozess.

Im nächsten Kapitel wird der Messzyklus in der Bearbeitungsmaschine anhand von Maschinendatenaufzeichnungen ausgewertet und analysiert. Darauf aufbauend erfolgt die Auslegung einer realisierbaren Variante zur hauptzeitparallelen Messung von Bauteilen vor der Bearbeitung. Eine Kostenüberstellung zeigt die möglichen Einsparungen auf und berücksichtigt diese in einer Investitionskalkulation. Abschließend wird anhand einer Vergleichsrechnung die Produktivitätssteigerung ermittelt.

Table of contents

Figures

Tables

Abbreviations

APC	Automatic Pallet Changer
BPMN	Business Process Model and Notation
CAM	Computer Aided Manufacturing
CMM	Coordinate Measuring Machines
CNC	Computerized Numerical Control
CT	Casting Tolerance
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DNC	Distributed Numerical Control
EN	Europäische Norm (European Standards)
FMS	Flexible Manufacturing System
IPM	Integrated Process Monitoring
LASER	Light Amplification by Stimulated Emission of Radiation
MDX	Manufacturing Data Exchange
MES	Manufacturing Execution System
MMS	Manufacturing Management Software
NPV	Net Present Value
PLC	Programmable Logic Controller
RMA	Required Machining Allowance
SAP	Systems, Applications & Products in Data Processing
SRM	Storage and Retrieval Machine

1. Introduction

The efficient manufacturing of metal components is a key challenge for production companies. Market demands with high product quantity based on series productions together with requirements of customized product configurations are difficult to accomplish with conventional production systems. Flexible manufacturing systems are needed to fulfil this task. Production on multiple, equally equipped machines, is an approach to lower production costs. In addition, an automated supply and material feed system for the machines ensures efficient logistics. Today, flexible manufacturing systems have proven their value and companies are not able to produce without them. In order to increase the productivity, a detailed investigation is necessary to find wasted process steps in this highly sophisticated system.

1.1 Problem statement

The research focus of the Institute of Production Engineering on Advanced Manufacturing includes the productivity increase in future-oriented shop floor applications. Highly flexible manufacturing systems are used for a high variety of parts and batch sizes. Therefore, the increase of productivity is vital for ongoing success.

This thesis is based on the central problem of non-value adding measurement cycles during the manufacturing process.

1.2 Aim of the thesis

The following research questions are covered in this thesis:

- How can the measurement cycle be changed to increase machine productivity?
- What does an externalized measurement process look like?

1.3 Structure of the Thesis

In order to address the above mentioned research questions, the comprehensive explanation is based on a chronological structure.

The initial status of the existing system is described in greater detail in the second chapter. It starts with a brief insight into the manufacturing systems used and closes with the data of workpieces and rejections.

The third chapter introduces various measurement systems and shows the advantages and disadvantages of the methods. A benefit analysis identifies a suitable measurement tool on the market.

Chapter four explains how the measurement time is generated and analysed.

The next chapter deals with the process optimization and covers all necessary components and changes to the existing system.

The calculation of cost savings, financial investments and effects on the productivity of the systems are included in chapter number six.

Finally, chapter number seven gives a brief conclusion of the developed process and summarizes the approach

1.4 Introduction of the company

ENGEL Austria GmbH was founded in 1945 by Ludwig Engel in Schwertberg, Upper Austria. Plastic presses had been produced until the launch of the injection moulding machine in 1952. The machines produce plastic parts by the injection of plasticized and melted plastic granulate into a mould cavity. Due to the high-pressure during the injection process, mechanical components are used to apply the required clamping forces. The machines cover a range of clamping forces from 280 kN up to 55,000 kN. They are powered with different configurations such as hydraulic, electric or combinations of these. Over the years, the company has been growing with the development of the machines and production plants outside of Austria. The invention of the tie bar-less machine concept in 1989 set a milestone in the plastic production industry. Depending on the machine, different thermoplastic or elastomer materials can be used. Furthermore, the application fields cover almost every plastic product such as automotive, packaging, teletronics, medical or technical mouldings. Today the company has become a global market leader and produces machines in plants located in Austria, Czech Republic, Germany, USA, China and Korea. The family-owned company with 6,900 employees worldwide produces machines to a high manufacturing depth with a global turnover of 1.6 billion euros.

2. Theoretical basis

The manufacturing of different steel components for production machines requires a capable process. The mechanical properties of the part have determined the manufacturing process since its design. Casting is therefore used for producing the geometrical shape in one process. In order to use the component for a machine, the geometry must be manufactured by milling, grinding or turning processes. A Flexible manufacturing system allows the manufacturing of different workpieces independent of batch sizes on multiple machines. That enables a higher part throughput and shorter production times. Nevertheless, the casted raw part features possible deviations from the original shape caused by the forming process. Those incidents are leading to downtime of the manufacturing machine if they are not recognized before machining.

2.1 Casting

The production processes of DIN 8580[1] lists casting in the category of primary shaping. Forming, cutting, joining, coating and changing properties are the other main processes. The hand formed gravity sand casting is common for parts with less quantity but large size. Other casting processes are investment casting, die casting, lost-foam casting, centrifugal casting or permanent mould casting. Sand casting is the oldest process used but is still relevant today.

Before a component is casted, a model has to be prepared according the design dimensions. Shrinkage during cooling and draft angles must be considered on the model. Depending on the size, a wooden or foam model is used for preparing the mould. The mould is formed in two parts by pressing sand around the model. To keep the sand in position, chemical binders like Furan are used. After all necessary elements like sprue, runner or feeder are implemented the two cavities are closed and clamped (Figure 2-1). Metal is heated up together with alloy components to its liquidus temperature of over 1480°C. The liquid melt is filled into the mould where the solidification begins. A poor filling system is responsible

[1]cf. (DIN 8580, 2003)

for occurring internal shrinkage cavity or porosity with part rejection as a result. The metal needs several hours to cool down and gets mechanical strength. Deforming take place by destroying the mould. However, the sand can be used multiple times. Now all process relevant features are cut off and the surface gets a corrosion resistance painting.[2]

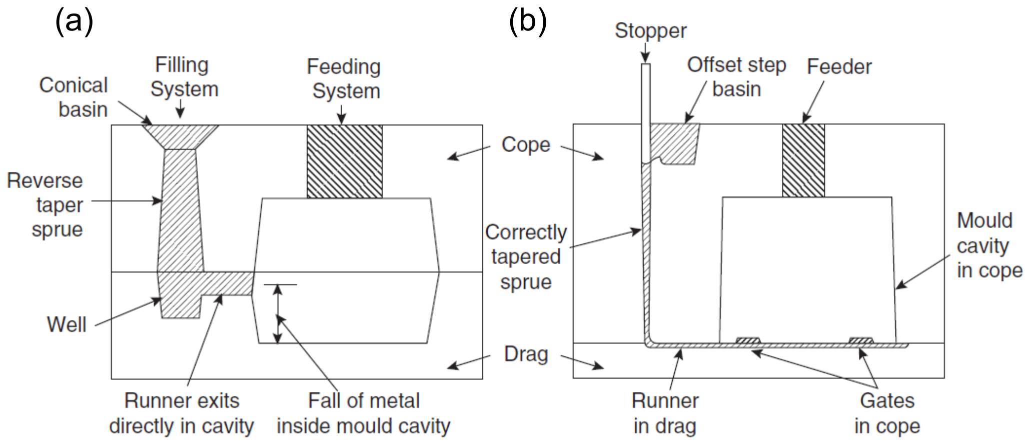


Figure 2-1: Mould cavity with poor filling system (a) and effective system (b)
Source: Campbell 2015, page 644

The material in use is defined as spheroidal graphite cast iron (EN-GJS-400-18U) according DIN EN 1563.[3] Magnesium is added to spherodise the containing graphite. This leads to the mechanical characteristic of ductile iron. The mechanical properties are Tensile strength (Rm) of 400 N/mm², a Yield strength (Rp0.2) of 250 N/mm² and an Elongation of 15 %. Furthermore, it is well suited for machine components.

The required machining allowance (RMA) together with the casting tolerances depends on the part size and is defined in ISO 8062[4]. Table 2-1 illustrate the permissible deviations referring the basic dimension. The grade of casting tolerance (CT) expresses moulding process. CT9 is used for machine-moulded sand-casting parts of smaller series. Individual products or larger parts are hand moulded and categorised with CT11 or CT12. The common machining allowance for all castings is referred group G. For example, the permissible deviation for a

[2] cf. (Campbell, 2015) p. 302-307, 383, 797-799

[3] cf. (DIN EN 1563, 2019/04)

[4] cf. (ISO 8062, 2007)

sand moulded part dimension of 800 mm is 8 mm in the classification of CT11 and the RMA is defined with 5 mm.

Table 2-1: Casting tolerances according ISO 8062

Casting Tolerance – Permissible Deviations in mm											
Basic Dim.	Over	100	160	250	400	630	1000	1800	2500	4000	6300
	To	160	250	400	630	1000	1800	2500	4000	6300	10000
		Total Casting Tolerance									
Grade	CT9	2.5	2.8	3.2	3.8	4	4.6	5.4	6.2	7	-
	CT10	3.6	4	4.4	5	6	7	8	9	10	11
	CT11	5	5.8	6.2	7	8	9	10	12	14	16
	CT12	7	8	9	10	11	13	15	17	20	23
		Required Machining Allowance									
Grade	RMA G	2.2	2.8	3.5	4	5	5.5	6	7	8	9

The high tolerances are necessary to accomplish unforeseen shrinkage effects or surface roughness caused by the sand mould. In addition, the tolerances are complicating the manufacturing process. Due to the bandwidth of several millimetres are unproductive air cuttings of the machine possible. Deviations on the surface could also harm the cutting tool with a crash as a result. The better a part can be checked before it gets manufactured, the less complications will occur.

2.2 Flexible manufacturing systems

Manufacturing companies nowadays have to react to the market demand of product customization and smaller batch sizes. Compared to the series production with high quantity and low part flexibility, the requirement of high product flexibility is increasing the production costs. Flexible manufacturing system (FMS) are used to close this gap (Figure 2-8). With a uniformed system of similar manufacturing machines, material supply system and a production control system, the resources of time, space and production costs can be reduced. Computer numerically controlled (CNC) milling machines with multiple axis, tool management, and workpiece transfer system are controlled by a main computer. It allocates the workload of the machines depending on the product orders. The manufacturing of the parts is only limited by the material dimension, the orientation of the manufacturing surfaces and the required tools. The use of similar machines with the possibility of producing one part in every machine causes a redundancy in case of a crash.[5]

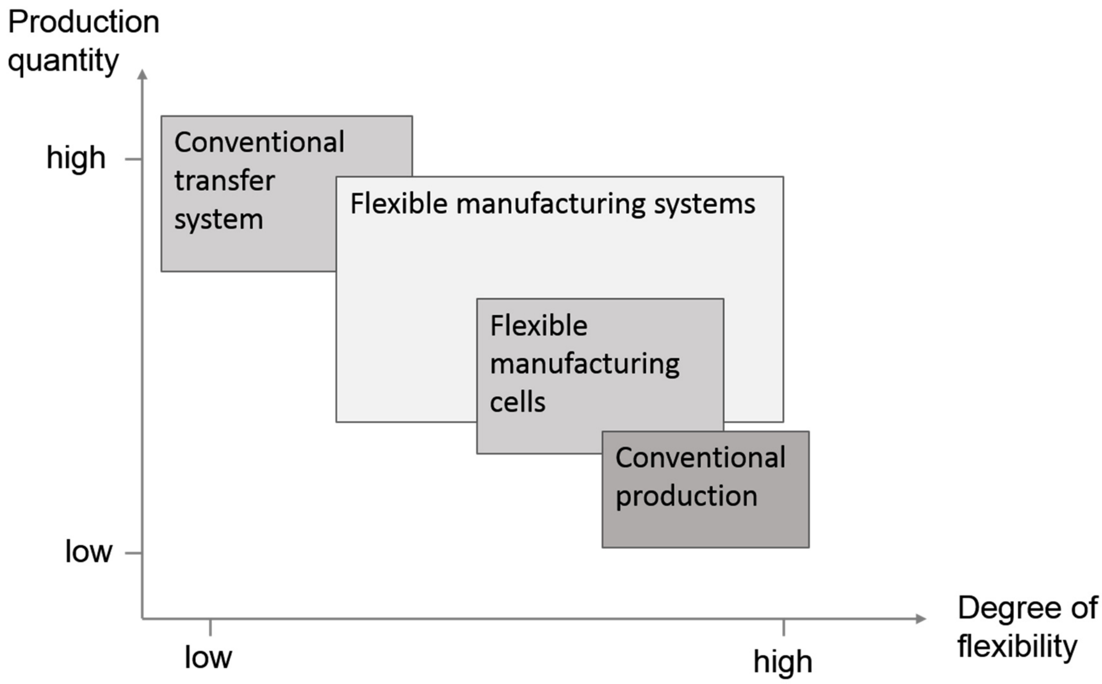


Figure 2-2: Application of manufacturing systems referring production quantity and degree of flexibility. Source: Kief / Roschiwal 2017, p. 407

2.3 Existing manufacturing system

The company ENGEL Austria GmbH uses three FMS in the shop floor at the factory site Schwertberg, Austria. The size of the produced components limits the machine dimension. Therefore, one FMS consisting of four CNC machining centres from type “Starrag Heckert HEC1250 Athletic” and “Fastems Multi-Level System Heavy Duty” for a pallet storage of 58 pallets with the dimension 1,250 mm x 1,000 mm is used for the biggest parts. Additionally, two FMS are used to manufacture smaller parts. Each consists of three machining centres from type “Heller H8000MC”[6] and a “Fastems Multi-Level System Medium Duty” with 148 storage positions for 800 mm x 800 mm pallets. The machining centre (Figure 2-3) is designed using Finite Element Method techniques and consists of the main components, machine bed, rotary feed table, column, spindle with machining unit,

[5] cf. (Kief/Roschiwal, 2017) p. 397 - 425

[6] cf. (Gebr. HELLER Maschinenfabrik GmbH, 2019)

pallet and tool changer, linear guideways with encoding measurement system and a weight compensation. The total FMS is linked to a casting's storage for raw material supply.

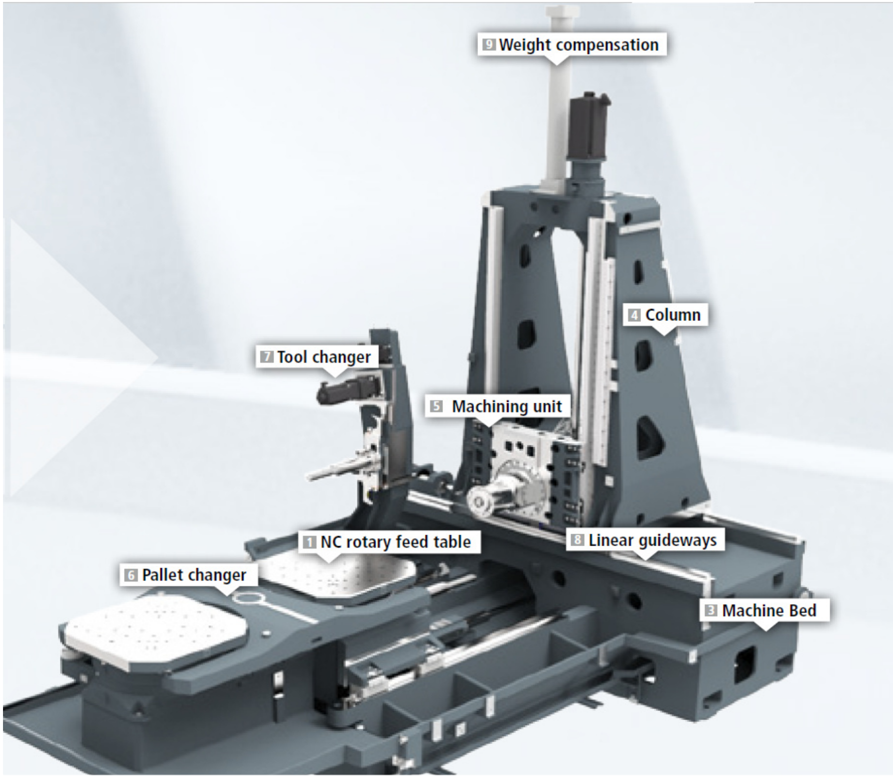


Figure 2-3: Components of a horizontal machining centre – Heller H8000MC
Source: Gebr. Heller Maschinenfabrik GmbH

For this thesis, the FMS with cost centre number 2556 should be investigated and consists of three Heller H8000MC machines. Every machine has its assigned number and starts with the company location code (Schwertberg- Austria: 0011), followed by the cost centre number (2556), the order in the FMS (one to three) and the version of the machine (one). For example, 0011255611 represents the first machine of the FMS 2556 at the factory site in Schwertberg.

2.4 Existing Process

After the income of a production order, the assigned cast component is requested from castings storage and manually set-up onto the existing clamping fixture at the set-up station. The pallet is then stored in the pallet storage after it has been released by the stacker crane which is also called storage and retrieval machine (SRM). To control the production steering, a Manufacturing Data Exchange

Interface (MDX) communicate with the Manufacturing Execution System (MES) of the company. Tool data and the machinery status like the productivity signal are the main examples for the transfers. The master computer receives the production job in processing order. In the background, the computer sends the corresponding Numerical Control (NC) programs from the central Distributed Numerical Control (DNC) storage to the assigned machine. This procedure is controlled by the Manufacturing Management Software (MMS) of the pallet storage. It checks whether all tools are ready for part manufacturing in the machine and at which time point it should be delivered.

At the required time slot, the machine pallet is conveyed to the respective processing machine by the SRM. Next, the pallet is transferred to the machine tool with a lowering movement of the stacker crane onto the Automatic Pallet Changer (APC). After completion of the previous machining process, the new pallet is loaded into the machine and clamped on the machine table with the aid of a zero-point clamping system. The NC program is then started. In the first program step, a radio transmission probe measures the component at predefined points. These coordinate points are used to calculate zero points. Furthermore, the machining allowance applied by the foundries is determined.

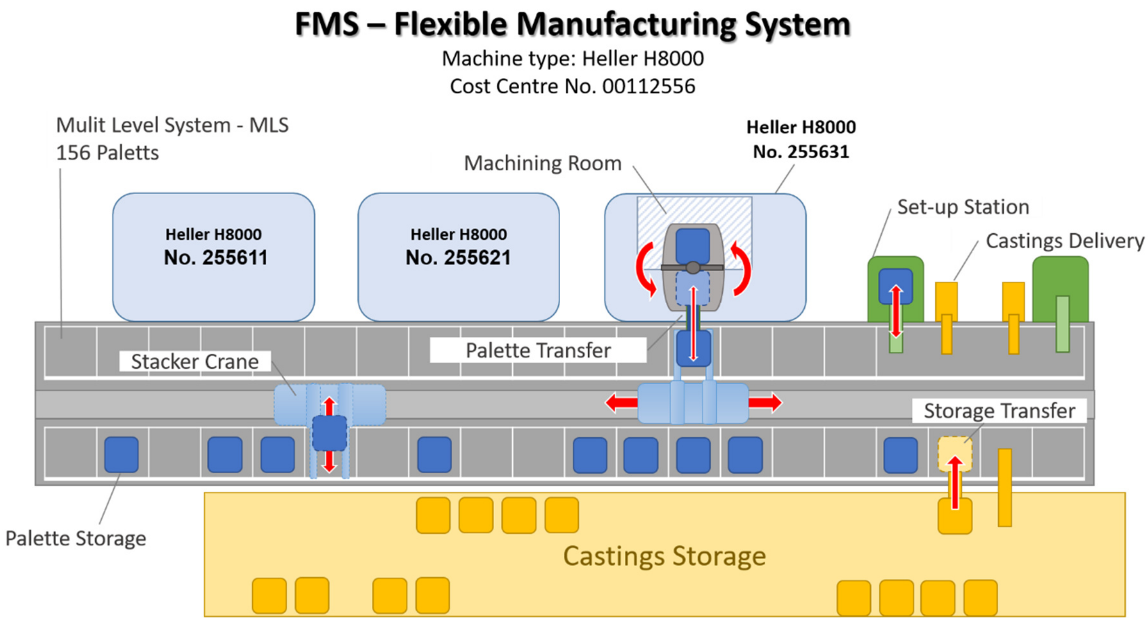


Figure 2-4: Flexible Manufacturing System

The coordinate points are used in the NC program as zero points for referencing the component in the machining area. A defined confidence interval tells the touch probe in which range the expected dimension lies. The machining allowance is removed step by step and controlled by a sub program, called “Jump-label”. If the confidence interval is exceeded or not reached, a fault message is triggered which causes a machining standstill. This is caused by geometrical deviations of the cast part. The machine operator is responsible for rectifying the fault and must decide how to proceed. He can either send the part from the processing machine to the set-up station or manually extend the confidence interval in the NC program in order to be able to manufacture the part after all.

Once this probing process is complete, the radio transmission probe is replaced by a milling tool and machining can begin. Dependent on the component, the probe is used to verify the tool geometry of precision-fit bores during the manufacturing process. After all main cycles are processed, a washing tool removes all metal chips from the part. Now the manufacturing is completed, and the finished pallet is exchanged with a new one via APC. Until the machine starts a new process, the stacker crane picks the waiting pallet up and transfers it to the set-up station. If the selected station cannot be supplied, the pallet is moved to the storage in the meantime. On the set-up station, a worker inspects the machined part of material failures and removes any burr with a grinder. In the final step, all clamps are removed and the part is placed on a transport box with a assigned routing card. The part leaves the area with a pallet truck to the assembly line.

2.5 Existing Measurement Cycle

Before the milling process can start, a measurement of the zero points and the part allowances must be measured. For this purpose, a radio transmission probe is used in the measurement cycle. A CAM worker must define all positions on the part surface to ensure all zero points and geometrical data of the part are detected. An example of one existing measurement cycle is shown in Table 2-2 with the defined zero points in Table 2-3.

The cycle starts with loading the tool number 79981 (Renishaw RMP60 PK.F). With the initiation of the work offset (G54) the position of the machine zero (M) in the machine coordinate system is changed to the workpiece zero (W) in the workpiece coordinate system as shown in Figure 2-5. The tool zero (F) is need for the tool reference during probing movement.

Table 2-2: Measurement Cycle – Prog. No. 00840998

```
N222 ;============================================================
N224 MSG("ANTASTEN-Z-G54 Point to Point")
N226 ; TOOL: Renishaw DM= 6.00 L=276.00 BT= 83.00 D= 6.0 RENISHAW
RMP60 PK.F
N228 ; IDNR: T79981 D= 6.00 L=276.00
N230 ;============================================================
N232 G54
N234 RP_POS
N236 RP_VALUE( 0.00)
N238 T_POSITION
N240 T_CHANGE("79981")
N242 T_PREPARE("78855",0)
N244 T_CHECK(0,0,0)
N246 PROBE_ON
N248 G17
N250 G54
N252 G0 X140. Y145. S0 D01 M03
N254 Z50.
N256 IF($P_SEARCH==1) GOTOF END_MESSEN
N258 G00 Z 5.00
N260 CYCLE978(0,0, ,1, -35.00, 20.00, 8.00,3,2,1, , , , , , , , , ,
,1,0)
N262 STOPRE
N264 L_ZO_WRITE("Z",1,10,_OVR[19])
N266 L_LOGWRITE("Differenz Messachse Z:" << _OVR[19],0,900,812)
N268 L_LOGWRITE("Istwert Messachse Z:" << _OVR[04],0,900,812)
N270 R698 = _OVR[19]
N272 R699 = _OVR[04]
N274 ; Ausgangspositon B = 0.00 Ausgangsnullpunkt = 1
N276 STOPRE
N278 L_ZO_WRITE("Z",21,(10),_OVR[19], 0.000)
N280 L_ZO_WRITE("Z",22,(10),_OVR[19], 0.000)
N282 L_ZO_WRITE("Z",2,(10),_OVR[19], 90.000)
N284 L_ZO_WRITE("Z",23,(10),_OVR[19], 90.000)
N286 L_ZO_WRITE("Z",24,(10),_OVR[19], 270.000)
N288 L_ZO_WRITE("Z",25,(10),_OVR[19], 180.000)
N290 L_ZO_WRITE("Z",3,(10),_OVR[19], 180.000)
N292 L_ZO_WRITE("Z",4,(10),_OVR[19], 270.000)
N294 END_MESSEN:
```

Table 2-3: Zero Points - Prog. No. 00840998

```
N40 WORKBEGIN
N42 L_ZO_FINE_DEL
N44 IF $P_SEARCH == TRUE GOTOF END_NPV
N46 $P_UIFR[ 1,X,TR]= 0.000;        G54
N48 $P_UIFR[ 1,Y,TR]= 202.000;      G54
N50 $P_UIFR[ 1,Z,TR]= 148.000;      G54
N52 $P_UIFR[ 1,B,TR]= 0.00;         G54

N54 $P_UIFR[ 2,X,TR]= 27.000;       G55
N56 $P_UIFR[ 2,Y,TR]= 202.000;      G55
N58 $P_UIFR[ 2,Z,TR]= 225.000;      G55
N60 $P_UIFR[ 2,B,TR]= 0.00;         G55

N62 $P_UIFR[ 3,X,TR]= -0.000;       G56
N64 $P_UIFR[ 3,Y,TR]= 202.000;      G56
N66 $P_UIFR[ 3,Z,TR]= 142.000;      G56
N68 $P_UIFR[ 3,B,TR]= 0.00;         G56

N70 $P_UIFR[ 4,X,TR]= -27.000;      G57
N72 $P_UIFR[ 4,Y,TR]= 202.000;      G57
N74 $P_UIFR[ 4,Z,TR]= 200.000;      G57
N76 $P_UIFR[ 4,B,TR]= 0.00;         G57

N78 $P_UIFR[ 21,X,TR]= 0.000;       G521
N80 $P_UIFR[ 21,Y,TR]= 202.000;     G521
N82 $P_UIFR[ 21,Z,TR]= 148.000;     G521
N84 $P_UIFR[ 21,B,TR]= 0.00;        G521

N86 $P_UIFR[ 22,X,TR]= 0.000;       G522
N88 $P_UIFR[ 22,Y,TR]= 202.000;     G522
N90 $P_UIFR[ 22,Z,TR]= 148.000;     G522
N92 $P_UIFR[ 22,B,TR]= 0.00;        G522

N94 $P_UIFR[ 23,X,TR]= 27.000;      G523
N96 $P_UIFR[ 23,Y,TR]= 202.000;     G523
N98 $P_UIFR[ 23,Z,TR]= 225.000;     G523
N100 $P_UIFR[ 23,B,TR]= 0.00;       G523

N102 $P_UIFR[ 24,X,TR]= -27.000;    G524
N104 $P_UIFR[ 24,Y,TR]= 202.000;    G524
N106 $P_UIFR[ 24,Z,TR]= 200.000;    G524
N108 $P_UIFR[ 24,B,TR]= 0.00;       G524

N110 $P_UIFR[ 25,X,TR]= -0.000;     G525
N112 $P_UIFR[ 25,Y,TR]= 202.000;    G525
N114 $P_UIFR[ 25,Z,TR]= 142.000;    G525
N116 $P_UIFR[ 25,B,TR]= 0.00;       G525
N118 END_NPV:
```

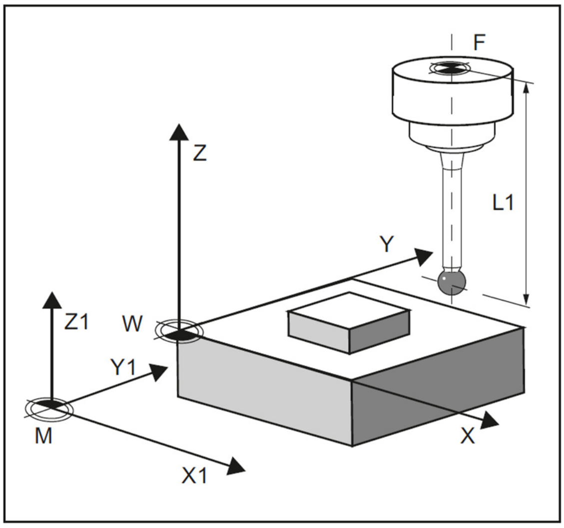


Figure 2-5: Reference points on the machine and workpiece,
Source: SINUMERIK 840D – Programming Manual

The probing in the direction of the Z-axis requires the machining plane of `G17`.The other machining planes are applied as illustrated in Figure 2-6. For example, the turning process needs only `G18` for machining plane.

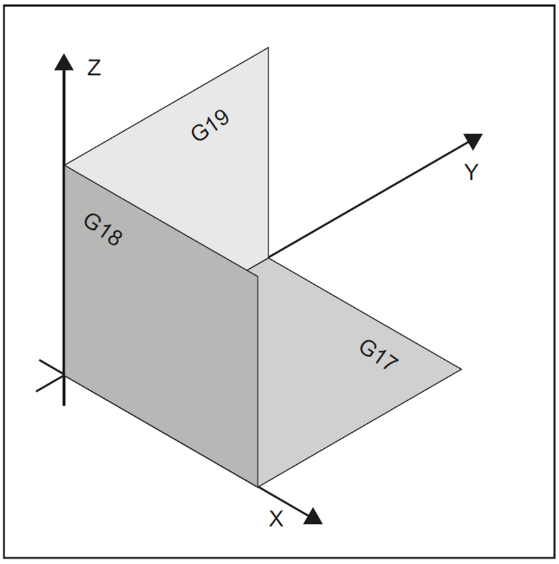


Figure 2-6: Machining planes for milling
Source: SINUMERIK 840D – Programming Manual

The command of `PROBE_ON` starts the radio transmission of the probe. After the direction of the probe is defined, Line N252 shows the necessary coordinate values of the probe, perpendicular to the measuring plane G17. An If-function asks for existing values and skips the cycle when possible.

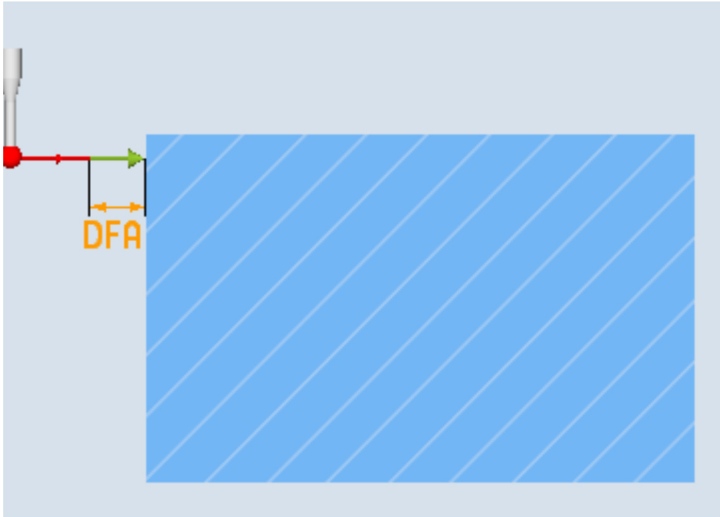


Figure 2-7: Starting Position - CYCLE 978
Source: SINUMERIK 840D – Programming Manual

With a rapid traverse (G0) the probe is positioned. Next, the distance in probing direction is decreased to the starting position (DFA) of the measurement procedure. The path of DFA is the distance from the starting position until the expected switching signal of the probe as shown in Figure 2-7. In the following, the “CYCLE 978 – Edge distance” is applied (Appendix 8). Together, Figure 8-1 and Table 8-1 are showing the needed data for this cycle. The main information’s are the setpoint, measurement path and the safe area values. After the cycle has been finished, the writing command gives out the value of the difference in Z-axis (`OVR[19]`) and the actual value of the measuring axis (`_OVR[04]`) for the first zero point `G54`. The storing of the value is done with the parameter assignment (`N270 R698 = _OVR[19]; N272 R699 = _OVR[04]`). At this moment, the measured values can be used in the NC program for positioning or calculation of the zero points. In the last steps, the write function defines all other zero points in the measured axis direction.[7]

The measurement cycle gives not only the figures for zero points, but also the manufacturing allowance on the castings. With the same cycle, a point number of one to nine is possible for a surface measurement. In the existing “Jumplabel” program the highest value of all measured points of a cycle are determined. Considering the cutting depth of the tool, the amount of necessary planar milling

[7] cf. (Siemens AG, 2011) p.229

steps to reach the final geometry, is calculated. However, the measurement cycle is not adding value to the workpiece but there is no other way to gather all information yet.

2.6 Product Quantity Analysis

In order to analyse the yearly production outcome, the SAP transaction “ZCFARMDET” gives detailed information about production orders. From the period of April 2018 to March 2019, all production orders for the cost centre number 00112556 are sorted to the 14 main component groups. With all standard and special options, more than 4600 parts are ordered in 295 different variants. For instance, the component “Platen MOV” is produced in more than ninety times.

The idea of the PQ method is to group the parts for production depending on their volume. It is used to enable an assessing on the parts. The amount of a product is expressed in “share of the total”. Next, the figures are counted cumulatively and sorted in descending sequence. Once the list has been calculated, classifying borders have to be defined.[8] In order to show the highest amount of orders, the analysis in Table 2-4 shows clearly the high, medium and low runner parts. The classification is chosen with 80 per cent for “A” parts, 15 per cent for “B” parts and all others for “C” parts. Typical examples of high runners are the components “Cylinder Body INJ” together with the “Housing INJ”. They took less than 80 per cent of all orders. Despite, “C” parts are made sporadically but are equally important than all other parts.

Based on the SAP transaction of “ZQFM4 – Failure Reports” the rejected parts are taken into account of the component group. The Cylinder Body INJ parts are responsible for more than two thirds of all rejected parts. A closer investigation on the reject reasons is shown in the following sub chapter.

[8] cf. **Es ist eine ungültige Quelle angegeben.** p.15

Table 2-4: Component Overview and PQ Analysis

Component Main Group	Component Variants	Orders	Share	Cumulated	PQ Analysis	Rejects
Total: 14	**295**	**4612**				**62**
Cylinder Body INJ *(Zylinderplatte)*	61	2447	53,1%	53,1%	A	**43**
Housing INJ *(Trägerplatte)*	39	1120	24,3%	77,3%	A	**5**
Flexlink	4	336	7,3%	84,6%	B	
Platen MOV *(Bew Aufspannplatte)*	93	252	5,5%	90,1%	B	
Link MOV PLN 2 Point *(Zwischenhebel)*	8	120	2,6%	92,7%	B	**7**
Housing BRG INJ *(Lagergehäuse)*	16	98	2,1%	94,8%	B	**2**
Plate HYD EJE MTG *(Auswerferträger)*	15	59	1,3%	96,1%	C	
Flexlink OP+RE *(Gelenk)*	2	51	1,1%	97,2%	C	**3**
Platen STA *(Fest Aufspannplatte)*	19	45	1,0%	98,2%	C	
Ejector Plate *(Auswerferplatte)*	12	26	0,6%	98,7%	C	**1**
Housing Belt *(Gehäuse Riemen)*	4	25	0,5%	99,3%	C	**1**
Heater Plate CLA *(Heizplatte)*	16	25	0,5%	99,8%	C	
Plate Sub EJE *(Abstützplatte)*	4	5	0,1%	99,9%	C	
Block Hopper Slide *(Gleitflansch)*	2	3	0,1%	100,0%	C	

2.7 Production rejects

The variation of casting defects of the raw part leads to less outcome of parts from the manufacturing process. In order to find errors for a better understanding of these problems, an analysis of the number of defects is necessary. A new workpiece is initially checked with a small batch of preproduction casting parts by the company´s quality assurance department. The casting sample is produced with standard manufacturing methods and mass production that is used for test purposes. In an initial sample test according to EN 10204[9], the material EN GJS-400-15 and EN GJS-400-18U is checked on its mechanical requirements. Tensile strength, yield strength and elongation are tested according to EN ISO 6892-1[10].

[9] cf. (EN ISO 10204, 2005)

[10] cf. (EN ISO 6892-1, 2017)

The Brinell hardness test is performed according to EN ISO 6506-1[11]. Furthermore, the dimensions indicated on the drawing must be kept with no dimensional deviations according to ISO 8062[12].
Another test is the graphite structure investigation according to ASTM E494. The ultrasonic-velocity is allowed with a minimum of 5560 meters per second for wall thickness over 200 mm. The measurement has to be taken from parallel surfaces, proven in different dimensions of the casting[13]. Furthermore, the part weight has to be tested and documented together with all other test results in the initial sample test report.
The external cast quality must be finely grinded, shot or sand blasted and primed. All features like risers or lifting aids that are required by the foundry and are no part of the drawing must be removed. The casting surface must be free of cracks, hot tears, gas porosity, adhering sand, scale or inclusions. After verifying the repeatability with the initial sample test report, the founder is allowed to produce in full quantity. In case of unallowed deviations as dimensional deviations, machining allowances, surface defects, hardness deviations or shrinkage cavity, the supplier must be reported immediately. During series production, a sampling inspection is done with a test volume according to ISO 2859[14]. In addition, every casting is visually checked by the set-up worker before clamping.

Nevertheless, defects can occur randomly. During production, only geometric deviations can be detected during the initial probing cycle. As illustrated in Figure 2-8 examples for this are too high or too low material allowances. Too little material causes unfinished holes after production. This means that surface deviations are visible with raw cast skin. If the workpiece is casted with a displaced core, the entire geometry is distorted. Furthermore, shrinkage effects cause geometric defects for instance deviations of wall-thickness, orthogonality and draft angles.

[11] cf. (EN ISO 6506-1, 2015)

[12] cf. (ISO 8062, 2007)

[13] cf. (ASTM E494-15, 2015)

[14] cf. (ISO 2859, 2014)

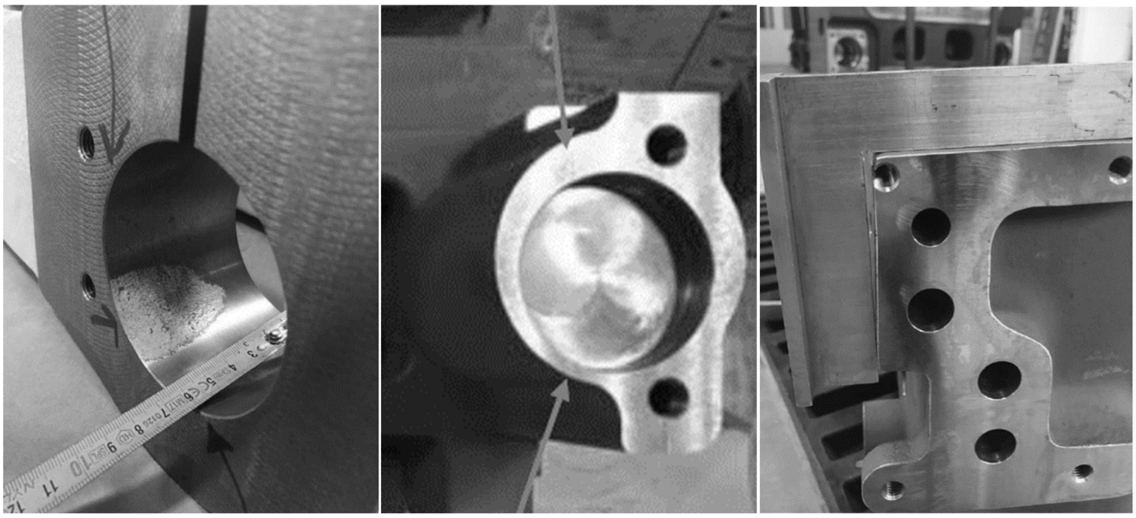


Figure 2-8: Typical casting errors of raw surface, wall thickness and angle deviation (source: ENGEL Austria GmbH)

If the tolerances allow a production within the deviation, the process is stopped briefly. To ensure the designed quality of the manufactured parts, the operator must change the geometric parameters of the NC program if still possible. In more detail, the probing cycle has a confidence area where the processing is possible without any risk. Beyond this boundary, the manufacturing machine stops and reports the geometric deviation to the operator. In consultation with a responsible expert, the value of the confidence area is allowed to change. This process leads to a certain downtime of the machine. A closer look on this downtime analysis can be seen in chapter 4. Otherwise the manufacturing process ends, and the workpiece will be sent to the quality assurance for a closer investigation. In any case, the machine operator has to decide and make a judgment on the following steps.

In the worst scenario, the probing cycle is not even able to detect the deviation and the NC program starts and finally produces an incorrect part. If the allowance is too high without consideration, a tool breakage may occur with a possible damage to the part or the machine. In most of the cases, hidden deviations are seen by the set-up worker after unclamping the processed part from the pallet. Any errors on threaded holes or surfaces can be easily seen after processing. In this case the part gets an inspection of the quality assurance department as already mentioned before. In this investigation the workpiece is measured via portal-coordinate-machine and material defects are identified. A conclusion defines the next steps of the workpiece. If no clearance is feasible, a rework of the manufacturing is instructed. Otherwise, a rejection of the component is ordered. The rejected parts impact the company in two ways. On the one hand, the productivity decreases with less good parts. On the other hand, the manufacturing of parts that are not able to pass the quality criteria, induces additional costs. After the occurring costs are evaluated by the departments of quality assurance and accounting, the costs are passed on to the originator. The SAP transaction "ZQFM4 –failure reports", publishes the amount of errors during the period of April 2018 and March 2019 for the cost centre number 00112556 (FMS Heller H8000) and the number 00114100 of the quality assurance department. Considering the material numbers in use of the FMS, the valid figures can be analysed.

In Table 2-5 and Table 2-6 the figures of the business year 2019 are presented and separated into the error cause and the report decision. If an error occurs, the decision on rejection, rework or release is made depending on its scope. More than half of all rejects are caused by material defects, like shrinkage cavity and porosity. This cannot be prevented without complete ultrasonic testing. Less than a third of all rejected parts is caused by the manufacturing process. Examples are tool breakages or errors in dimensional accuracy of the machine. Apart from this, the costs caused by casting geometry errors can be saved with a preventative measurement. With the external measurement of the raw geometry, the part will be not allowed to enter the machine and start processing. If a component is released for assembly, there are no additional error costs.
Another aspect are the different foundries of the components. The company applies a two-supplier strategy for economic reasons. That means at least two different foundries deliver for one component. In case of delivery difficulties of one supplier, the other one can perform in higher quantity. Apart from this, an easier negotiation of price conditions is possible with more suppliers. However, different casting strategies of the suppliers generate slight deviations of the components. In order to produce the same quality with the manufacturing process, handling the different raw geometries is a main target of the machine operators. In the Table 2-7 the rejections due material defects and casting geometry of each supplier can be seen of the business year 2019. The rejections are opposed to the batch size of the affected material.

Table 2-5: Amount of Errors during Production

Error caused by	Decision						Total
	Rejection		**Rework**		**Release**		
	Amount	Share	Amount	Share	Amount	Share	
Material defect	36	58 %	17	40 %	8	47 %	61
Manufacturing process	18	29 %	19	45 %	4	24 %	41
Casting Geometry	8	13 %	6	14 %	5	29 %	19
Total errors	**62**	**100 %**	**42**	**100 %**	**17**	**100 %**	**121**

Table 2-6: Error costs during Production

Error caused by	Decision					Total
	Rejection		**Rework**		**Release**	
	Amount	Share	Amount	Share	Amount	
Material defect	€12,364	37 %	€1,534	34 %	0	€13,899
Casting Geometry	€2,381	7 %	€334	7 %	0	€2,715
Manufacturing process	€18,554	56 %	€2,668	59 %	0	€21,221
Total errors	**€33,299**	**100 %**	**€4,536**	**100 %**	**0**	**€37,835**

Table 2-7: Rejected components of the Foundries p.a.

Foundries	Number of Rejections	Batch-size	Share
GF Casting Solutions Leipzig GmbH	17	45	38 %
Eisengießerei Hans Dhonau e.K.	1	3	33 %
Johann Nemetz & Co. GmbH	3	15	20 %
F3TEC Fonderies	1	5	20 %
Jebens GmbH	3	20	15 %
Wagner Schmelztechnik	4	36	11 %
Kemptner Eisengießerei	2	18	11 %
Samchully Metal. Co. Ltd	7	91	8 %
Ergocast Guss GmbH	5	82	6 %
Schmiedeberger Gießerei GmbH	1	20	5 %
total	**44**	**335**	

In conclusion, it can be said that the errors caused by casting geometry are only a little share of the total error costs. The failures during the manufacturing process are responsible for more than half of the rejection costs. Tool breakages or deviations of the manufactured geometry are typical examples. Only the casting geometry can be avoided before processing with an external measurement system. The high amount of material defects is a result of the foundries and can only be changed with an expansive ultrasonic analysis of each part. Nevertheless, a system that is able to detect deformations before the machining take place could reduce rejections and assure only good parts for manufacturing. The idea of relocating the measurement process out of the manufacturing machine is a logical step in this optimization process.

3. Industrial Metrology

The ongoing development of measurement technology enables a change of the production processes. With the enhanced accuracy of optical methods, some work of the tactile coordinate measuring machines can be shared and allocated from clean measurement conditions directly to the manufacturing process. Nevertheless, the accuracy of tactile measurement is not easily surpassed and has still legitimacy.

During the last centuries, the measurement of parts was strictly separated from the manufacturing departments. The main task was the production of parts in the needed quantity. The quality of these parts was inspected by a different department. Small tasks like diameter verification with a measurement gage were allowed by the operator. It was possible to check whether the part geometry was manufactured properly and if necessary, react by setting machine parameters. However, the total part check was done after the part had been transported to the foreseen inspection place. Depending on the batch size and restrictions of a product, not every part needs to be checked. The longer ways between the different departments in form of place and communication leads to disadvantages on the whole production process. A logical outcome is the production of a greater number of non-correct products until the measured result shows a failure in the manufacturing. Furthermore, the delivery date of a product could not be kept, if the quality assurance finds an incorrect component long after production. The price and the economic success of a product depends heavily on their production process including measurement and verification. With the development of quality management methods like continuous improvement processes of ISO 9000 the importance of controlling the results immediately after production was essential. An immediate reaction and communication from quality assurance to the operators decreases the rejected parts in manufacturing processes.

Another impact comes from the optimization of the general part production based on Lean Theories. This means that any activity that generates no value to the customer is wasted. Typically, the price of a product is the decisive criterion of a customer. The theory is based on minimizing the production costs by optimizing its process. Taiichi Ohno developed seven major wastes as chief engineer of the

Toyota Production System in the 1990s. The acronym “TIMWOOD” describes the seven deadly wastes as followed:[15]

- ***Transportation***: Unnecessary product moving between process activities
- ***Inventory***: Store inventory that is not used for production process
- ***Motion***: Excessive motion that requires unnecessary time an energy
- ***Waiting:*** A machine or a worker waits for finishing of a process
- ***Overproduction***: Produce more than the customer demands
- ***Over-processing:*** Do more than the customer requires
- ***Defects***: Rework or rejections caused by defective process

With the reduction of wasted process steps, the outcome are cheaper production costs and a benefit against market competitors. In order to reach the defined goals, not every step can be exchanged. The ongoing trend of checking parts directly after manufacturing is only possible with a loss of accuracy. Mechanical vibrations, temperature differences, dirt and the shop floor surroundings are limiting the results. The technological improvement of measurement techniques can deal with some of the interferences by electronical compensation but is limited to the application. Nevertheless, the measurement systems are changing over time as Figure 3-1 shows.

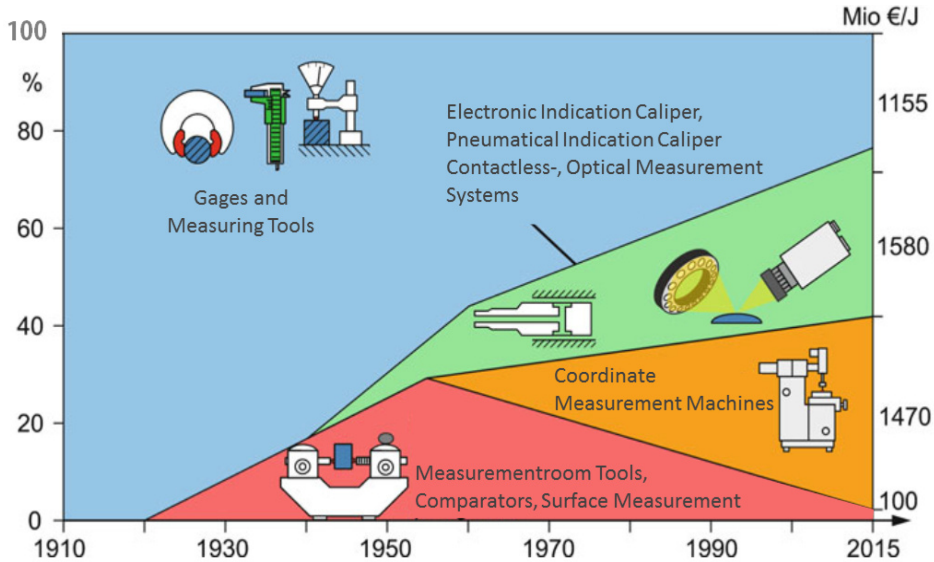


Figure 3-1: Commercial Relevance and Market share of different Measurement Systems
Source: compare Keferstein 2015, p. 5

[15] cf. (Chiarini, 2013) p. 15

The following subchapters give an overview of the common measurement systems and their field of application.

3.1 Tactile Measurement

A universal technique to measure and control the nominal geometry of a part is the application of tactile metrology. A workpiece to be measured is brought into mechanical contact with a probing element. This allows the acquisition of geometric information like basic dimensions and orientations in order to set their tolerances with a measurement probe. The material of a typical probe consists of ruby (monocrystalline aluminium oxide) due to its hardness and wearing resistance. Different sizes allow a broad range of applications like extension stylus for deep boring holes or undercuts. The measurement result is based on measurement points on the surface of a specimen. The point data is used for the position of the coordinate point and can be compared with the original geometry of the part. Influencing factors are the surface roughness of the workpiece, approach speed and probing direction. The elastic deformation (*3-1)* of the probe element and the workpiece in the contact point is linked to the applied force during measuring as shown in Figure 3-2.

F_p $\ldots Probing\ force$

w_o $\ldots Elastic\ deformation\ of\ tip\ ball\ and\ workpiece$

w_1 $\ldots Elastic\ deformation\ of\ stylus\ stem$

σ $\ldots Hertzian\ contac\ stress$

d_{eff} $\ldots Effective\ tip\ ball\ diameter$

E $\ldots Youngs\ modulus\ of\ the\ stylus$

l $\ldots Length\ of\ the\ stylus$

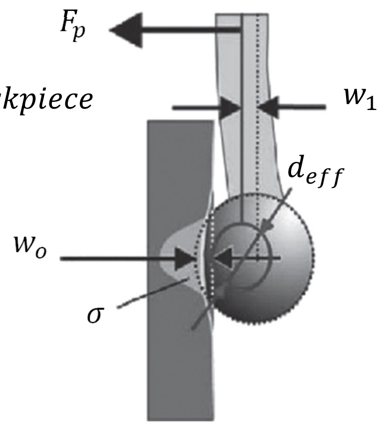


Figure 3-2: Elastic deformation at the contact point
Source: Hoken 2012, p.111

To ensure the best results, a spherical artefact with precisely known dimensions and mechanical properties is used. Another application of tactile measurement is the measurement of workpiece surface roughness. This sensible method records the vertical movement of a probe during scanning a surface. With the gained data the roughness can be determined.

The widely accepted coordinate measuring machines uses the explained tactile method for measuring the workpiece dimensions with highest accuracy. A closer look on these machines is given in the following chapter.

3.1.1 Coordinate Measuring Machines

Measuring the actual shape of a workpiece and comparing it with the desired shape explains the primary function of the machine type. Size, form, location and orientation as metrological information of a workpiece can be obtained by pointwise contact of the touch probe.

Reacting on market necessities, Sheffield brought the first operational measuring machines for industrial use in the 1960s. With development of the three-dimensional coordinate system by Mitutoyo in 1968 in Japan, the Coordinate Measuring Machine (CMM) proved to be more effective than the traditional measuring techniques. The ongoing evolvement with the use of controlling software and touch trigger probes made these machines essential for workpiece measurement. Cal Zeiss launched computer-aided accuracy on his machines in the 1980´s with a significant business opportunity. The improvement in measurement speed and accuracy grows in the following years and made the CMM to a versatile instrument for production control. [16]

Figure 3-3 shows the essential system components of a CMM. The geometrical product specifications of a coordinate measuring machine are defined by DIN EN ISO 10360-1.[17] The machine structure consists of a mechanical frame that moves the probe head on three axes around a workpiece. The frame and the machine bed are configured with high mechanical stiffness to ensure less deformation and dimensional stability during movement by a linear motor drive. A basic element for the machine bed is the naturally occurring material granite.

[16] cf. (Hocken, 2012) p. 21 to 30

[17] cf. (EN ISO 10360-1, 2003)

The structural loop is also affected by the bearing system. Dynamic stiffness, damping and frictional effects must be considered. For this reason, aerostatic air bearings or precision roller ball bearings are in use. Furthermore, a climate room ensures a low coefficient of thermal expansion. Displacement transducers are determining every linear axis of the machine. They give the actual position of the touch probe on the workpiece. Including optical scales, rotary encoders, magnetic scales and laser interferometers, a variety of displacement transducers is applied in a CMM. A controller is used together with an operation software on a computer to measure with the machine. The accuracy of less than 10 µm depends on the collaboration of all elements and is verified according several parts of EN ISO 10360.

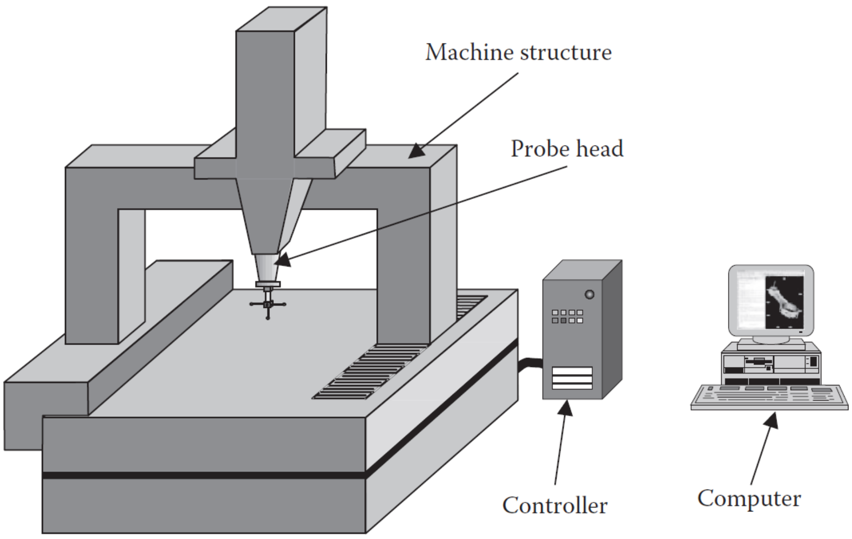


Figure 3-3: System components of a CMM
Source: Hocken, 2012, p. 60

The position of the probe on the workpiece surface is evaluated by vectored calculation of values from the length measuring axes (Figure 3-4). Therefore, a set of transformations are needed to calculate the real position ($\boldsymbol{p}$) in the contact point between probe and surface into the coordinate system of a CMM. The vector to the probing point in the machine coordinate system $\boldsymbol{r_m}$ (3-1) is defined by addition of the probing system reference point vector $\boldsymbol{r_r}$, the transformation of the tip ball position in the coordinate system of the probing system $\boldsymbol{r_p}$ and the corresponding probing vector $\boldsymbol{b}$ from the tip ball centre to the contact point. The transformation from the coordinate system of the probing system to the machine system can be described by a probing matrix $\boldsymbol{P}$ and a position vector of a point $\boldsymbol{p}$ (3-2). The reference point of the probing system can be described with a position vector and a position measuring matrix $\boldsymbol{M}$ in the coordinate system of the CMM (3-3). By inversion of the precisely known probing matrix and the position measuring matrix, the real coordinates of the probing points can be derived exactly (3-4 to 3-5).

$$\boldsymbol{r_m} = \boldsymbol{r_r} + \boldsymbol{r_p} + \boldsymbol{b} \qquad \textit{Equa. (3-6)}$$

$$\boldsymbol{r_p} + \boldsymbol{b} = \boldsymbol{p} \cdot \boldsymbol{P} \qquad \textit{Equa. (3-7)}$$

$$\boldsymbol{r_r} = \boldsymbol{p_r}(\boldsymbol{p}) \cdot \boldsymbol{M} \qquad \textit{Equa. (3-8)}$$

$$\boldsymbol{p_r}(\boldsymbol{p}) = \boldsymbol{p} - \boldsymbol{b} - \boldsymbol{r_p} = \boldsymbol{p} - \boldsymbol{p} \cdot \boldsymbol{P} \qquad \textit{Equa. (3-9)}$$

$$\boldsymbol{r_m} = \boldsymbol{M} \cdot (\boldsymbol{p} - \boldsymbol{p} \cdot \boldsymbol{P}) + \boldsymbol{p} \cdot \boldsymbol{P} \qquad \textit{Equa. (3-10)}$$

$$\boldsymbol{p} = \boldsymbol{r_m} \cdot (\boldsymbol{M} - \boldsymbol{P} \cdot \boldsymbol{M} + \boldsymbol{P})^{-1} \qquad \textit{Equa. (3-11)}$$

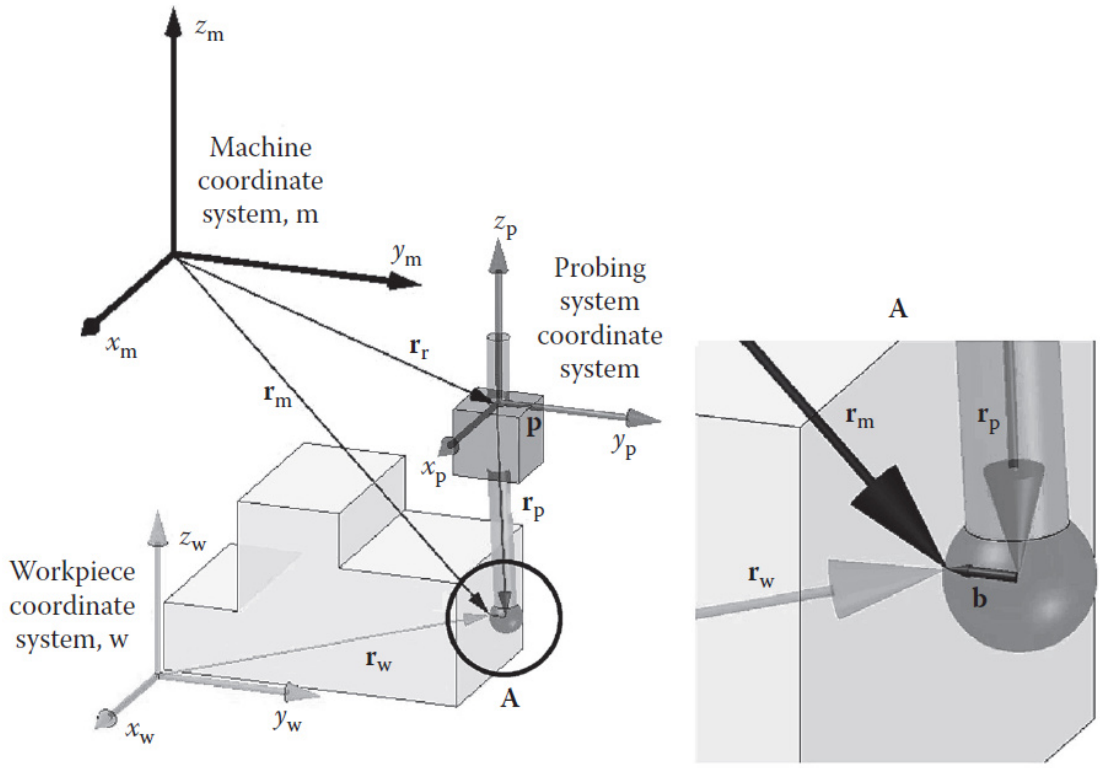


Figure 3-4: Vector diagram for measuring a surface point on a workpiece
Source: Hocken 2012, p. 95

In conclusion, the coordinate measuring machine is a metrological instrument with highest accuracy of controlling the workpiece dimensions. It is widely used in production industries for metal workpieces. Apart from that, the measuring can only take place in a clean environment with standardized temperatures. To measure the workpiece during the manufacturing process, touch probes for in machine usage were developed.

3.1.2 In Machine Probing

The efficient use of CNC machines requires a measuring instrument that can be implemented in the manufacturing room of a milling machine. The harsh environmental conditions of cooling lubricant and metal chips are tough requirements for a measurement system. Over the years, the development of the touch-trigger probe achieved these goals. It could be implemented into the spindle like additional cutting tools. The touch probe consists of a housing with a machine mounting system and an attached stylus with a tip ball on its end. A radio transmission interface is needed to send the trigger signal of the probe to the CNC control system (Figure 3-5).

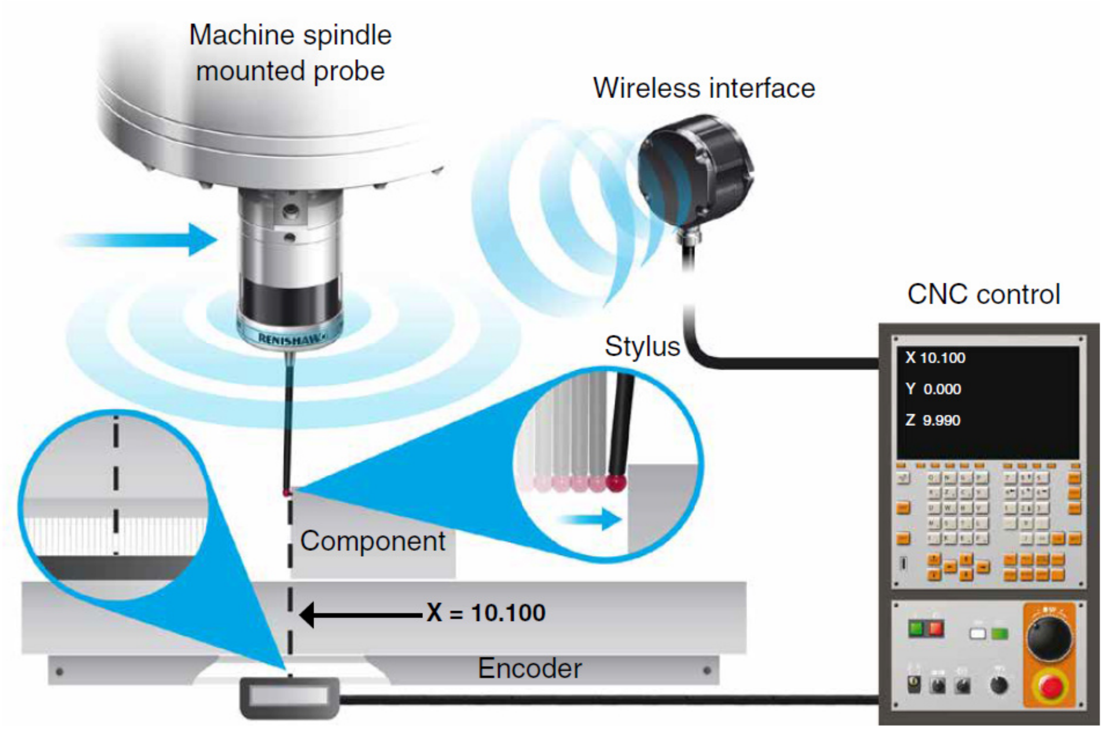


Figure 3-5: Components of a Machine mounted Radio-Transmission Touch Probe
Source: Renishaw – Technical Specifications, p.10

Together with the encoder on the moving axes of the machine, a coordinate point can be derived. For this reason, the tip ball of the probe is shifted via spindle to the assumed contact point on the workpiece surface. If the probe touches the surface, the contact force leads to a mechanical deflection of the stylus mounting. Two different types can be applied to trigger the signal for saving the exact coordinates of the contact point. The widely used kinematic resistive probe design (Figure 3-6) needs a spring-loaded stylus mount with rod and ball patches in three axes that are flown through by current. In the momentum of contact, the deflection of the mechanism leads to a change in the electrical resistance of the patches by separating the electrical contacts. The reduction of the current flow triggers a probe output when a defined threshold is reached. The measurement system reseats after triggering within 1 µm of positioning accuracy.

The other possibility is a strain gauge probe design. Separated from the kinematic mechanism the strain gauges are arranged to sense the summed stylus force during probing.[18] This enables to set the threshold much lower than the conventional probe. It is used for complex and sensitive 3D shapes or components with very high accuracy.

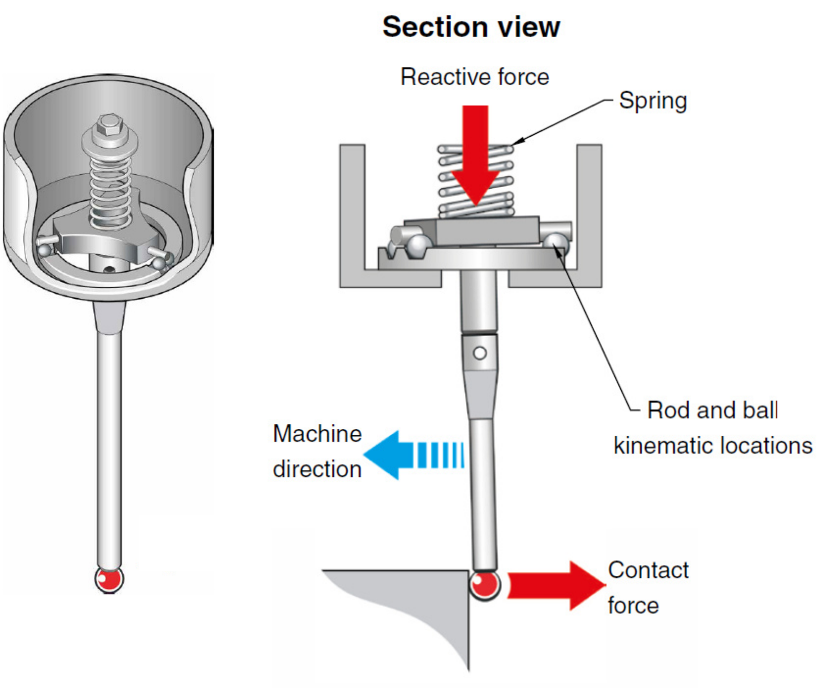


Figure 3-6: Kinematic Resistive Probe Design
Source: Renishaw – Technical Specifications, p. 22

[18] cf. (Renishaw, 2014)

The touch probe enables a preventative control by measuring the machine condition during calibration settings. Component orientation and design identification are the main tasks of this measurement system. In-process control allows an additional information of part distortion, tool deflection or thermal effects. Updating the parameters and offsets of the NC program ensures the required accuracy. A post-process measurement could also give information on the material situation or condition monitoring of the manufacturing process. The touch trigger probe is nowadays an indispensable tool in the mechanical manufacturing machines.

3.2 Optical Measurement

Despite a wide application of tactile measurement instruments, the development and improvement of optical measurement systems increases over the years as shown in Figure 3-1. The optical method overcomes the slow point after point detection of the tactile measurement by applying light as measurement medium. This enables a fast and non-tactile scanning of surfaces and dimensions of a workpiece. Measurement uncertainty and area are depending on the measurement method (Figure 3-7) that allows different fields of applications.

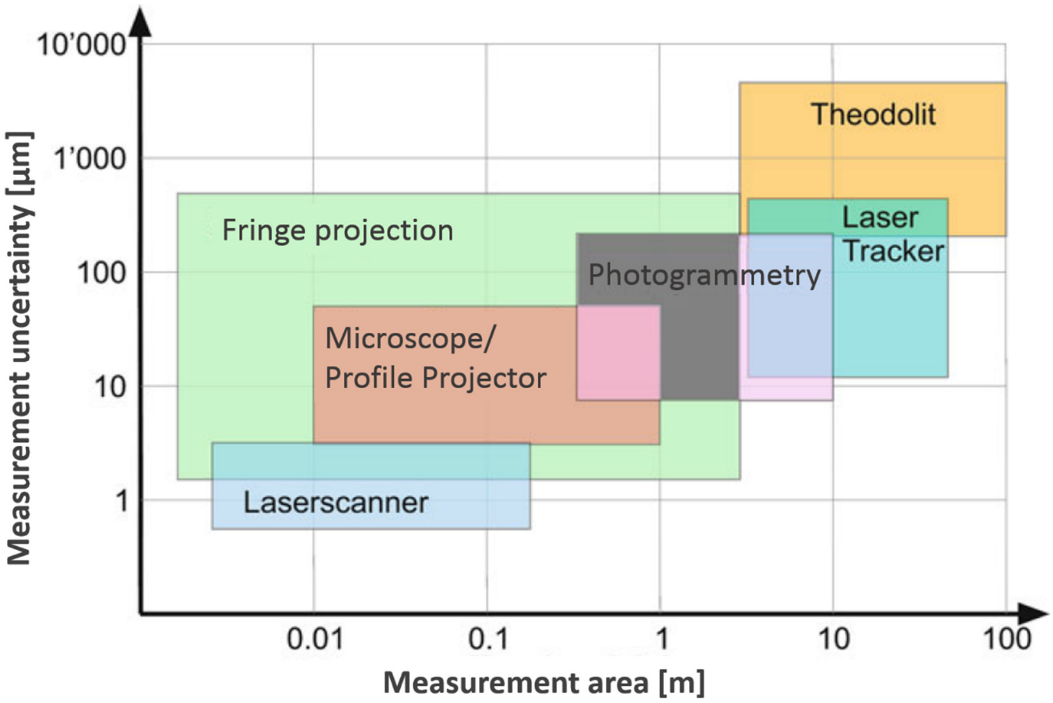


Figure 3-7: Comparison of optical systems in measurement area and uncertainty
Source: compare Keferstein 2015, p.199

In the following methods the common types and their typical usage are described in more detail.

3.2.1 Photogrammetry

The purpose of the oldest optical method is deriving the three-dimensional shape and location of an object. It is based on measurement of multiple photographs taken in different orientations by central projection imaging. The passive method sends no specialized light up to the surface and only a sophisticated camera is needed.
Since the 19th century images are used to measure buildings. The digitalisation improves this technique to a powerful tool. At least two images are necessary to achieve a stereo photogrammetry object point.[19] With increasing number of images, a higher accuracy can be received. Typical applications are measuring landscapes and cities done by an airplane. In addition, close-range photogrammetry is used for objects like ships or industrial applications. The object is imaged from additional angles. Prepared spots on defined positions mark the measurement point on each image.

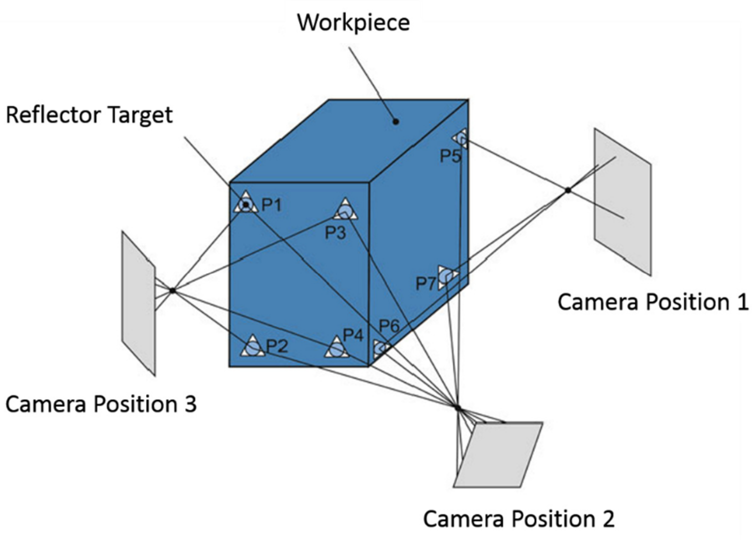


Figure 3-8: Measurement Principle - Photogrammetry
Source: Keferstein 2014, page 240

A software overlayers the images and uses a calculation technique of bundle triangulation. Targets on the workpiece surface are used to set up a three -

[19]cf. (Atkinson, 1996) p.13

dimensional image of the object and their coordinates can be computed. The mathematical model for calculating the coordinates from a two-dimensional image into a three-dimensional object are referred as collinearity equations.

Therefore, the vector of point P (3-12) can be described in the primary cartesian coordinate system (Figure 3-9) with the basic vector $\boldsymbol{X_o}$ and the rotation matrix $\boldsymbol{R}$ (3-13) for an image parallel to the object. A reverse transformation of equation (3-14) and substitution in (3-15) gives the collinearity equations (3-16) and (3-17).[20] Now all points can be described by solving the equation system.

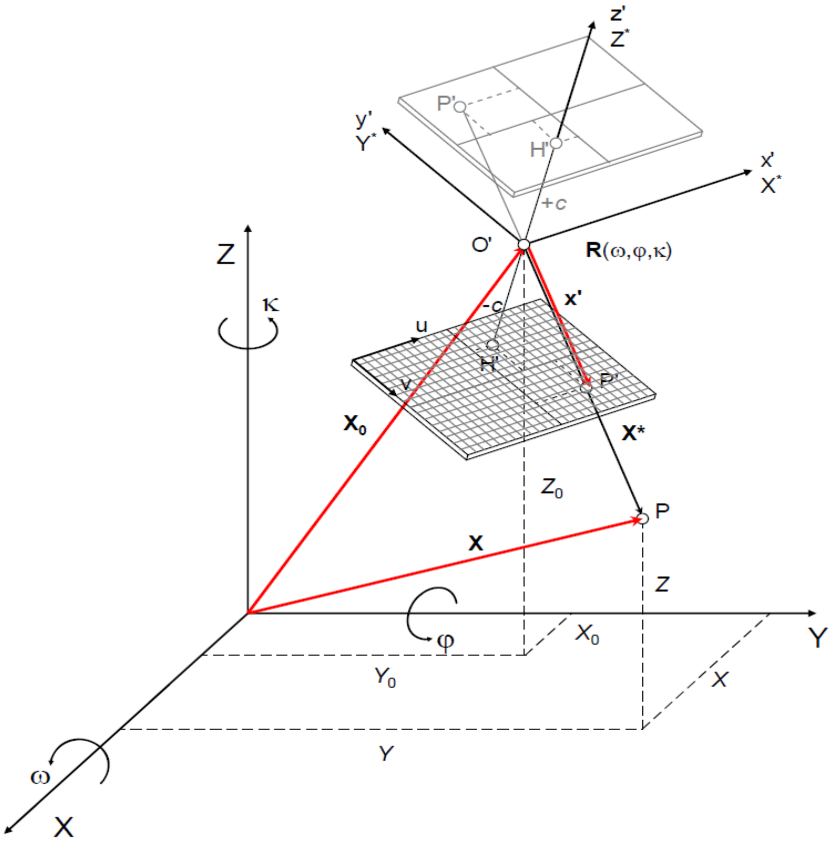


Figure 3-9: Position and orientation of an object with respect to camera
Source: Luhmann 2014, p. 275

$$\boldsymbol{X} = \boldsymbol{X_o} + m \cdot \boldsymbol{R} \cdot \boldsymbol{x'} \quad \text{Equa. (3-18)}$$

$$\boldsymbol{x'} = \frac{\boldsymbol{1}}{m} \cdot \boldsymbol{R^{-1}} \cdot (\boldsymbol{X} - \boldsymbol{X_o}) \quad \text{Equa. (3-19)}$$

[20]cf. (Luhmann, Robson, Kyle, & Boehm, 2014) p. 275

$$\boldsymbol{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{matrix} \cos(\kappa) & -sin(\kappa) & 0 \\ sin(\kappa) & cos(\kappa) & 0 \\ 0 & 0 & 1 \end{matrix} \qquad \text{Equa. (3-20)}$$

$$x' = x'_O + z' \cdot \frac{r_{11}\cdot(X-X_O)+r_{21}\cdot(Y-Y_O)+r_{31}\cdot(Z-Z_O)}{r_{13}\cdot(X-X_O)+r_{23}\cdot(Y-Y_O)+r_{33}\cdot(Z-Z_O)} + \Delta x' \qquad \text{Equa. (3-21)}$$

$$y' = y'_O + z' \cdot \frac{r_{12}\cdot(X-X_O)+r_{22}\cdot(Y-Y_O)+r_{32}\cdot(Z-Z_O)}{r_{13}\cdot(X-X_O)+r_{23}\cdot(Y-Y_O)+r_{33}\cdot(Z-Z_O)} + \Delta y' \qquad \text{Equa. (3-22)}$$

Single-lens reflex (SLR) cameras are in use to ensure high quality of the images. Furthermore, the portable system can be used for object dimensions of several meters but with less accuracy. In comparison with other systems, the low camera weight leads to a high flexibility with the advantage of less investment costs. The manually preparation with targets or markers is necessary for detecting the measurement points. This leads to a disadvantage of an automated system.[21] Nevertheless, the photogrammetry principle is used in other optical measurement systems for example the so called “Fringe Projection Method”.

3.2.2 Fringe-Projection

In order to measure complex shaped parts a total surface detection is necessary. The development of digital projectors and charge-coupled device (CCD) sensor cameras received another optical measurement tool to the market.

The active method of structured light technique requires a light source for measurement. Fringe projection is the most common form of structured light techniques. The principle comprises a device that has a projector and a sensor camera implemented (Figure 3-10). Both angles and positions to each other are well known. By a defined distance of the tool to the measurement object, the projector illuminates a predefined fringe pattern on the surface. Spacings and orientation of the pattern changes during the projection. The shape of the part leads to a distortion of the pattern that can be imaged by the camera. Several images are taken before a controlling software calculates a three-dimensional point cloud of the workpiece by using photogrammetry equations. The static

[21] cf. (Schuth & Buerakov, 2017) p. 75

method needs many repositioning´s around the part to create a full 3D model. An additional second camera can help to track the pattern in difficult contrast conditions.[22] By the limited light source of the projector surfaces with high reflection grades are hardly able to scan. In this case a preparation with a matt finish is inevitable. With different lenses on camera and projector are object dimensions from the size of a teeth up to car bodies possible. Despite a proportional behaviour of the accuracy to the measurement size, it is far lower than traditional photogrammetry. Another aspect is the fast interpretation after computed meshing of the point cloud in a three-dimensional model and compare the real with the designed shape. For industrial applications a mounting on a robotic arm is typical. The configuration of the measurement movement can be well adjusted on the workpiece. The restrictions of difficult light conditions can be covered with substitution of the stripe pattern against a structured light pattern. Apart from that, Scan boxes are often used to protect the measurement against changing environmental light conditions.

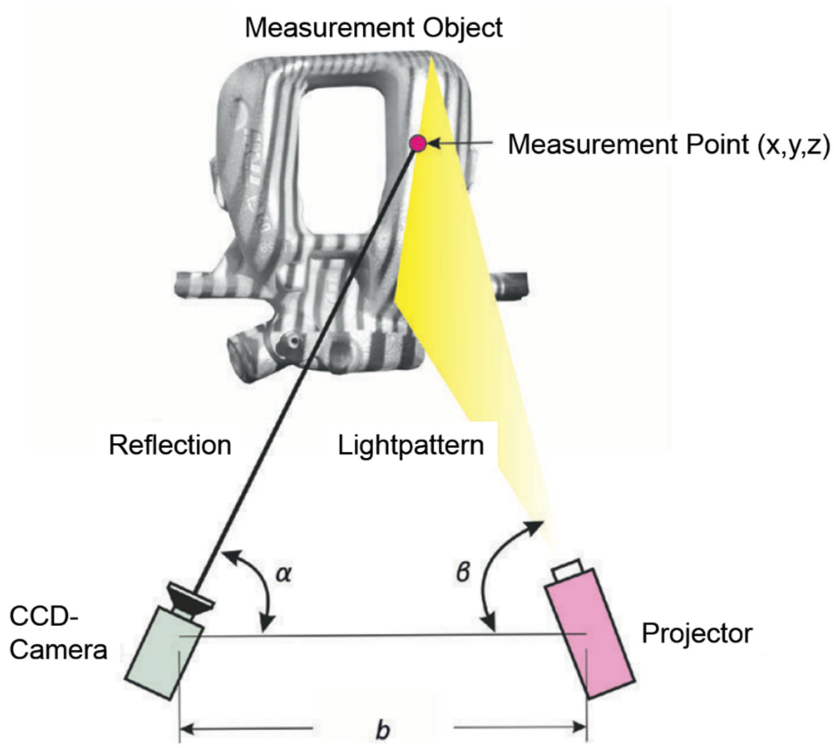


Figure 3-10: Fringe Projection Method
Source: Schuth & Buerakov 2017, p.45

[22] cf. (Schuth & Buerakov, 2017) p. 44

3.2.3 Light Sheet Method

This method works again with the triangulation principle but substitutes the light sensitive projector with a laser line. The laser beam is sent through an expansion optic at the surface of the measurement object. A sensor in the camera receives the distorted laser light through optics after reflection (Figure 3-11). The distance *a* (3-23) is calculated by knowing the angles *α* (3-24) and *β* (3-25) together with the fixed distance *b*.[23]

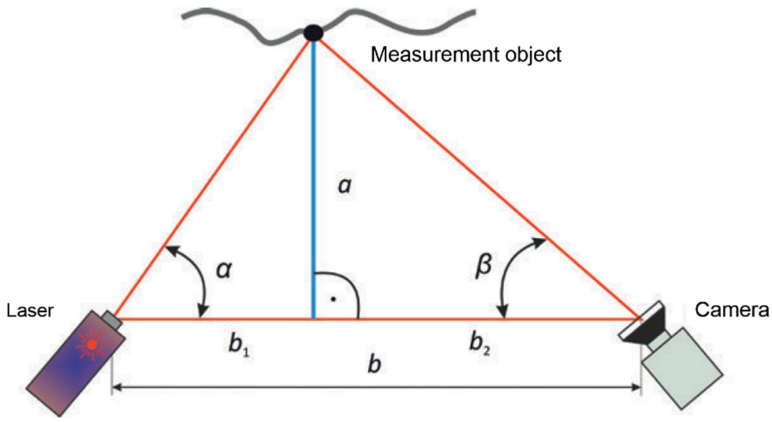


Figure 3-11: Method of Light Sheet Technique
Source: Schuth & Buerakov 2017, p.11

$$\tan\alpha = \frac{a}{b_1}$$ Equa. (3-26)

$$\tan\beta = \frac{a}{b_2}$$ Equa. (3-27)

$$a = b \cdot \frac{\tan\alpha \cdot \tan\beta}{\tan\alpha + \tan\beta}$$ Equa. (3-28)

By moving the instrument around the object, many images are received with the camera and simultaneously calculated in a measurement software. The connection between the different points are made by feature-based methods. It takes geometrical characteristics in distance and position of already scanned points to build up the point cloud. Orientation references can be set by markers on or around the object. Another possibility is the application of a tracking system that automatically follows the orientation of the measurement head via laser optic interferometer.

[23] cf. (Schuth & Buerakov, 2017) p. 11

The advantage of the method is a handheld and light device that can be moved by human or robotic arms. Furthermore, the accuracy is limited by the size of the camera sensor but a measuring uncertainty of less than 0,05 mm can be fulfilled. The system also allows a dynamic measurement after reference marks are fitted to the object. Reflections on the surface are not disturbing the measurement result. Compared with the previous methods the light sheet technique allows the fastest scanning of a workpiece. This is caused by the dynamic movement during the measurement process together with the luminous intensity of the laser light.

3.3 Evaluation of Measurement Data

The output in all explained methods before consists of the measurement data points. Each device is producing a point cloud that is stored in the data format of “Initial Graphics Exchange Specification” (IGES/.igs). Other formats like “Drawing Interchange Format” (DXF) or “Virtual Reality Modelling Language” (VRML) are less common. The received points must be converted into a polygon structure and a CAD readable format like stereolithography file format (STL). For high accuracy the popular algorithm “Iterative Closest Point” (ICP) is applied to transfer the points of different scans together. [24] The requirements for an automated point set up must met an adequate overlapping of the individual scans with unique characteristics and a sufficient point density. This generates the three-dimensional point cloud for design investigations.

In order to set up a 3D model a meshing process is necessary. The spatial “Delaunay – Triangulation” is used to create a polygon mesh similar to the finite element method. One polygon is defined with three corner points and has to fulfil the constraints of circumference condition. It states that no other point can stay in a circle or sphere that is already defined with three points (Figure 3-12).[25] The

[24] cf. (Schuth & Buerakov, 2017) p. 12

[25] cf. (Daniel, 2015) p. 96

amount of points is proportional to the number of triangles and defines the accuracy of the mesh model.

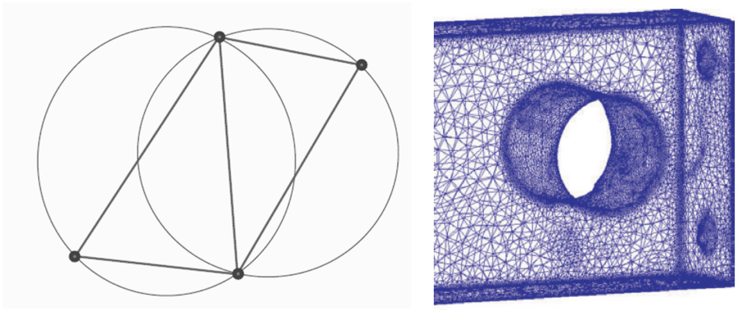


Figure 3-12: Principle of Delaunay Triangulation
Source: Daniel S.H. 2015, p.96
Schuth & Buerakov 2017, p. 13

After the intensive calculation is completed by the software, a meshed 3D model is derived out of the point cloud. That is now used to compare the real and the designed surfaces analytical by superposition inspection. A measurement report and a 3D model are the output of the analysis (Figure 3-12).

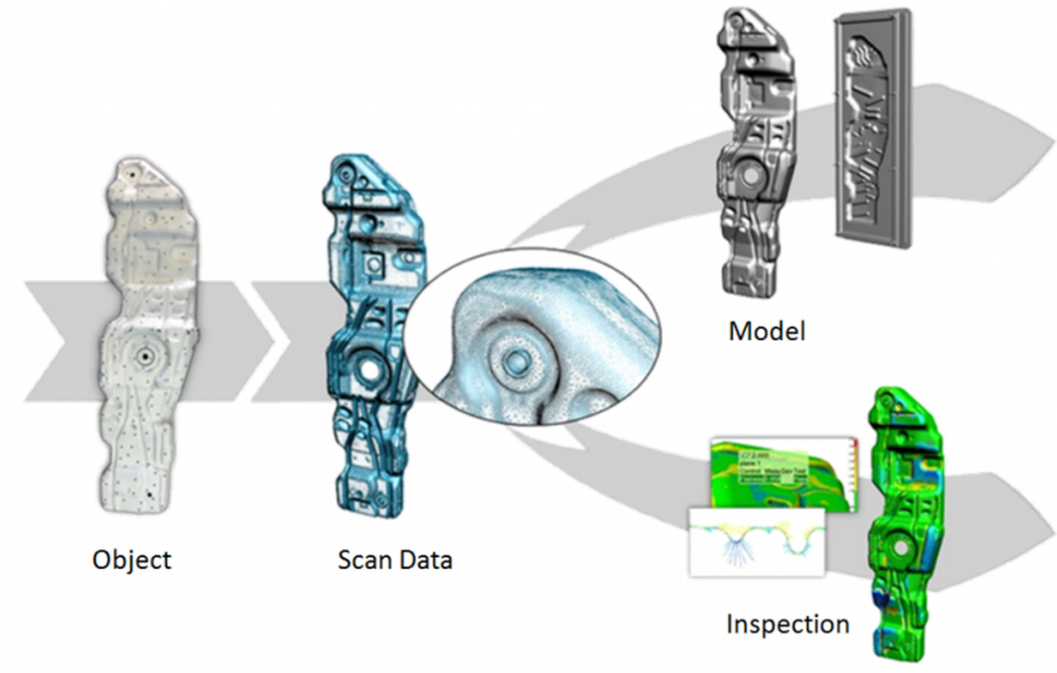


Figure 3-13: 3D Scan Evaluation Process
Online Source: compare 3dscanningservices.net, date of access 22.10.2019

3.4 Market overview

Based on the different advantages of each metrology system a benefit analysis helps to figure out the most appropriate device. A pairwise comparison lists the criteria on their relevance and impact to the requirements. The criteria are needed to evaluate the different measurement devices by their degree of fulfilment.

3.4.1 Definition of evaluation criteria

With the list of criteria all relevant requirements are covered. The measurement of casted workpieces needs an independency of environmental light conditions or surface reflexions after machined processes. For an automation application the suitability for industrial usage is necessary. Reliability and durability must be granted. Furthermore, a robot mounting which is needed for reaching all positions of the measurement object must be possible. In addition, a dynamic measurement of the system will be favoured. Static variants are more time consuming and could lead to a bottleneck in the whole measurement process. The next criteria are dealing with the integration effort for implementing the system. The expenses of the system are also taken into account. For the result of the measurement the accuracy and the amount of measurement points of the system is crucial. The measurement distance and the field of view during the process are also relevant characteristics. In order to move the measuring device, its weight is relevant for the automation system. Lastly, due to company alignments of default software programs, the use of independent evaluation software usage must be possible.

In an criteria weighting matrix (Table 3-1) all criteria are compared against each other. The evaluation is done by assigning three possible numbers from “less important” (0) to “equal important” (1) and “more important” (2) than the compared criterion. The share of each criterion on the total value represents the weightage and the priority can be easily seen.

Table 3-1: Criteria Weighting Matrix

	Criteria
A	Independency of reflexions & environmental light conditions
B	Suitable for industrial use
C	Ability for robotic mounting
D	Dynamic movement measuring
E	Integration effort
F	Expenses
G	Accuracy
H	Amount of Measurement points
I	Measurement distance
J	Field of View
K	Weight of measurement device
L	Independent software use

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**Sum**	**Share %**
A	-	1	2	2	2	1	1	2	2	2	2	2	19	**14.4**
B	1	-	2	0	1	0	0	1	0	0	2	0	7	**5.3**
C	0	0	-	1	2	0	0	1	1	1	0	0	6	**4.5**
D	0	2	1	-	1	0	1	1	1	1	2	2	12	**9.1**
E	0	1	0	1	-	1	0	0	1	2	0	1	7	**5.3**
F	1	2	2	2	1	-	0	2	2	2	2	0	16	**12.1**
G	1	2	2	1	2	2	-	2	2	2	1	0	17	**12.9**
H	0	1	1	1	2	0	0	-	2	1	0	2	10	**7.6**
I	0	2	1	1	1	0	0	0	-	2	0	2	9	**6.8**
J	0	2	1	1	0	0	0	1	0	-	0	2	7	**5.3**
K	0	0	2	0	2	0	1	2	2	2	-	0	11	**8.3**
L	0	2	2	0	1	2	2	0	0	0	2	-	11	**8.3**
0 = less important, 1 = equal important, 2 = more important													**132**	**100**

3.4.2 Benefit Analysis

After the criteria weighting is completed, different measurement devices can be evaluated. The different products are voted by their degree of fulfilment of each criterion. Next, the degree of fulfilment is graded in a range from zero (not fulfilled) up to the six (totally fulfilled). A result per product is calculated by adding up the share of each criteria times the particular weighting. The overall outcome represents the evaluation of a product with regard to the defined criteria. Table 3-2 shows the comparison of the selected products: FARO - Dynamic Machine Vision Sensor (DMVS)[26], CREAFORM - Metra SCAN 3D-R[27] and a ZEISS –

[26]cf. (FARO, 2019)

[27] cf. (CREAFORM, 2019)

Comet 8[28]. An evaluation of other relevant measurement system can be seen in the appendix (8.2). For a better understanding the grading is declared in the following steps.

Table 3-2: Benefit analysis of optical measurement devices

		Product 1 FARO DMVS		**Product 2** CREAFORM Metra SCAN 3D-R		**Product 3** ZEISS Comet 8	
Criteria	Weighting %	Fulfil-ment	Utility Value	Fulfil-ment	Utility Value	Fulfil-ment	Utility Value
A	14.39	6	0.86	6	0.86	3	0.43
B	5.30	6	0.32	5	0.27	3	0.16
C	4.55	6	0.27	6	0.27	6	0.27
D	9.09	6	0.55	6	0.55	0	0.00
E	5.30	5	0.27	3	0.16	5	0.27
F	12.12	6	0.73	4	0.48	4	0.48
G	12.88	2	0.26	4	0.52	4	0.52
H	7.58	2	0.15	2	0.15	5	0.38
I	6.82	4	0.27	3	0.20	6	0.41
J	5.30	4	0.21	3	0.16	5	0.27
K	8.33	5	0.42	4	0.33	3	0.25
L	8.33	5	0.42	5	0.42	2	0.17
Total	100	**57**	**4.72**	**51**	**4.37**	**46**	**3.60**

Criterion A - Independency of reflexions & environmental light conditions: Beginning with the criterion A for independency of reflexions and light conditions, product one and two are both using a light sheet method. It works unaffected from those conditions, whereas product three is based on a fringe projection system, that is more vulnerable.

Criterion B - Suitable for industrial use: The criterion takes a protection against dirt and liquids for granted. Product one is certified with IP67 and gets the highest grade. Product two is certified with IP50 and gets the second-best grade but product three gives no information of protection.

Criterion C – Ability of robotic mounting: Every product totally fulfils the requirement of robot mounting and gets the best grade

Criterion D – Dynamic movement measuring: For the criterion of dynamic movement during measurement, the Light Sheet methods are very appropriate

[28] cf. (ZEISS, 2019)

and both get the best grade. Product three measures with a static system and is not able to fulfil this criterion.

Criterion E – Integration effort: Product one gets not the best grade for the necessity of reference marks around the measurement object. Surface preparations and reflector marks on the object for product two leads to a higher effort and is graded with a three. The third product needs a tracking system for measurement. Therefore, a bigger space is needed that results in grade five.

Criterion F – Expenses: According to price enquiries at the vendors gets product one the best grade for a price of 25,000 €. The prices for product two and three are 80,000 € and 95,000 €, respectively, and are valued at four.

Criterion G – Accuracy: The technical data sheets provide the information that product one has a volumetric accuracy of 0.2 mm, which is rated lower than the others. The volumetric accuracy of product two belongs to 0.1 mm and 0.078 mm for product three.

Criterion H – Amount of measurement points: With 0.48 million points per second get the first and the second product the lowest grade. Product three is able to produce 8 million points per second by its sensor and get a grade of five.

Criterion I – Measurement distance: Product one keeps a measurement distance of 500 mm, product two has less with 300 mm. Product three is able to measure with a distance up to 760 mm and gets the highest grade.

Criterion J – Field of view: With a field of view of 380 mm x 383 mm (0.14 m²) product one stays between product two (0,068 m²) and product three (0.24 m²).

Criterion K – Weight of measurement head: For a robotic application a low weight is preferable. Product one with a weight of 2.3 kg therefore gets the highest grade. Product two with 4.5 kg and product three with 5.2 kg are get lower grades.

Criterion L – Independent software use: Not every measurement producer allows a universal software implementation. Product one and two are open for other software programs. Product three runs on its own software Visio 7. The implementation of other tools is not intended.

The benefit analysis clearly shows the strengths and the weaknesses of each product. The highest score is achieved by product one, caused by independency of light distortions, easier to integrate, the ability of dynamic measuring and a low price compared the other systems.

This chapter hints out that the measurement processes are changing over time in the manufacturing industry. Nowadays, from the tactile instruments and coordinate machines up to the optical three-dimensional scanners a broad variety of applications is possible. The accuracy of the tactile machines cannot be totally exchanged by the new technology. Nevertheless, some of the measurement tasks can be now accomplished faster and with less effort of resources than before.

4. Analysis of unproductive times

In this chapter different analytical research methods are applied to analyse the existing process. During the manufacturing cycle, the unproductive time is mainly caused by the measuring process inside the machine, which interrupts the machining cycle. The amount of this time is relevant to specify a future external measurement system. First, the time for the initial measuring cycle of a workpiece is calculated. It is based on data recordings of the manufacturing machine. After that, the duration of downtime, provoked by incorrect geometric shape is analysed.

4.1 Measurement time analysis

The analytical research of the manufacturing process starts by generating data out of the manufacturing machine recordings from type Heller H8000MC. Apart from conventional machines, an online machine data acquisition system, called Integrated Process Monitoring (IPM) interface (Figure 4-1) is used to track the machine status, during its manufacturing cycles. These data consist of figures like runtime, downtime, production status, NC program number, pallet-number, tool-number, tool status, error messages, statistical evaluation and maintenance intervals. Via the factory ethernet network, each Heller machine can be examined from any place in the company with this interface.

The aim is to evaluate the duration of measuring inside the manufacturing machine. In order to identify the sequences of this process, the tool number indicates the time at which the measurement starts and ends. In more detail, the Renishaw® RMP60 radio transmission probe with the tool number $t_p = 79981$ is responsible for acquisition of the coordinate points. These points are directly integrated in the Sinumerik® controller software and manipulate the starting points or surfaces from the theoretical to the real part with a new zero offset. The number of measuring points is defined by the CAM worker who also prepares the NC program. For economic reasons, the amount of points is reduced to a minimum, considering the fulfilment of the measurement output. Because of the production and manufacturing tolerances of the casted part, which is clamped on the machine pallet, the true geometry is necessary for the milling process.

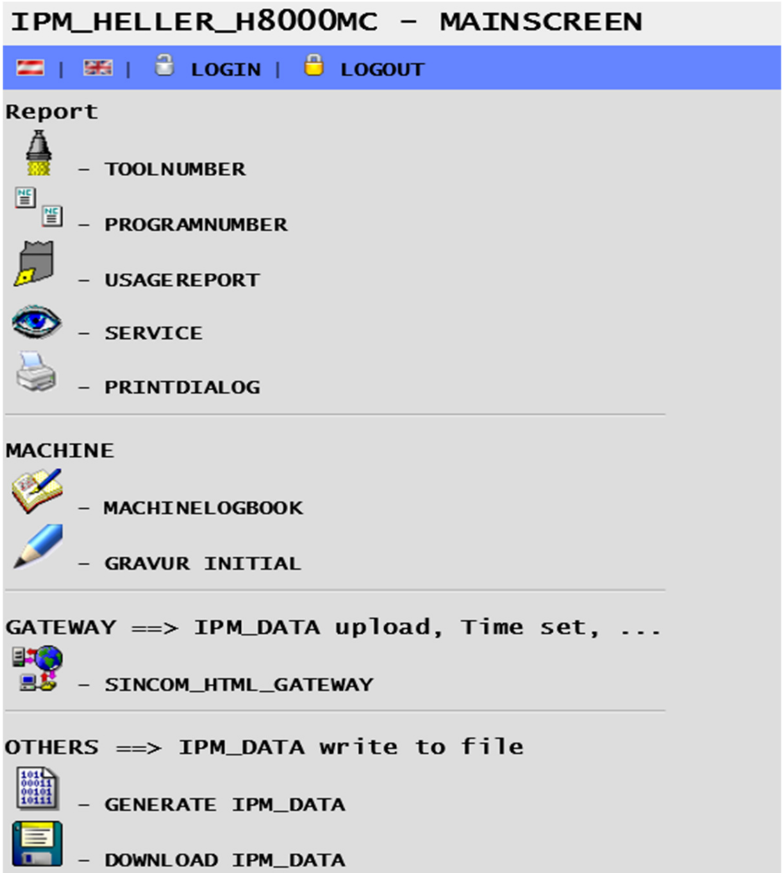


Figure 4-1: IPM Interface, Heller H8000MC
Source: ENGEL Austria GmbH

Inside the IPM interface the machine logbook from every Heller machine can be chosen (Figure 4-2).

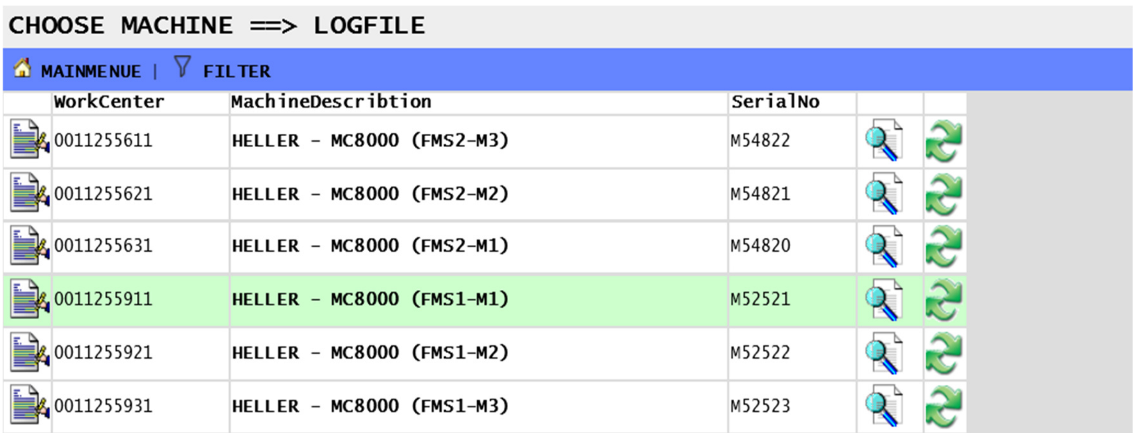


Figure 4-2: IPM- Machine Selection
Source: ENGEL Austria GmbH

The IPM logbook (Figure 4-3) assigns a time stamp with the information of date, message text, tool carrier number, pallet number, main program number and sub program number to each event in the NC cycle. Furthermore, the data can be filtered for a better research.

LOGBOOK - 0011255611 - HELLER - MC8000 (FMS2-M3)

MAINMENUE | CHOOSE MACHINE | REFRESH | FILTER

TimeStamp	Message --> ⚠ FILTER ACTIV ⚠	Tool Carrier	PAL	MainProg L1Prog L2Prog CallProg
8/Apr/19 Mon 9:59:57 am	L_ZO_WRITE ==> NULLPUNKT G56 - 3 - (Z) Z = 315.7076 (GROB) GESETZT !! ==> KORR um 0	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:57 am	L_ZO_WRITE ==> NULLPUNKT G56 - 3 - (Z) X = 371.6285 (GROB) GESETZT !! ==> KORR um -0.8715	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:57 am	L_ZO_WRITE ==> NULLPUNKTKORREKTUR UNTER WINKEL ==> Winkel = 270 KORRWERT Z = -0.871 SPEICHER = 3 ==> X= -0.871 Z= 0	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:57 am	00830009 ==> Istwert Messachse Z :2.631297111	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:56 am	00830009 ==> Differenz Messachse Z :-0.8714963716	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:56 am	L_ZO_WRITE ==> NULLPUNKT G54 - 1 - Z = 371.6285036 (GROB) GESETZT !! ==> KORR um 0.06564855573	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:48 am	00830009 ==> Istwert Messachse Z:1.562855073	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:48 am	00830009 ==> Differenz Messachse Z:-0.9371449273	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:48 am	L_ZO_WRITE ==> NULLPUNKT G54 - 1 - Z = 371.5628551 (GROB) GESETZT !! ==> KORR um - 0.9371449273	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:39 am	L_ZO_WRITE ==> NULLPUNKT G56 - 3 - Y = 500.97586 (GROB) GESETZT !! ==> KORR um 1.47586	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:39 am	00830009 ==> Ist Nut/Steg:348.2122588K-Wert:-1.606129378	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:39 am	00830009 ==> Nut/Steg ist Breite :348.2122588	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:39 am	00830009 ==> Nut/Steg differenz Y-IST :1.47586	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:39 am	00830009 ==> Nut/Steg differenz X-IST :0	79981 1	48	HP48.MPF 00830009
8/Apr/19 Mon 9:59:39 am	L_ZO_WRITE ==> NULLPUNKT G54 - 1 - Y = 500.97586 (GROB) GESETZT !! ==> KORR um 1.47586	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE
8/Apr/19 Mon 9:59:16 am	L_ZO_WRITE ==> NULLPUNKT G56 - 3 - (X) Z = 315.7076 (GROB) GESETZT !! ==> KORR um 0.7076	79981 1	48	HP48.MPF 00830009.MPF L_ZO_WRITE

Figure 4-3: Machine Logbook
Source: ENGEL Austria GmbH

4.2 Short term Time Analysis

As a next step the survey methodology was developed. Based on the average method, a model is built up that defines, how the data acquisition should work. For this purpose, the arithmetic mean is applied to calculate an average time.

$$\overline{t_m} = \frac{\sum t_m}{n} \qquad \text{Equa. (4-1)}$$

It starts by choosing a representative sample. In this case, machine number 0011255631 is selected at the IPM interface. The published data is inserted into a Microsoft Excel sheet in ascending order. Afterwards, the measuring duration is calculated from the time stamps of the first and the last time of tool number $t_p = 79981$ (measuring probe) in action. This calculation is made for each manufacturing cycle in the period. The processing time is calculated via subtraction the first one from the last time when this pallet number occurred.

Considering the main time parallel metrology, the measuring duration of the first time the probe came into action during the cycle, is relevant. In total, the NC program requires more measuring cycles after some certain process steps.

The result after a period of 12 hours analysis clearly shows, that the probe is operating for an average of less than two minutes (Table 4-1). This is a share of two per cent of the total processing time. During the analysis, four different parts were manufactured. The pallet number eight at the beginning was processed on the first clamp setting for raw material. In order to finish the workpiece, a second clamp setting is used later, which leads to a small measurement but a longer processing time. The Cylinder Body Injection on pallet number 24 was representing a common part with a measuring time of two minutes. The Housing Injection on pallet number 17 has the longest measuring time with nearly two and a half minutes. The Cylinder Body Injection on pallet number 27 has a shorter measuring time but a longer processing time in comparison with pallet number 24. The total processing time during the period amounts to 715 minutes and 52 seconds. The first measuring of the probe lasts about eight minutes of this time.

Table 4-1: Time analysis - 12 hours period

Date	Time [h]	Part Name	Pallet No.	Tool No.	Measuring Time - t_{m1}	Processing Time	Measuring Share
24.04. 2019	18:09 h	Housing BRG Screw	8	79981	01:26 min	41:28 min	3.1 %
24.04. 2019	19:00 h	Cylinder Body INJ	24	79981	02:00 min	174:34 min	1.1 %
24.04. 2019	21:56 h	Housing INJ	17	79981	02:23 min	117:32 min	2.0 %
24.04. 2019	23:54 h	Housing BRG Screw	8	79981	00:48 min	193:34 min	0.4 %
25.04. 2019	03:08 h	Cylinder Body INJ	27	79981	01:40 min	188:44 min	2.0 %
BRG… Bearing				Total	08:07 min	715:52 min	1.1 %
INJ…Injection				Av.	01:53 min	143:10 min	2.0 %

4.3 Extended measurement analysis

The period of 12 hours, randomly chosen for one of the three machines, is a very short time but gives a first impression on the duration of measuring in the manufacturing cycle. The next model enhances the filtering of the data by adopting the logic of the first model, to the period of April 2019 and on all three machines.

At first, the period was chosen from 31st of March 2019 until the 1st of May 2019. Due to the large volume of data, each machine had to be analysed individually. The data collection was made by selecting a set of 45,000 data records to reach the whole month April. The data set of the first machine, with the number 0011255611, was pasted from the IPM interface into a MS Excel sheet. The ascending date form made the handling easier for the following calculations. The syntax is based on a three-step logic (Figure 4-4). First, the start and end of the measurement process in the program cycle were displayed. The Tool number was therefore used for constraints. In the second step, the duration of the probe in use was calculated. The final step is to evaluate and sum up the probe usage during the first measuring process of the manufactured parts.

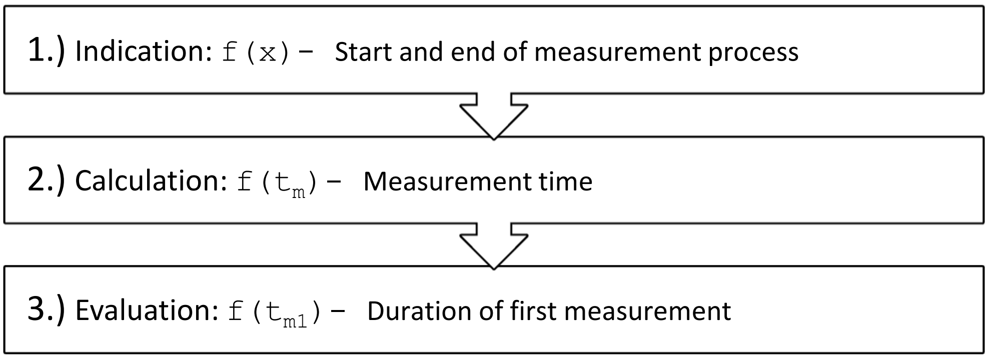


Figure 4-4: Three steps of Measurement time acquisition

An if-function compares the tool number on different time stamps. The actual time stamp was chosen with the index `t0`, the following stamp with `t1` and the previous with `t-1`. The measurement probe with the tool number $t_p = 79981$ remains the same for every machine. In the first if-function, the tool number of the current and the subsequent time stamp is checked in the constraints.

4.3.1 Syntax of step one

```
tp = 79981;                         // tool: measuring probe

tΔg = 1.5/ (24*60);                 // gap time: 1.5 s

If

(TOOL_t0 = tp) & (TOOL_t1 ≠ tp)

Or

(TOOL_t1 = tp) & (TOOL_t0 = tp) & (t1 - t0 ≥ tΔg)

{

      x = 1;                        // measuring start

}

Else

{

      If (Tool_t0 = tp) & (Tool_t-1 ≠ tp)

      {

            x = 2;                  // measuring end

      }

      Else

      {

            x = "";

      }
}
```

The end of a measuring process can be figured out in two ways. Firstly, the actual time stamp (t0) has the tool number $t_p = 79981$ and the following has any different. Secondly, the actual and the following time stamp have both the tool number $t_p = 79981$. Furthermore, the difference between both time stamps must be greater equal one minute and 30 seconds ($t_{\Delta g} = 1.5\ min$). Because of the occurring effect of more than one measuring processes during the manufacturing cycle, the gap of one and a half minute ensures that a certain process is finished before the next begins. MS Excel uses the digital hour format for calculating. Therefore, the gap is divided by 1440 minutes (24 hours times 60 minutes) and shows the value of `0.0010416`*.

The constraints for the IF-function are fulfilled, when the following time stamp of the actual had a different tool number or a gap of more than one and a half minutes. Therefore, the result of the if-statement is true, that returns the value `x = 2` in the foreseen cells. If the constraints are not accomplished, the result is false. In this case the nested IF-function compares the actual tool number with the previous one in a constraint. Therefore, the actual tool number must be t_p `= 79981` and the previous tool number is not allowed to be identical. If this statement is true, the function returns the `value x = 1`. This stands for the beginning of the measuring probe action. Otherwise, no value will be returned for the false result. The indication column is now filled with the values `x = 1` for beginning and `x = 2` for ending a measuring cycle. During and outside of the measuring process, no value is allowed in the cells.

4.3.2 Syntax of step two

```
datamatrix = [indication column, date column];

If (x_t0 = 1)

{

      tm = VLOOKUP (x = 2, datamatrix, date column, false) - datet0;

}                               // tm = measuring time

Else

{

      tm = "";

}
```

In the second step, the duration of every measuring process is calculated. Therefore, an if-function compares the actual value in the indication column with the value for the measuring start (`x = 1`). If they are identical, the result is true. This leads to a vertical lookup-function (`VLOOKUP`) that searches for ending the measuring process (x = 2) in the two-dimensional matrix of the indication and the date columns. The VLOOKUP function returns the exact match (false) from the indication column, expressed with the value x = 2. Finally, the actual time must be subtracted to return the duration of the measuring (tm). If the statement of the function is false, no value will be returned. The time for each measured process is now shown next to the indication column. The total time of measuring with the radio transmission probe amounts to 21 hours and 39 minutes (21.66 h) during the whole period.

4.3.3 Syntax of step three:

```
If (PALLET_t0 = PALLET_t-36)
{
      tm1 = "";              // tm1 = first measuring time
}
Else
{
      tm1 = tm_t0;
}
```

The third step returns the measuring time only from the first measuring process (tm1). Therefore, an if-function compares the actual pallet number with the number in the previous 36 lines. This ensures that the pallet has never been used before. If both pallet numbers are identical, the statement is true and does not return a value. In this case the false statement returns the duration of the first measurement process (tm1).

After these three steps have been applied to all 44,911 data lines in the MS Excel sheet, the total time of the first measuring (tm1) can be summed up. This results in 8 hours and 43 minutes (8.72 h) during the period of 31st March and 1st May 2019 on the machine 0011255611. This is a share of 1,8 % of the total processing time that amounts to 479 hours and 36 minutes (479.60 h). In average, the first measuring has a duration (tm1) of two minutes and 41 seconds (2.69 min).

The analysis model consists of the step's: indication, calculation and evaluation. It is also applied to the machines 0011255621 and 0011255631 to complete the measurement time research. Similarly, to the first machine, the data is chosen from the IPM interface for each machine and pasted into a separate MS Excel sheet. The syntax of the three steps returns the relevant information of the measuring time in the processing cycle. As a result, the overall processing time, the overall measuring duration and the first measuring time of the workpiece can be seen in Table 4-2. For this purpose, the time is decreased by 75 per cent according to company experts. About half of the probing time of the components produced on the second clamp must be measured with the probe to guarantee the full accuracy in the following finishing process. The measuring time duration of more than 24 hours per month can be scaled over a yearly time span of eleven production months. This results in the amount of more than 268 hours per year.

Table 4-2: Measurement Analysis

Machine Heller H8000:	**255611**	**255621**	**255631**	**Average p.m.**	**Total p.m.**
∑ Processing time	479.60 h	496.00 h	495.30 h	490.30 h	1,470.90 h
∑ Total Measuring time	21.66 h	16.36 h	23.51 h	20.51 h	61.53 h
∑ 1st Measuring time (75%)	8.72 h	7.34 h	8.36 h	8.14 h	24.42 h
Share of Processing time	1.8 %	1.5 %	1.7 %	1.6 %	
Average Measuring time	2.69 min	1.61 min	3.22 min	2.51 min	
1st Measuring time p.a.	**268.6 h** (in eleven production months)				

A second source is used to ensure the accuracy of the entire processing time. The monthly report of the Overall Equipment Effectiveness (OEE) consists of the key figure’s: quality, availability and performance, using data of the manufacturing execution system (MES). This enables a closer look at the operating time that is used for calculations. Therefore, the operating time of every machine is listed on the base of the machine signal. In addition, downtime for tool, machine or program errors will be included in the published operating time corresponding to the machining time. The average probing time amounts to two and a half minutes per month. In total, the first measuring cycle during April 2019 has an average time of ten and a half hours and a total of nearly 32 hours. In comparison, the first measurement cycle is more than half the probing time in action, during manufacturing. During the analysis period, the processing time amounts to almost 1,471 hours. In Average, the first measuring time responds to more than two per cent of the total processing time. A closer insight is published in the appendix at Figure 8-2: Process Frequency - April 2019 and Figure 8-3. The analysis clearly shows that the single measuring time can fluctuate between a peek of six and a half minute and a minimum of less than a minute

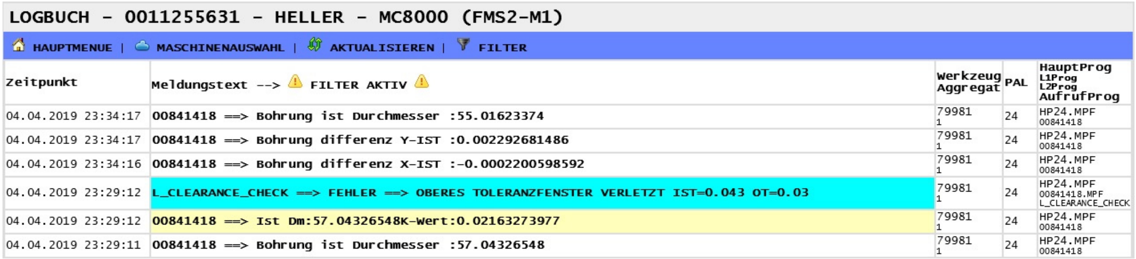
To sum up, the regarded period of April 2019 represents a typical production month with a broad range of manufactured workpieces. The average value of over two per cent confirms the first 12 hours of the short-term analysis. Moreover, the total measuring time of a whole production year can be seriously calculated on this basis. As already mentioned, the NC-program and its structure is relevant for the measuring cycle. Based on the geometrical complexity of a workpiece, the amount of probing points is the time influencing factor.

4.4 Measurement Failure time

The downtime analysis shows that the part geometry cannot be sufficiently tracked with this tool due to incorrect message generation. For every probing point, a defined confidence range is set by the CAM worker. The probe determines if the production allowance is inside the pre-set range. If the measured value is outside the range, two cases occur. With a lower raw material value, the confidence range leads to a possibly unfinished work piece because

there is not enough material available. A geometrical error or a wrong clamped part is indicated by overshooting the range. In this case the operator has to decide if the work piece can be manufactured by setting a new range value manually.
Either way, the machine stops and sends an interruption message to the logbook with the title: "L_CLEARANCE_CHECK ==> ERROR ==> UPPER/ LOWER TOLERANCE RANGE HURT _ TARGET = Value _ ACTUAL = Value".
During a normal shift, two operators are responsible for three machines. In addition to working on the machine, the operator has to fulfil also other like tool change, workpiece inspection and administrative duties on the master computer of the MES. An additional set-up worker clamps the workpieces on the pallets. In a night shift, two workers operate three machines and do the set-up work. Depending on the operator´s current work, it takes a certain amount of time until he is able to react, decide and switch on the machine when it comes to a standstill. Indication lamps on the shop floor way and a graphical picture on the master computer informs the worker of a machine stoppage. In the worst case, several machines are down at the same time.
Due to less information on downtime caused by measurement interruptions (Appendix: Table 8-6), the stoppage duration is calculated on the basis of the IPM figures. In order to analyse the frequency and the duration of these incidents, the logfiles of all three machines are inserted from the IPM interface into a MS Excel sheet. During the period of April 2019, every message indicating an interruption of the probing cycle was tracked. The current time stamp of the message "L_CLEARANCE_CHECK" was subtracted from the subsequent time stamp that removed the incident.
For example, in Figure 4-5 the duration between the stoppage and the subsequent measurement result is 5 minutes and two seconds.
The analysis (Table 4-3) of all three machines of FMS 00112556 shows that machine number 0011255611 has only 3 stoppages caused by overshooting the confidence range. Each other machine deals with more than fifty incidents. The less occurrence can be explained by the workpiece material steel on the machine 0011255611 and cast iron on the other machines. Steel parts enable a higher accuracy of the raw geometry than cast iron parts. As shown in Table 4-3, the total incident duration of all three machines during April 2019 was less than nine

hours. With eleven production months the yearly duration can be scaled up with a result over 96 hours per year.



LOGBUCH - 0011255631 - HELLER - MC8000 (FMS2-M1)

HAUPTMENUE | MASCHINENAUSWAHL | AKTUALISIEREN | FILTER

Zeitpunkt	Meldungstext --> FILTER AKTIV	Werkzeug Aggregat	PAL	HauptProg L1Prog L2Prog AufrufProg
04.04.2019 23:34:17	00841418 ==> Bohrung ist Durchmesser :55.01623374	79981 1	24	HP24.MPF 00841418
04.04.2019 23:34:17	00841418 ==> Bohrung differenz Y-IST :0.002292681486	79981 1	24	HP24.MPF 00841418
04.04.2019 23:34:16	00841418 ==> Bohrung differenz X-IST :-0.0002200598592	79981 1	24	HP24.MPF 00841418
04.04.2019 23:29:12	L_CLEARANCE_CHECK ==> FEHLER ==> OBERES TOLERANZFENSTER VERLETZT IST=0.043 OT=0.03	79981 1	24	HP24.MPF 00841418.MPF L_CLEARANCE_CHECK
04.04.2019 23:29:12	00841418 ==> Ist Dm:57.04326548K-Wert:0.02163273977	79981 1	24	HP24.MPF 00841418
04.04.2019 23:29:11	00841418 ==> Bohrung ist Durchmesser :57.04326548	79981 1	24	HP24.MPF 00841418

Figure 4-5: Clearance Check, Source: ENGEL Austria GmbH

Table 4-3: Measurement incidents - April 2019

Machine	No. of incidents	Total incident duration	Average incident duration
0011255611	3	0.68 h	13.0 min
0011255621	53	4.22 h	4.52 min
0011255631	57	3.85 h	4.36 min
Total	**113**	**8.76 h**	**7.30 min**
Total incident duration p.a.		**96.3 h**	

The analysis of the failure time caused by a geometric deviation during measurement, points out that the casted components are regularly out of the selected boarders. The machine stoppage caused by those incidents leads to a downtime of more than one worker shift per month. A machine downtime analysis can be seen in the appendix (8.3.2).

This chapter quantifies the measurement and down time of each machine. The outcome shows that externalisation of the measurement procedure leads to more available machine time and a higher number of additionally produced workpieces. In conclusion, the processing of casted components contains many different failure causes. An optical measurement of the casting before machining will save essential production time and decreases downtime and failure costs. As a result, the productivity of the flexible manufacturing system will be increased.

5. Process optimization

In the previous chapter, the time savings of an external measurement are pointed out. This leads to the research question: How does an externalized measurement procedure look like? The existing process must be changed to ensure an enhanced and stable production process. Based on the focus of optical measurement systems and the results of the market analysis in chapter three, a new unit has to be implemented into the existing plant. The following sub chapters deal with a possible approach.

5.1 Optical Measurement Unit

The focus on removing the non-value-adding process steps out of the manufacturing machine can be achieved with the integration of additional steps. The existing process of delivering the clamped components into the pallet storage with a stacker crane, transferring it to the machine and shifting it back to the set-up station after machining must be changed. Therefore, a measurement cell must be implemented in the production line. The stacker crane of the pallet storage is used to supply this cell with the raw components. Due to less space requirement on the shop floor, a rotary table in combination with a robot supported optical measurement system is preferred. Basically, the entire cell should work autonomously without human monitoring. The casting must be compared with the existing 3D designed part in the background. A suitable measurement system has to decide whether the part can be machined or if the deviation is too large for production.

The productivity increase of the machine can only be achieved with an outsourced measuring procedure that is able to obtain the same results and parameters of a part as the existing probe. The aim is an exchange of the castings into the machine with a direct start of the machining process without a probing cycle. In traditional mass production, this is a common procedure to be time efficient. The difference in the raw part situation is responsible for less failure during manufacturing. The analysis of measurements incidents in chapter 4 clearly shows that steel parts with raw geometry are manufactured with a higher accuracy than it is possible for castings. For this reason, the rough casting surface with geometrical deviations causes machine downtime by exceeding the specified values. In order to guarantee the manufacturing of lot size one parts, the machining of cast parts is only possible with knowing the geometrical deviations to the designed shape. Otherwise, the deviations lead to rejects with surface defects, geometrical errors or additional costs for rework.

The new manufacturing process is illustrated in Figure 5-1 and starts with the existing process step of clamping the unmachined part on the pallet with appropriate devices. The part is convoyed from the casting's storage in a standardized Euro-pallet which is used for transportation and logistics to the set-up station. There, a worker moves the part with the help of a crane and a magnetic mount to the machining pallet. The different clamping systems are explained in more detail in the subchapter 5.2.1. After the part has been mounted, the pallet moving station conveys it to a stacker crane of the pallet storage. In the next step, the stacker crane picks the pallet and moves it to the measuring cell. If the cell cannot be supplied, the pallet is stored at the assigned place. Every pallet gets an identification number in the MMS, the number is used to order all manufacturing jobs. With the release of a pallet into the storage System, he ensures that the correct part is clamped on the right pallet. The MMS software defines the time when a pallet must arrive at the machine, referring to the production plan. Considering the manufacturing start, the pallet has to be delivered to the measurement cell in time.

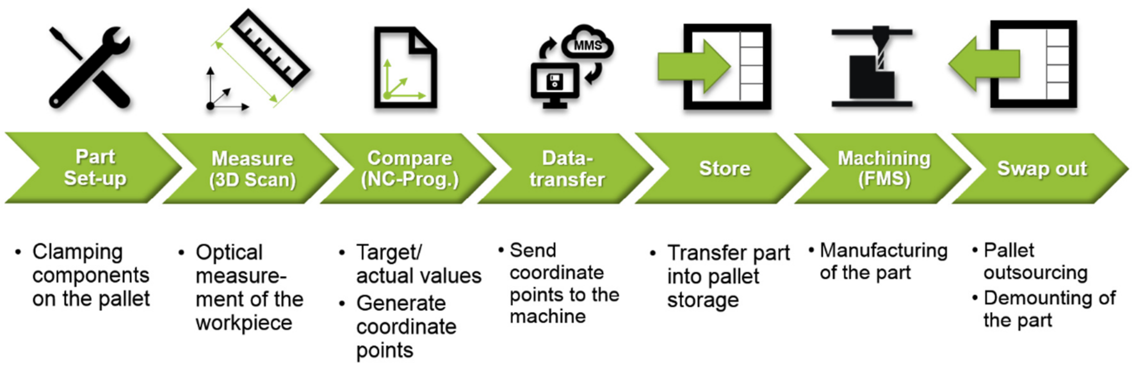


Figure 5-1: New Manufacturing Process

Inside the cell, the stacker crane supplies the pallet on a rotary table. A safety door ensures that no person or moving part can be hurt or damaged. Otherwise, the multi-level system will be stopped automatically. Due to less space in the storage system, a measurement system moved by a robotic application is needed. Together with the rotation of the pallet table, the system starts scanning the clamped casting. In order to load the correct programmed trajectory for the part, the identification number must be transferred from the master computer to the cell steering. For each raw component group, an additional program must be created. The system must be capable of measuring only the surfaces that are machined in the later process. For this purpose, the measuring of the second clamp is necessary to receive the manufacturing allowances.

The applied measurement software must be prepared in more detail before scanning. First of all, the correct version of the digital part must be transferred into the software. After that, all attributes and measurement points must be defined. The points are equal to the probing coordinates of the existing NC program. After the scanning has been completed, the software compares the actual and the target value in an inspection cycle. The actual values of the selected attributes are prepared for the NC sub program and stored in the DNC storage of the machine. After the software has checked the geometry, the pallet sends a release signal to the manufacturing management system. Otherwise, a geometrical deviation leads to a process end of the part. In this case, the measurement software informs the operator with a report. Next, the pallet will be transferred to the set-up station. In addition, the system is able to detect failures of the part clamping early enough in the process and with a “OK – Not OK” decision. The benefit is less downtime of the machine in case of failure detection inside the machine or after machining. A retransfer of the pallet allows possible adjustments and corrections on the clamping set-up. This ensures that only “OK” parts will be manufactured in the future.

The steps after the pallet has passed the measurement station are not changed from the existing process. The pallet will be conveyed to the machine exchange station with the stacker crane. In the background, all necessary NC programs are transferred from the DNC server to the selected machine by the MMS. Besides that, the sub program with all measurement coordinates is included in the data transfer of the main programs. After the machine has finished the previous part, the exchange table rotates and delivers the new part into the machining room. The manufacturing process starts by loading the new NC program and applying the milling cycles. After the machining is completed with showering the part for removing all chips, the pallet is shifted into the pallet storage if the set-up station cannot be supplied.

5.2 System Specifications

First of all, the requirements for the future system must be defined in a way that implementation is possible. The main aim is to prevent rejected parts after machining. This means, only parts with a suitable casting geometry are allowed to enter the manufacturing machine. To fulfil this requirement, the geometry of every casting must be measured and compared with the designed shape. The requirements on the measurement system are already mentioned in chapter 3.4.1. As shown in chapter 2.7, unseen geometrical errors can lead to tool crashes or defects if the NC program cannot take this deviation into account.

5.2.1 Components

In order to establish an external measurement system inside the pallet storage, it is necessary that all manufactured parts are able to enter the cell. This means that the pallets with the dimension of 800 x 800 mm together with the holding attachment and the clamped part are used. Based on DIN 55201-A1[29] the pallets are standardized and designed with a zero-point clamp system to ensure the high change accuracy of the machine. The dimension of the part is limited by the pallet storage housing and the machine traverse path .
Table 5-1. The maximum size belongs to 1400 mm in length and width respectively as well as 1525 mm in height. In addition, the interference area of the machine is expressed with 1250 mm in diameter as shown in Figure 5-2. This is also a representative figure for the rotary table in the cell.

[29] cf. (DIN 55201-1, 1985)

Table 5-1: Machine Traverse Path

Axis Direction	Min. Position	Max. Position	Traverse Path
X	-625 mm	625 mm	1250 mm
Y	120 mm	1320 mm	1200 mm
Z	200 mm	1300 mm	1100 mm

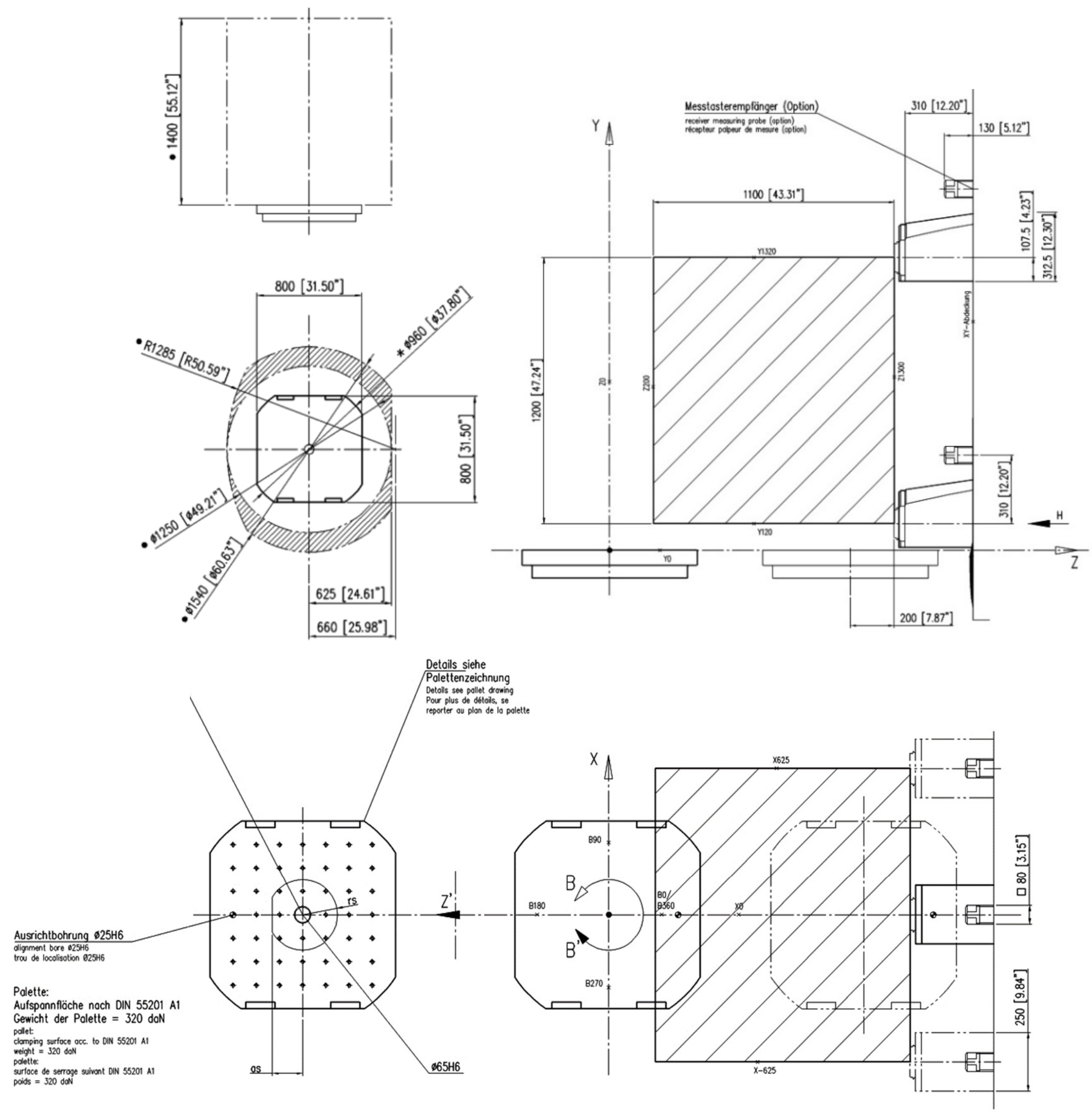


Figure 5-2: Axes movement and machining area (Source Heller)

The component diversity (see Table 2-4) needs a lot of different clamping devices built on the pallet. In Figure 5-3 the main groups are illustrated. Depending on the first or second set-up of the part, different clamps are used. Typical for the first clamping a nut tightened clamp is fixing the component on three contact points for statically determination. If this is not possible a statically overdetermined clamp in which the component is tighten with a predetermined torque is used. In this case, the set-up worker controls the clamping with a dial gauge to guarantee that no deformation of the part occurs. On the second clamp, the component is

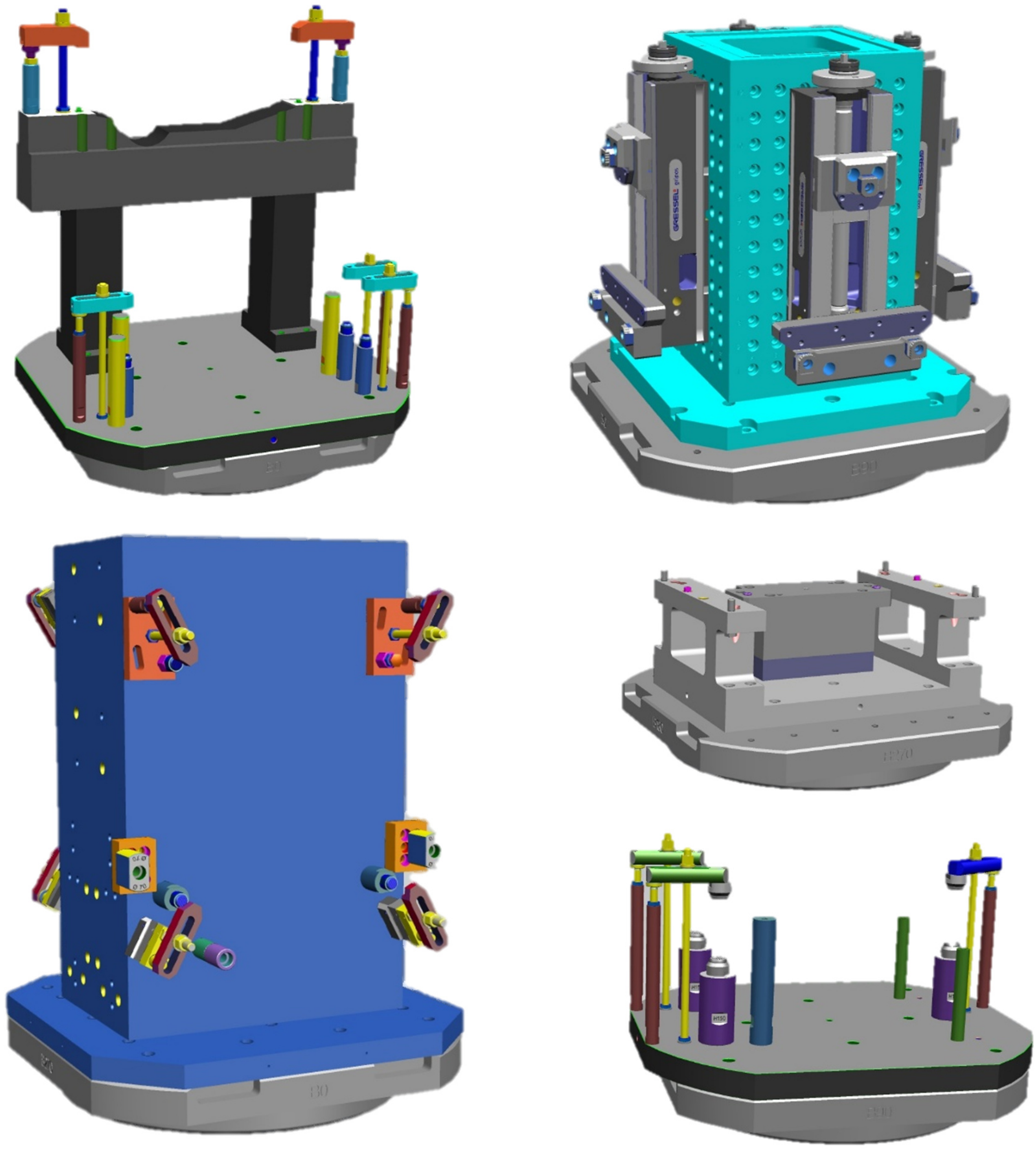


Figure 5-3: Different Clamping Devices

screwed on the machined surface for the final process. If possible, a clamping on a machine vice is used to save more set-up time. Similar in all variants a fixed stop is used to simplify the positioning on the pallet. Towers are mostly used for all kinds of plates with the additional possibility of fixing the first and the second clamp on one pallet.

Larger components have their own pallet, but with decreasing size, a shared pallet is used. Therefore, two or more components are fixed on the pallet with different clamps. Table 5-2 gives an overview of the different clamping concepts. It shows that more than one third is used with both, first and second clamping position on one pallet.

Table 5-2: Clamping positions of the used pallets

Clamping positions on the pallet	Amount of pallet
Only first clamp	26
First and second clamp	29
First, second and third clamp	1
Only second clamp	19
Only third clamp	2
Total Amount	77

Depending on the position on the pallet, the analysis in Table 5-3 shows that the geometry can variate in every direction. For an automated optical measurement system the nearest and farthest surfaces are relevant. Figure 5-4 shows the minimum and maximum dimensions in the coordinate system of the pallet edge.

Table 5-3: Dimensions of the clamped parts

Part Dimension											
Part groups			[mm]								
			X min	**X max**	**Xb**	**Y min**	**Y max**	**Yb**	**Z min**	**Z max**	**Zb**
1	**Injection Body**	min	-25	-44	425	135	507	300	-105	-110	290
		max	175	283	869	205	925	790	252	265	1015
2	**Moving Link**	min	-35	-35	216	222	172	80	49	64	295
		max	292	332	870	232	367	394	250	255	687
3	**Injection Housing**	min	-60	-60	295	134	404	270	15	20	460
		max	210	235	920	254	784	530	155	185	765
4	**Various Parts**	min	-43	42	81	139	462	270	-43	-41	50
		max	240	395	770	304	1185	990	211	342	1020
		total	**X min**	**-60**		**Y min**	**134**		**Z min**	**-110**	
		total	**X max**	**395**		**Y max**	**1185**		**Z max**	**342**	

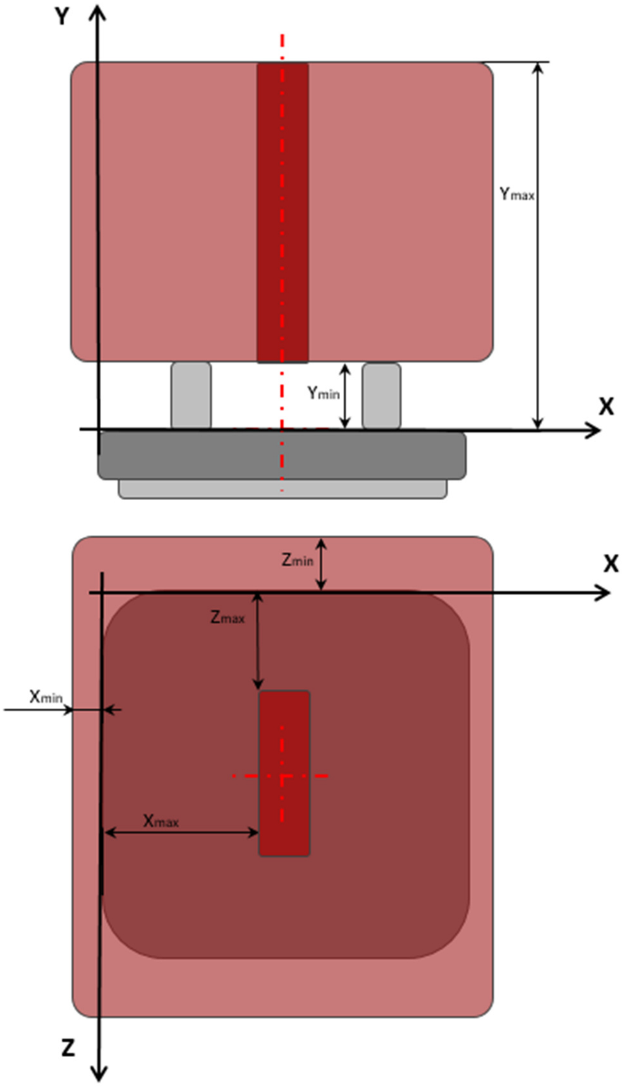


Figure 5-4: Part dimension on the pallet

5.2.2 Measurement accuracy

The accuracy of the measurement system for the casted raw parts is defined to 0.2 millimetres together with company experts. Due to raw and non-reflecting cast surface with corrosion protection, a more detailed resolution does not allow more output. The allowance varied between five millimetres for pre-machined and up to ten millimetres for casting surfaces. The part size and the casting approach of the foundries are defining the allowance bandwidth.

The clamping devices together with machined surfaces can cause reflections which could influence optical measurement systems. For this reason, the system must be able to measure independent of environmental influences like changing day light conditions or strong vibrations of neighboured machines.

5.2.3 Coordinate Points Acquisition

The replacement of the probing cycle can be only fulfilled by the detecting the ident information with the optical measurement system. Therefore, every coordinate point of the existing cycle must be replaced. In more detail, the values for all R-parameters must be assigned.

Change of the existing NC - program

In order to keep the initiation work as low as possible, the current program codes are changed in various ways. The program header must include the information of the needed sub program in the main program. Therefore, the sub program must be existent and named similar to the main program number for an easier identification. Before the needed tools are loaded, the necessary sub program is assigned as shown in the example syntax:

```
N136 ;P-START
N138 ;P00841234_SCANDATA         //Measurement file name
N140 ;P-END

N142 ;T-START                    //Start Tool initiation
N144 ;T79981;00-02-54; Renishaw DM= 6.00 L=276.00 BT
```

After all tools are initiated in the machine, an if- function assures that the sub program consists of all needed values from the optical measurement system. Assuming that no values are found, the function jumps to the first probing cycle. Therefore, nothing has changed from the previous program. Furthermore, the cycles are used as a redundant system if an unexpected error occurs with an inoperable measurement cell as result.

```
N220 ;L_IF_SCANDATA_EXIST("LB_END_PROBING")
…
N1040 ;LB_END_PROBING
```

The function “L_IF_SCANDATA_EXIST” is calling the measurement file that is already prepared in the header. An if-function checks if the program exists in the machine data storage. The positive statement opens the subroutine that is prepared in the header. The scanned coordinate points must be prepared in the order to the correct R values. With the call function of the subroutine, all parameters are now transferred and stored in the fine memory of the machine. The function “GOTOF” guides directly to line N1040 in the main program. If the decision statement cannot be fulfilled, the existing syntax of the probing cycle is run through. In the final lines, the “RETURN” function jumps to the last counting line which is used for starting procedure after a stoppage. At least, the “ENDIF” command ends the if-function. According to this explanation, the following example shows the structure of the additional sub program:

```
L_IF_MESSWERTE_EXIST           //function name

  ;IF PROG_EXIST == TRUE       //decision issue
  ;CALL 00841234_SCANDATA  //call subroutine

      ;R698=
      ;R699=
      ;R720=
      ;R721=              //Values according SCANDATA
          …
      ;R780=

  ;GOTOF LB_END_PROBING
  ;ELSE
  ;START PROBING CYCLE
  ;RETURN TO NEXT LINE
  ;ENDIF
```

After the program has received all inevitable parameters, the manufacturing process starts with the first face milling step right after the command “LB_END_PROBING”. The measurement probe is exchanged with the prepared milling tool and the milling process starts. Therefore, the “JUMPLABEL” sub program gives the information of the largest measured value. The number of milling steps, which are necessary to target at the defined dimension, are calculated. The different values define the target value, the cutting depth, and systems information like the number and amount of the R -parameters.

```
N1066 ;L_JUMPLABEL( 10.00, 3.00,740,9)
```

The sup program is prepared with predefined labels in the spacing of the cutting depth. With the use of the measured points as R-parameters, the highest one is chosen and divided by the jump label value. Depending on the result, the position of the label is allocated. Figure 5-5 illustrates that label four is needed to achieve the dimension down to step zero. If only three milling paths are chosen, a crash with tool damage may occur because of too high cutting forces.

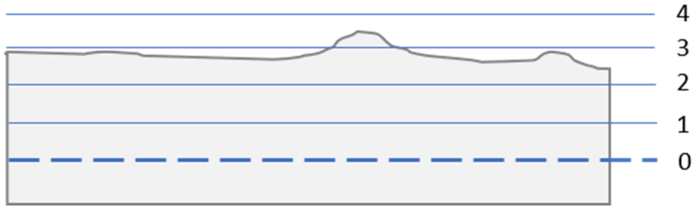


Figure 5-5: Jump label steps

5.2.4 Business Process Model and Notation

In the chapter of coordinate acquisition, it is announced that different preparation work must be carried out before the external measurement receives results. With the illustration in a Business Process Model and Notation (BPMN), the process flow can be explained in an easier way (Figure 5-6). The modelling convention and notation is based on Allweyer 2015. The model is built on four pools, representing the main categories in use and includes a closed process. Each is divided into separate lanes, for explaining the individual responsibilities. Events, activities and gateways are the core elements in this model. Information transfer between pools and lanes are shown with connection links. Every process starts and ends with an event. Activities in between are describing the process in a lane.[30]

The first pool is called Flexible Manufacturing System and consists of the two lanes “MMS Fastems” and “CNC Machine HellerH8000”. With a trigger of an initial manufacturing order from the MES, the process starts in the MMS lane. The first activity in this system is the command of loading a clamped pallet from the set-up station to the stacker crane. Next, the pallet is moved at the defined time slot to the measuring box inside the MLS. Therefore, the MMS directs information

[30] (Allweyer, 2015)

about the pallet number to the cell software for identification. The stacker crane unloads the pallet on the rotary table at the box. For the measurement process the central software loads the path for moving the measurement head by robot and the metrology program for evaluation. That is prepared by the CAM department together with the designed model, the evaluation criteria coordinates on the part and the NC program. All files are saved in a separate measurement storage. The evaluation software generates a protocol and stores the coordinate points in a measurement data file at the program storage.

After the scan has been completed, the measurement data is verified whether the part can be manufactured, or geometrical deviations are detected. The gateway allocates whether the result is in order or not in order. In the last scenario, the pallet will be stored in the pallet storage. A report is sent to the operator and the set-up station is supplied for rework or rejection. If the measurement result releases the part for manufacturing, the stacker crane shifts the pallet into the pallet storage.

Next, the MMS software decides the correct manufacturing time and the corresponding NC program together with the measurement sub program are sent to the machine from the DNC storage. Then the pallet is moved to the production machine and switched against the already processed pallet. The machine starts the program by fine storage deleting. After that, the measurement sub program and tools are verified. If a sub program exists, the measurement data gets verified and the measurement data defines the values as “R-Parameter”. If no measurement data is available, the existing touch probe cycle starts and the parameters are set. The manufacturing cycle can start after all measurement cycles have been completed. Finally, the workpiece is manufactured and the stacker crane shifts the pallet to the set-up station for demounting.

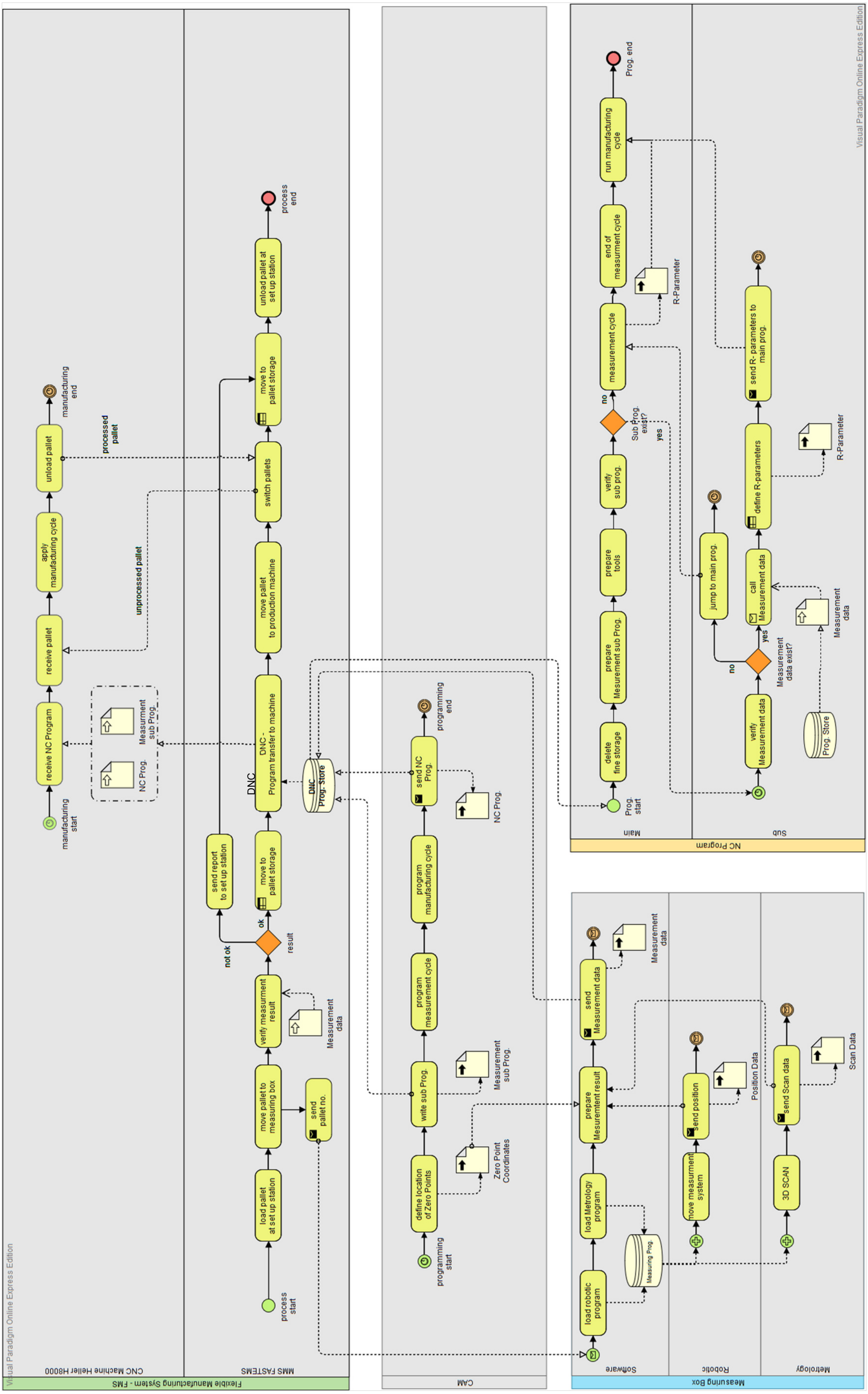


Figure 5-6: BPMN of the automated workpiece measurement

5.3 Visualization of the measurement cell

The company department of Automation Systems (EAS) visualizes the requirements in the existing pallet storage system (Figure 5-7).

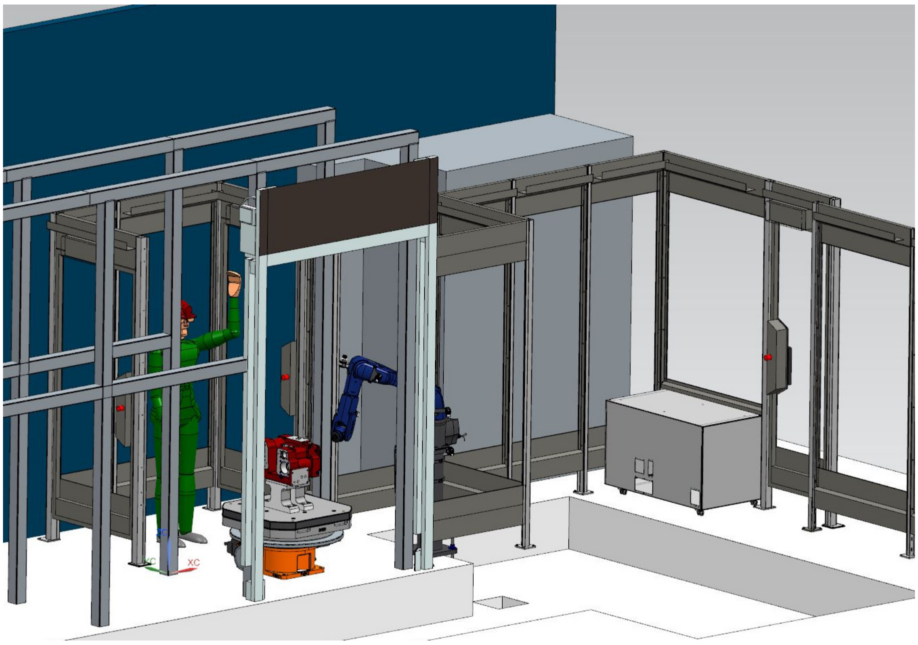


Figure 5-7: Isometric visualization of the measurement cell
Source: ENGEL Austria GmbH - EAS

Before a rotary table can be implemented, the storage structure must be modified and a new safety fence has to be adapted. The cell is designed isolated from the existing system. A roller shutter separates the cell from the pallet storage but allows the pallet delivery with the stacker crane. The safety fence with additional safety doors allows service and teaching work only when the roller shutter is closed. The company product "KUKA easix KR10[31]" is recommended from experts for moving the measurement system to the defined positions by a robot with six degrees of freedom. Furthermore, a rotary table allows the total measurement of a pallet clamped workpiece. The cell is controlled by a programmable logic controller (PLC) that is linked with the pallet storage system. The information of which pallet will arrive to the cell is responsible for loading the correct measurement programs to the system. The robot with the measurement

[31] See (ENGEL, 2019)

system and the evaluation software are running autonomously after all programs have been set up and implemented.

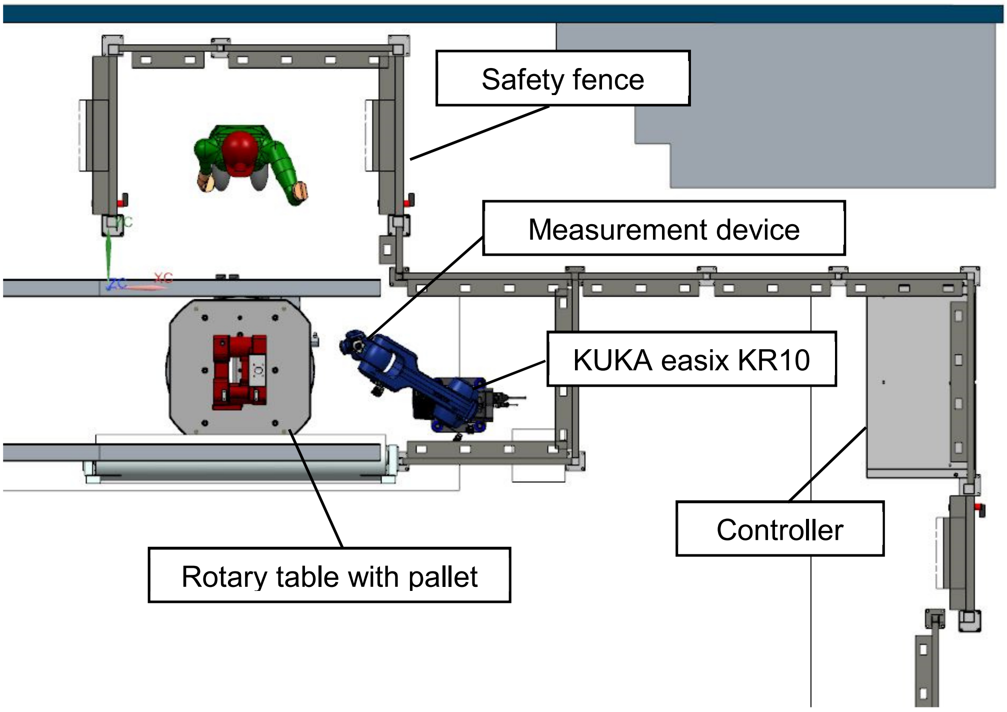


Figure 5-8: Top view of the measurement cell
Source: ENGEL Austria GmbH - EAS

The new process of workpiece measurement outside of the manufacturing machine can be only achieved with a measurement cell. Since the available space in the storage system is low a compact solution must be found. A robotically moved measurement system together with a rotary table allows a total part scan. The gathered measurement data is converted into a sub program and implemented into the main NC program of a part. As a result, only correct casted parts are manufactured in the machines

6. Financial Investment calculation

The main consideration of the investment calculation is to fill up the time saved with manufacturing time of additional parts. The time savings are based on the measurement time and the machine downtime caused by incidents shown in chapter four. This reduction of cycle time enables the production of more parts during the same machining time. A possible financial benefit arises if the investment costs are less than the benefit of producing more parts in the same time period.

6.1 Cost savings calculation

By externalisation of the measurement procedure from the machine into a measurement cell a lot of machining time can be saved. That time can be replaced by inhouse manufacturing of outsourced workpieces. In order to express the incidental cost savings, the hourly rate for outsourced workpieces is multiplied with the saved time.

According to company´s material procurement and purchase department the average hourly rate for external labour amounts to 159 Euros per hour in the month October 2019 (GSC-PP-M, 10/2019). This value is multiplied by the total savings time by external measurement.

The sum of the measurement time and the machine downtime caused by incidents amounts to 364.9 hours yearly. For the calculation of the cost savings, a main time transformation to the specified is indispensable. The company defined uniform allowance value of 9.5 per cent is considered here. That amounts to a total saving of specified time of 399.5 hours per year. Due to production variances the savings are reduced by an average factor of 15 per cent according to the accounting department. The new saving time belongs to 338.3 hours (Table 6-1) and is multiplied with the external labour rate to calculate the savings. In addition, the costs for rejection based on geometric deviations are allocated in production costs as shown in Table 2-6 and total material costs of €4,537 according the respective failure reports. The cost savings amounts to a total of €61,284 per year (Table 6-2).

Table 6-1: Total time savings p.a.

Savings main time	
+ Program Main Time (1st Measuring time)	*268.6 h*
+ Machine downtime due incidents	*96.3 h*
= Total Main Time	*364.9 h*
+ Allowance time rate (9.5%)	*34.6 h*
= Total specified time	*399.5 h*
- Production variances rate (15%)	*59.9 h*
= Total time savings p.a.	***339.6 h***

Table 6-2:Total cost savings p.a.

Total time savings		*339.6 h*
× Average external labour hourly rate		*€159 /h*
= Cost savings		*€53,996.4*
Rejection Manufacturing costs	*€2,715*	
Rejection Material costs	*€4,573*	
+ Total Rejection costs		*€7288*
= Total cost savings p.a.		***€61,284.4***

6.2 Dynamic investment appraisal – Net Present Value

To support the question whether an investment should be undertaken, a financial calculation enables clarification. The financial appraisal is highly depending on the time span of the investment calculation. Therefore, static investment methods are less suitable due to time independency. The discounted cash flow method considers the time value of capital. This means that all future cash flows are transformed to their equivalent time value at the start of the investment. The Net Present Value (NPV) is a method to calculate the monetary gain by summing up the difference of the cash in and out flows discounted to the project start (6-1). If the NPV is greater than zero, the absolute profitability will be achieved.[32] A uniformed discount rate is typical for this method (6-2). Besides, a differing debt and credit interest rate also called Weighted Average Cost of Capital (WACC) can be applied if all data is available. The companies accounting department has set the discount rate to four point two five per cent. In the cash flow calculation, the inflation rate in future time periods is taken into account at two per cent.

$$NPV = \sum_{t=0}^{T}(CIF_t - COF_t) \cdot q^{-t} \qquad \text{Equa. (6-3)}$$

$$q^{-t} = \frac{1}{(1+i)^t} \qquad \text{Equa. (6-4)}$$

$t \ldots Time\ index$

$T \ldots Last\ year\ of\ cash\ flow$

$CIF_t \ldots Cash\ inflows\ in\ t$

$COF_t \ldots Cash\ outflows\ in\ t$

$q^{-t} \ldots Discounting\ factor$

$i \ldots Discount\ rate$

The cash out flow includes the costs of the measurement system components according to vendors sales specifications, the automatization components and estimated adaptations of the necessary programs. Furthermore, costs for implementation and yearly maintenance costs of additional departments are considered. The cash inflow is calculated with the total cost savings of chapter 6.1.

The outcome of the NPV investment calculation (Table 6-3) shows that the first alternative is amortised before the fifth year ends. The next alternatives are paid off due to higher investment costs after more than seven and eight years, respectively. With a lifetime estimation of ten years, the alternatives two and three cannot be recommended. Furthermore, the set-up costs and additional costs are

32 c.f. (Götze, Northcott & Schuster, 2018) p. 50-52

affecting every variant. The total investment calculation can be seen in the appendix 8.4.

Table 6-3: Amortisation of investment costs

Investment costs (€)	**Alternative 1** **FARO DMVS**	**Alternative 2** **Creaform Metra Scan-R**	**Alternative 3** **GOM ATOS ScanBox**
Measurement System	*85,000*	*179,000*	*160,000*
Automatization components (Robot, Turning system)	*105,000*	*140,000*	*190,000*
Adaption of Programs	*75,000*	*75,000*	*75,000*
Set up costs	*15,000*	*15,000*	*15,000*
Costs of additional departments/ Maintenance	*2,000*	*2,000*	*2,000*
Total Investment	***282,000***	***411,000***	***442,000***
Amortisation in years	***4.9***	***7.4***	***8.1***

6.3 Productivity increase

With the total time saving of 339.6 hours the effect of producing more parts in the same amount of time can be calculated. The equation of productivity in economic systems is based on the total number of manufactured products as output divided by the input that is necessary to produce the output.[33] The output consists of the yearly product orders according to the manufacturing data for the FMS (6-5). In order to calculate the productivity increase, the required manufacturing time is compared with the reduced time due measurement saving.

$$Productivity = p = \frac{Output\ volume}{required\ input} = \frac{work\ orders}{production\ time} \qquad \text{Equa. (6-6)}$$

$$p_{old} = \frac{4615\ work\ orders}{16{,}411\ h} = 0.281\ orders/h \qquad \text{Equa. (6-7)}$$

$$p_{new} = \frac{4615\ work\ orders}{(16{,}411 - 340)\ h} = 0.287\ orders/h \qquad \text{Equa. (6-8)}$$

$$\eta = 1 - \frac{p_{old}}{p_{new}} = 0{,}0201\ \approx 2\ \% \qquad \text{Equa. (6-9)}$$

[33] (Usubamatov, 2018) p. 3

The comparison between the old (6-10) and the new process (6-11) shows a total productivity increase of two per cent (6-12). This results in additional 95 work orders that can be manufactured in the same production time of 16,411 hours.

The financial analysis of the measurement investment provides a clear evidence of the cost savings achieved. Due to high costs of the measurement systems, not all variants are profitable and suitable for the productivity increase of two per cent. Nevertheless, a cross-departmental workforce for the automation system, combined with an effective measurement tool, leads to an economic successful system.

7. Conclusion

In order to increase the productivity of a flexible manufacturing system, the externalisation of measurement procedures is necessary to shorten the manufacturing time. Therefore, the initial program cycles of the touch-probe tool must be removed from the machine. The application of optical measurement systems significantly generates more information in less time than a tactile specimen is able to. The accuracy of highly sensitive coordinate-measuring machines is not required for raw parts. In addition, an automated system with an optical measurement system is more suitable because of its lightweight properties. Not all of these are capable of working independently of industrial conditions such as varying light. The price, in relation to the system properties is also a relevant criterion for an investment decision. Based on the results of this thesis, an optical measurement cell inside the pallet storage is recommended to ensure an increase of productivity. With the technology of a dynamically working light-sheet laser instrument and the knowledge of the automation department of the company, an economically successful solution can be implemented.

Summary

The approach of measurement procedure externalisation starts by an investigation of the work-pieces produced. Due to the procedure of casting, not only material defects inside the part but also geometrical deviations of the part itself lead to downtime of the manufacturing machines.

Furthermore, the manufacturing process of the machine has been analysed with a closer look taken at the measuring cycle of the radio transmission touch-probe in use. The function of the probe is to measure and reference the workpiece in the machining space. During this time, no value is added to the part. The analysis of unproductive times shows that an amount of 268 hours per year are needed just for initial measurement of the raw parts in the machines. Together with the downtimes caused by casting deviations, a total of 340 hours productive time could be saved every year. This time could be used for producing additional work-pieces that are currently outsourced due to unavailable production resources.

To fulfil the criteria of external measurement, the process requires implementation into the existing system. The workpieces are clamped in set-up stations on a machine pallet and then moved into a pallet storage before being transferred to the manufacturing machines. This defines the limits for a future external measurement system. The new process shows the implementation of a separate cell inside the pallet storage. Due to the space restraints, the cell consists of a rotary table for fixation of the pallet and a robot-supported optical measurement system for scanning the entire part. The analysis of the generated digital point cloud takes place in a measuring software and compares the real with the designed geometry. In addition, an inspection report and a file including all essential manufacturing coordinates are generated and stored in the respective databases.

With the new process, the manufacturing of a part without dimensional deviation starts directly with a cutting cycle in the machine. This is only possible when all the essential data is collected beforehand.

References

Götze, Northcott & Schuster. (2018). *Investment Appraisal - Methods and Models.* Berlin: Springer.

Allweyer, T. (2015). *BPMN 2.0 - Business Process Model and Notation - Einführung in den Standard für die Geschäftsprozessmodellierung.* Norderstedt: BOD- Books on Demand.

ASTM E494-15. (2015). Standard Practice for Measuring Ultrasonic Velocity in Materials. Pennsylvania: ASTM International.

Atkinson, K. (1996). *Close Range Photogrametry and Machine Vision.* Latheronwheel, UK: Whittles Publishing.

Campbell, J. (2015). *Casting Handbook - Metal Casting Processes, Metallurgy, Techniques and Design.* Birmingham, UK: Butterworth-Heinemann.

Chiarini, A. (2013). *Lean Organization: from the Tools of the Toyota Production System to Lean Office.* Milan: Springer- Verlag Italia.

CREAFORM. (2019, 10 21). *Datasheet Metra SCAN 3D*. Retrieved from https://www.creaform3d.com/de/messtechnik/optische-cmm-scanner-metrascan-3d

Daniel, S. (2015). *Finite Element Mesh Generation.* Boca Raton, USA: CRC Press.

DIN 55201-1. (1985, 09). Machine tools; pallets for machine tools, nominal sizes up to 800 mm; form A. Frankfurt, Germany: Beuth.

DIN 8580. (2003). *Manufacturing processes - Terms and definitions, division.* Berlin: Beuth .

DIN EN 1563. (2019/04). *Founding - Spheroidal graphite cast irons.* Berlin: Beuth.

EN ISO 10204. (2005). Metallic products - Types of inspection documents. Berlin: Beuth Verlag.

EN ISO 10360-1. (2003). *Geometrical Product Specifications (GPS)- Acceptance and reverification tests for coordinate measuring machines - Part 1.* Berlin: Beuth Verlag.

EN ISO 6506-1. (2015). Metallic materials- Brinell hardness test- Part 1. Berling: Beuth Verlag.

EN ISO 6892-1. (2017). Metallic materials- Tensile testing - Part 1: Method of test ant ambient temperature. Berlin: Beuth Verlag.

ENGEL. (2019, 11 01). *Datasheet -Easix Robot*. Retrieved from https://www.engelglobal.com/en/uk/products/automation/articulated-robot-easix.html

FARO. (2019, 10 21). *Datasheet DMVS*. Retrieved from https://early-adopter.faro.com/ea-products/

Gebr. HELLER Maschinenfabrik GmbH. (2019, 09 11). *4-Axis Machining Centres H*. Retrieved from https://uk.heller.biz/products/4-axis-machining-centres-h/?no_cache=1

Gopalakrishnan, S. (2011). *Materials Management - An Integrated Approach* (3. ed.). New Delhi: PHI Learning Private Limited.

Hocken, R. (2012). *Coordinate Measuring Machines and Systems.* Boca Raton, FL, USA: CRC Press.

ISO 2859. (2014). Sampling procedures for inspection by attributes- Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot by lot inspection. Berlin: Beuth Verlag.

ISO 8062. (2007). Geometrical product specifications- Dimensional and geometrical tolerances for moulded parts. Berlin: Beuth Verlag.

Keferstein, C. (2015). *Fertigungsmesstechnik - Praxisorientierte Grundlagen, moderne Messverfahren.* Wiesbaden, Germany: Springer Vieweg.

Kief/Roschiwal. (2017). *CNC - Handbuch.* München: Carl Hanser Verlag.

Luhmann, T., Robson, S., Kyle, S., & Boehm, J. (2014). *Close-Range Photogrammetry and 3D Imaging.* Berlin: De Gruyter .

Lynch, M. (1995). Managing Computer Numerical Control Operations. Michigan: Society of Manufacturing Engineers.

Perreault, D. (2019, 10 22). *3dscanningservices*. Retrieved from http://3dscanningservices.net/blog/

Renishaw. (2014, 10 04). *Technical Specifications: Probing systems for CNC machine tools.* Gloucestershire, UK: Renishaw PLC. Retrieved from https://www.renishaw.com/en/machine-tool-probes-and-software--6073

Schuth, M., & Buerakov, W. (2017). *Handbuch Optische Messtechnik: Praktische Anwendungen für Entwicklung, Versuch, Fertigung und Qualitätssicherung.* München: Carl Hanser Verlag.

Siemens AG. (2011, 09). SINUMERIK 840D sl Programming Manual - Measuring cycles. Nürnberg.

Usubamatov. (2018). *Productivity Theory for Industrial Engineering.* Boca Raton: CRC Press.

ZEISS. (2019, 10 21). *Datasheet COMET 6*. Retrieved from https://www.zeiss.co.uk/metrology/products/systems/optical-systems/3d-scanning/zeiss-comet-6.html

8. Appendix

8.1 Description of Measurement Cycle 978

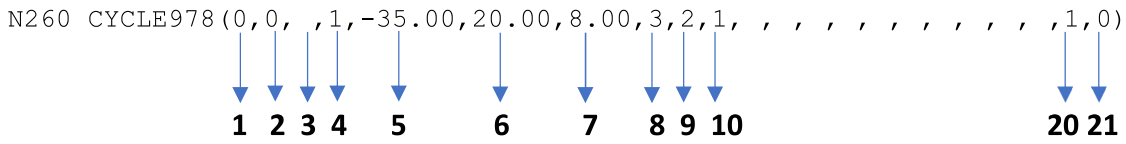


Figure 8-1: Measurement Cycle 978

Table 8-1: CYCLE 978 – Description
Source: SINUMERIK 840D – Programming Manual, p. 229

	Screen from parameters	Cycle parameter	Meaning:
1		S_MVAR	Contour element; 0 = Measure surface
2	Selection	S_KNUM	Correction of the Work offset; 0 = No correction
3	Selection	S_KNUM1	Correction in tool offset; 0 = Fine correction
4	icon + number	S_PRNUM	Number of the field of the probe parameter (field 1 out of 12)
5	X0	S_SETV	Setpoint (-35.00 mm)
6	DFA	S_FA	Measurement path (20.00 mm)
7	TSA	S_TSA	Safe area (8.00 mm)
8	X	S_MA	Number of measuring axis (3 = 3^{rd} axis of the plane (for G17 Z) Measurement in tool direction
9		S_MD	Measuring direction of the measuring axis (2= negative measuring direction)
10	Measurements	S_NMSP	Number of measurements at the same location (one measurement)
11	TR	S_TNAME	Tool name
12	DL	S_DLNUM	Setup additive offset DL-Number
13	TZL	S_TZL	Work offset
14	DIF	S_TDIF	Dimensional difference check
15	TUL	S_TUL	Upper tolerance limit
16	TLL	S_TILL	Lower tolerance limit
17	TMV	S_TMV	Offset range for averaging
18	FW	S_K	Weighting factor for averaging
19	EVN	S_EVNUM	Number of the empirical value memory
20		S_MVBIT	Reserved
21		_DMODE	Display mode; (1 = G17 only active in the cycle

22	_AMODE	Alternative mode; (0 = No)

8.2 Measurement System Benefit Analysis

Table 8-2: Measurement System Benefit Analysis - 1/2

			FARO Cobalt Array Imager 9MP		**FARO DMVS**		**HEXAGON WLS400A**		**HEXAGON q FLASH-A**		**Leica Absolute Scanner LAS**	
	Criteria	Weighting %										
1	Independent of reflections & light conditions	14,39	3	0,43	6	0,86	3	0,43	3	0,43	6	0,86
2	Suitable for industrial use	5,30	5	0,27	6	0,32	4	0,21	4	0,21	5	0,27
3	Ability for robotic mounting	4,55	6	0,27	6	0,27	6	0,27	6	0,27	6	0,27
4	Dynamic movement during measuring	9,09	0	0,00	6	0,55	0	0,00	0	0,00	6	0,55
5	Integration ability	5,30	3	0,16	5	0,27	4	0,21	4	0,21	5	0,27
6	Expenses	12,12	4	0,48	6	0,73	2	0,24	3	0,36	1	0,12
7	Accuracy	12,88	5	0,64	2	0,26	5	0,64	6	0,77	4	0,52
8	Measurement points	7,58	6	0,45	2	0,15	6	0,45	6	0,45	1	0,08
9	Measurement distance	6,82	4	0,27	4	0,27	6	0,41	4	0,27	1	0,07
10	Field of View	5,30	3	0,16	4	0,21	6	0,32	4	0,21	2	0,11
11	Weight of Measurement Head	8,33	2	0,17	5	0,42	1	0,08	1	0,08	1	0,08
12	Free Software use	8,33	1	0,08	5	0,42	1	0,08	1	0,08	5	0,42
	Total	100	**42,00**	**3,39**	**57,00**	**4,72**	**44**	**3,36**	**42**	**3,37**	**43**	**3,60**
			Ful-filment	Utility value	Ful-filment	Utility value	Ful-filment	Utility value	Ful-filment	Utility value	Ful-filment	Utility value
	Ranking		7		1		9		8		5	

The degree of fulfilment is graded in a range from zero (not fulfilled) to the six (totally fulfilled).

Table 8-3: Measurement System Benefit Analysis- 2/2

	Criteria	Weighting %	ZEISS T SCAN		ZEISS Comet 8M		CREAFOMR Metra SCAN 3D-R		GOM Atos 5	
1	Independent of reflections, light conditions	14,39	6	0,86	3	0,43	6	0,86	3	0,43
2	Suitable for industrial use	5,30	4	0,21	3	0,16	5	0,27	6	0,32
3	Ability for robotic mounting	4,55	6	0,27	6	0,27	6	0,27	6	0,27
4	Dynamic movement during measuring	9,09	6	0,55	0	0,00	6	0,55	0	0,00
5	Integration ability	5,30	4	0,21	5	0,27	3	0,16	2	0,11
6	Expenses	12,12	4	0,48	4	0,48	4	0,48	3	0,36
7	Accuracy	12,88	5	0,64	4	0,52	4	0,52	6	0,77
8	Measurement points	7,58	1	0,08	5	0,38	2	0,15	6	0,45
9	Measurement distance	6,82	1	0,07	6	0,41	3	0,20	5	0,34
10	Field of View	5,30	2	0,11	5	0,27	3	0,16	4	0,21
11	Weight of Measurement Head	8,33	6	0,50	3	0,25	4	0,33	1	0,08
12	Free Software use	8,33	5	0,42	2	0,17	5	0,42	1	0,08
	Total	100	**50**	**4,40**	**46**	**3,60**	**51**	**4,37**	**43**	**3,44**
			Fulfilment	Utility value	Fulfilment	Utility value	Fulfilment	Utility value	Fulfilment	Utility value
		Ranking	3		4		2		6	

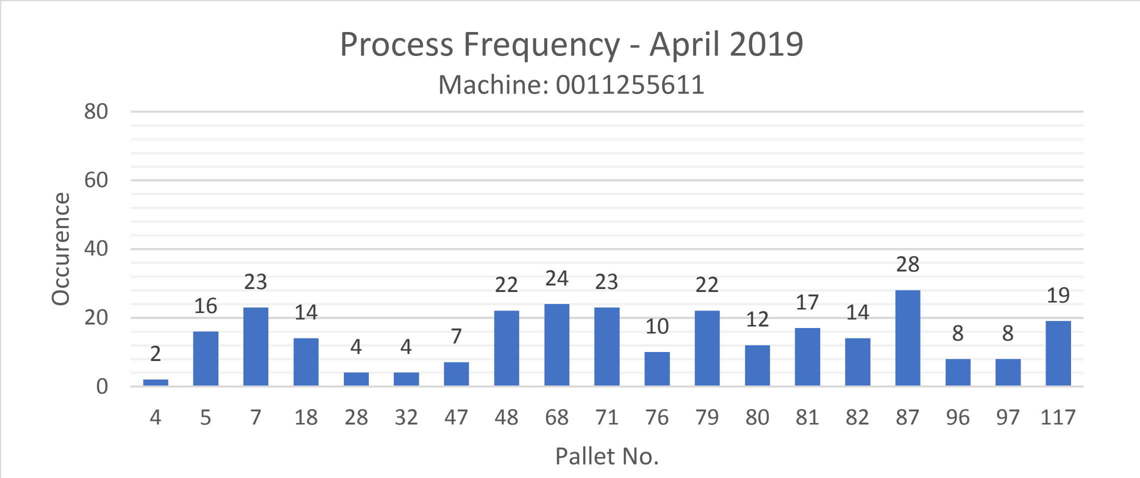
Table 8-4: Result of the Measurement System Benefit Analysis

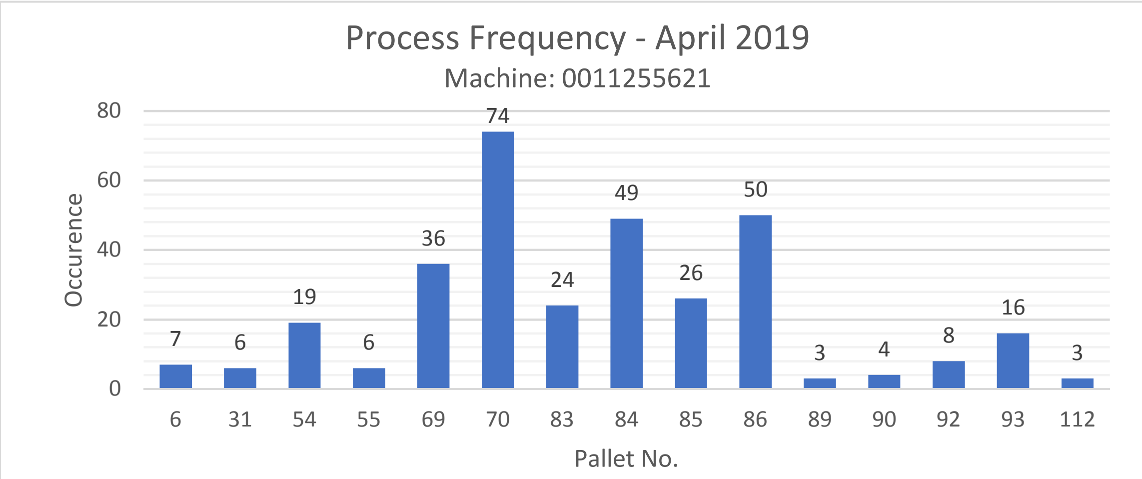
Ranking	Measurement System	Fulfilment	Utility value
1	FARO DMVS	55	4,63
2	CREAFOMR Metra SCAN 3D-R	52	4,45
3	ZEISS T SCAN	50	4,4
4	ZEISS Comet 8M	46	3,6
5	Leica Absolute Scanner LAS	43	3,5
6	GOM Atos 5	43	3,44
7	FARO Cobalt Array Imager 9MP	42	3,39
8	HEXAGON qFLASH-A	42	3,37
9	HEXAGON WLS400A	44	3,36

8.3 Integrated Process Monitoring Data

8.3.1 Measurement Time Analysis

The process frequency shows the distribution of the different pallets on the three machines, that are used for manufacturing.





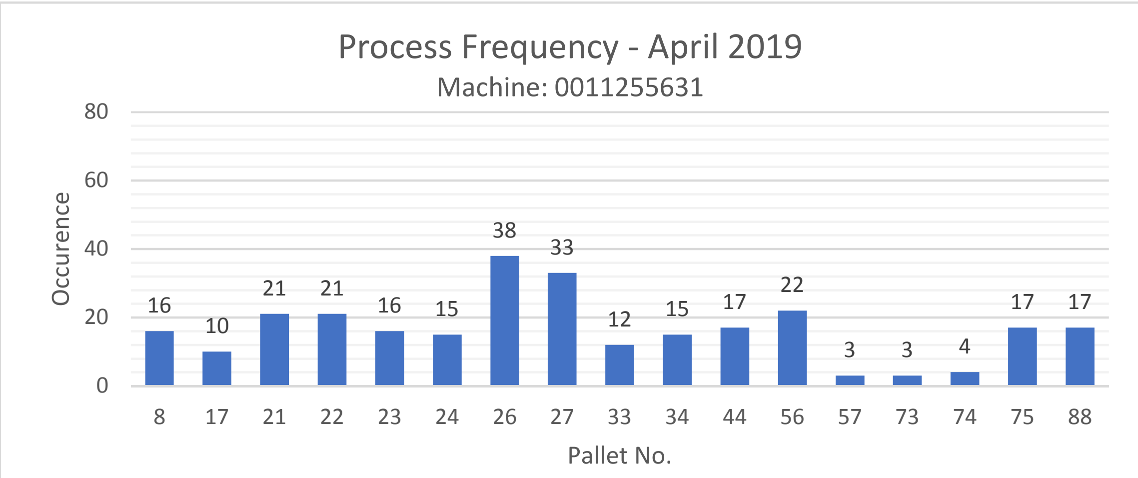


Figure 8-2: Process Frequency - April 2019

The duration of the first measuring cycle during processing is listed over each pallet in use.

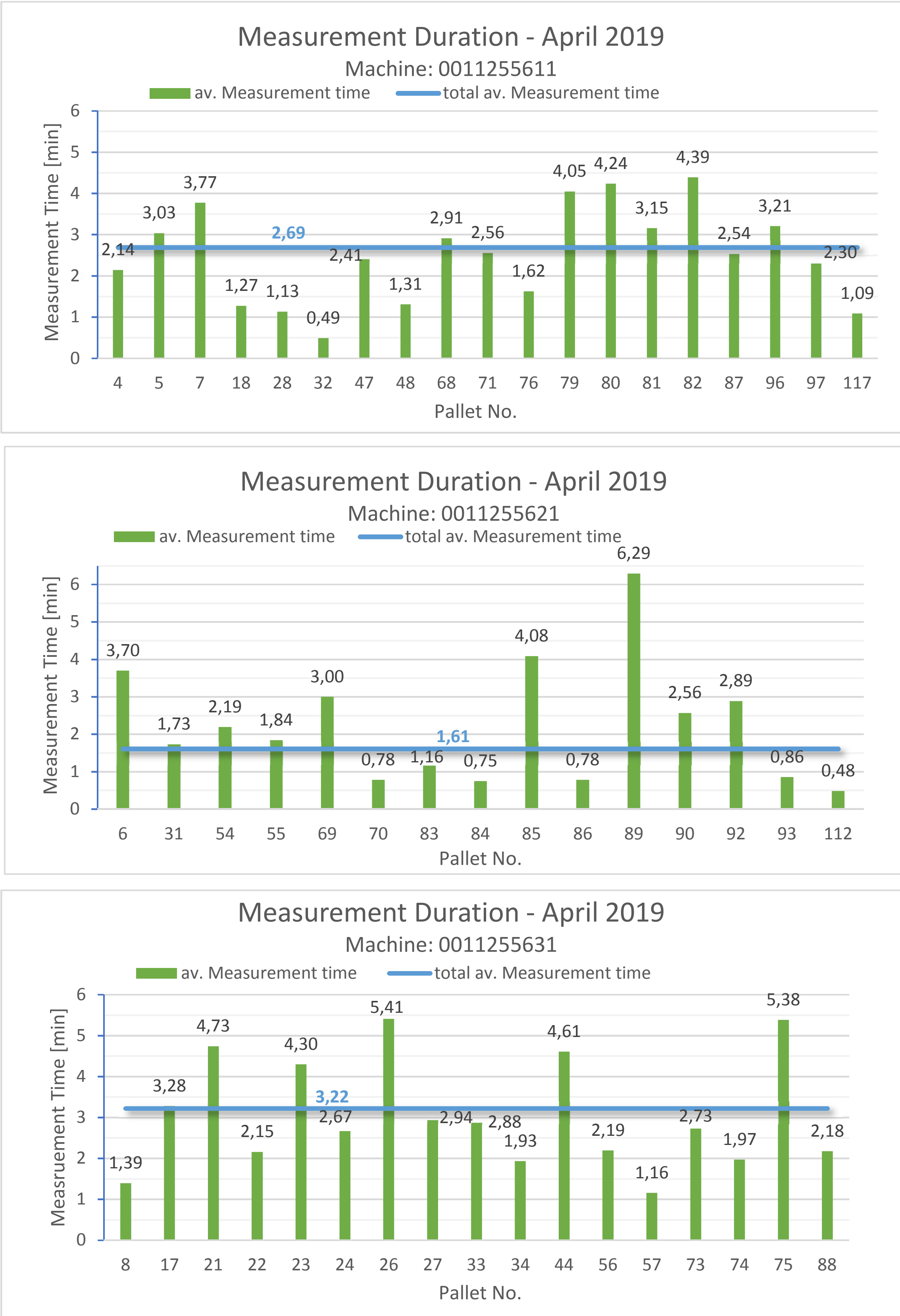


Figure 8-3: Measurement Duration - April 2019

8.3.2 Downtime analysis

The productivity of any manufacturing machine heavily depends on its availability. Due to the high costs of interruptions, planned downtime for example will be only done in defined intervals. Typical periods are the company vacation or before a production switch. Examples for planned downtime are service and maintenance work. The production structure and planning can react to this situation long before the machine will be down. Another example is the setup time. The near end of a production run indicates that a new setup will be needed for the next production. Unplanned downtime, on the other hand, severely affects the production line. If a machine crash or a malfunction of engine, gearbox, tools occurs, the production losses can lead to an amount of costly consequences. Therefore, a preventive maintenance during the whole production can reduce the amount of unplanned downtime. For instance, by cleaning and lubricating the machine or changing filters in appropriate intervals can counteract the unplanned downtime.[34] Despite, the corrective maintenance must be performed as soon as it is required.

To gather and analyse the production data, centralized in a SAP ERP system, a MS Excel Analysis sheet is used with the title “Analyse – Malfunction report”. The downtime for the flexible manufacturing system number 2556 amounts to nearly 113 hours during the period of April 2019 as shown in Table 8-5. Machine Malfunction with over 96 per cent come to the highest amount. A planned system update on the FASTEMS multi-level-storage resulted in a complete stop. All three manufacturing machines add up to 78 hours of electrical malfunction. Other machine malfunctions are based on failures of mechanic, hydraulic, computer or service and maintenance and come to more than 10 hours. The defects on material and part geometry are interesting for the analysis. Less than two hours give the information, that this did happen not very often during a month. A closer look on the defects shows, that only material defects like cavities occurred. The third failure group publishes the tool failures with more than two hours. Any staff shortage or various waiting times were not detected in this period. Therefore, a longer period is chosen for more details.

[34] see. (Lynch, 1995) p. 356

Table 8-5: Downtime- April 2019, FMS 2556

Failure Group	Status Message	Duration	Ratio
Total Downtime		**112.92 h**	**100.0%**
1 Machine Malfunction		**109.12 h**	**96.6%**
21	Electrical malfunction	97.31 h	86.2%
22	Mechanical, hydraulic failure	7.66 h	6.8%
23	Computer malfunction	0.61 h	0.5%
24	Service/Maintenance	3.54 h	3.1%
2 Program Failure		**1.54 h**	**1.4%**
31	NC Program error	0.05 h	0.0%
32	Material defect / part geometry error	1.49 h	1.3%
3 Tool failure		**2.26 h**	**2.0%**
46	Tool defect	2.00 h	1.8%
48	Tool service	0.26 h	0.2%
4 Staff shortage		**0.00 h**	**0.0%**
5 Various Waiting Times		**0.00 h**	**0.0%**

Long term Downtime

The period from business year 2019 provides a better overview of the yearly downtime. Similar to the monthly analyse, the SAP ERP data is analysed with the use of the “Analyse – Malfunction report” – sheet. Table 8-6 shows that, during the first of April 2018 and the 31st of March 2019, 1130 hours are caused by downtime. The machine malfunctions took the highest amount with less than 90 per cent as it is imaged in Figure 8-4. The share of fifty per cent of the service and maintenance occurred mostly to the standstill during Christmas vacation. Less than thirty hours per year ran up to program failures. Most of them due to shrinkage cavity defects. Tool failures occurred mostly by defects of tool breaks. A small amount is generated by various waiting times and special standstills.

Table 8-6: Downtime 2019, FMS 2556

Failure Group	Status Message	Duration	Ratio
Total Downtime 2019		**1 128.58 h**	**100%**
1 Machine Malfunction		**992.24 h**	**87,9%**
	21- Electrical malfunction	376.29 h	33,3%
	22- Mechanical, hydraulic failure	43.50 h	3,9%
	23- Computer malfunction	1.18 h	0,1%
	24- Service/Maintenance	571.27 h	50,6%
2 Program Failure		**28.48 h**	**2,5%**
	31- NC Program error	0.37 h	0,0%
	34- Material defect / part geometry error	28.11 h	2,5%
3 Tool failure		**78.79 h**	**7,0%**
	41- Tool not prepared	0.37 h	0,0%
	42- Tool unsuitable	0.25 h	0,0%
	43- Setup not useable	0.45 h	0,0%
	46- Tool defect	71.28 h	6,3%
	48- Tool service	6.45 h	0,6%
4 Staff Shortage		**0.00 h**	0,0%
5 Various Waiting Times		**4.98 h**	**0,4%**
	53- Probe calibration	0.49 h	0,0%
	56- Zero -Point inspection	2.32 h	0,2%
	71- Transport process malfunction	1.38h	0,1%
	88- Logistic	0.79h	0,1%
Special Standstill		**24.09h**	**2,1%**
	Machine offline	24.09h	2,1%

To sum up, the machine malfunction is responsible for nearly 90 per cent of the non-productive time. Besides, the tool failures add up to only seven per cent. Although, program failure and the various waiting times did not occur not very often. It must be considered, that a standstill less than three minutes will not be automatically detected. This company agreement prevents the productivity-linked worker from underpayment. Moreover, the status message of the incident receives only information, if the case is typed in correctly.

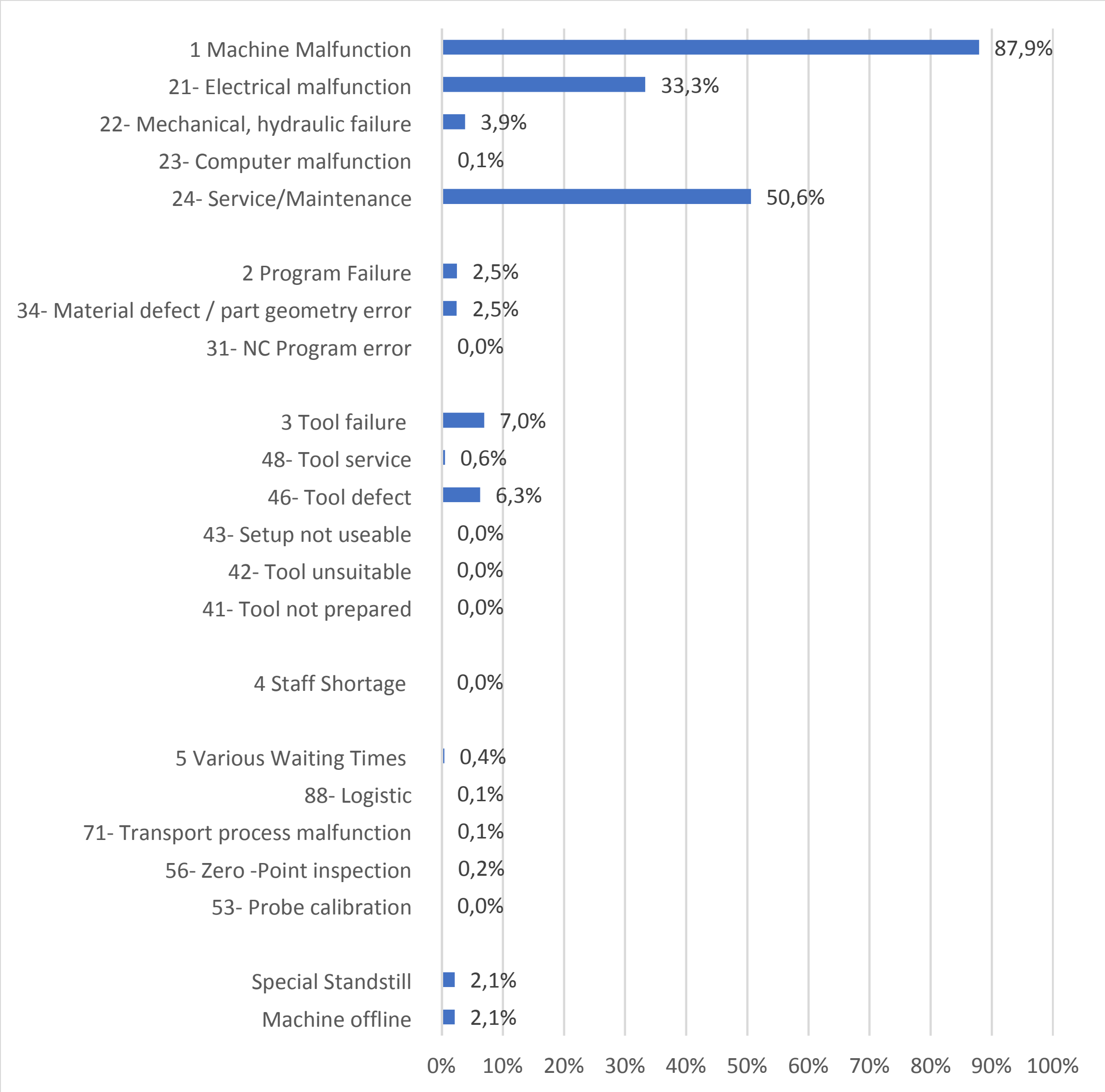


Figure 8-4: Downtime 2019, FMS 2556

8.4 Investment Calculation

Table 8-7: Investment calculation - Alternative 1

Alternative 1 - FARO DMVS								
Required rate of return:	*Interest rate: 4.25%*		*Inflation rate: 2%*					
End of Year (EOY)	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Cash Out Flow (COF)								
Initial investment	*-265,000.00*							
Set up costs	*-15,000.00*							
Costs of additional departments	*-2,000.00*	*-2,040.00*	*-2,080.80*	*-2,122.42*	*-2,164.86*	*-2,208.16*	*-2,252.32*	*-2,297.37*
Total COF	***-282,000.00***	***-2,040.00***	***-2,080.80***	***-2,122.42***	***-2,164.86***	***-2,208.16***	***-2,252.32***	***-2,297.37***
Cash In Flow (CIF)								
Saving costs - external labour	*€ 53,996.40*	*55,076.33*	*56,177.85*	*57,301.41*	*58,447.44*	*59,616.39*	*60,808.72*	*62,024.89*
Rejection costs	*€ 7,252.00*	*7,397.04*	*7,544.98*	*7,695.88*	*7,849.80*	*8,006.79*	*8,166.93*	*8,330.27*
Total CIF	***61,248.40***	***62,473.37***	***63,722.84***	***64,997.29***	***66,297.24***	***67,623.18***	***68,975.65***	***70,355.16***
(CIF - COF)								
Cash Flow	*-220,751.60*	*60,433.37*	*61,642.04*	*62,874.88*	*64,132.37*	*65,415.02*	*66,723.32*	*68,057.79*
Discounted difference	*-220,751.60*	*57,969.66*	*56,718.51*	*55,494.37*	*54,296.65*	*53,124.78*	*51,978.20*	*50,856.37*
Net Present Value (NPV)	***-220,751.60***	***-162,781.94***	***-106,063.43***	***-50,569.06***	***3,727.60***	***56,852.38***	***108,830.59***	***159,686.96***
Amortisation in years:				***4.9***				

Table 8-8: Investment calculation - Alternative 2

Alternative 2 - Creaform Metra Scan-R								
Required rate of return:	*Interest rate: 4.25%*		*Inflation rate: 2%*					
End of Year (EOY)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Cash Out Flow (COF)								
Initial investment	-394,000.00							
Set up costs	-15,000.00							
Costs of additional departments	-2,000.00	-2,040.00	-2,080.80	-2,122.42	-2,164.86	-2,208.16	-2,252.32	-2,297.37
Total COF	**-411,000.00**	**-2,040.00**	**-2,080.80**	**-2,122.42**	**-2,164.86**	**-2,208.16**	**-2,252.32**	**-2,297.37**
Cash In Flow (CIF)								
Saving costs - external labour	53,996.40	55,076.33	56,177.85	57,301.41	58,447.44	59,616.39	60,808.72	62,024.89
Rejection costs	7,252.00	7,397.04	7,544.98	7,695.88	7,849.80	8,006.79	8,166.93	8,330.27
Total CIF	**61,248.40**	**62,473.37**	**63,722.84**	**64,997.29**	**66,297.24**	**67,623.18**	**68,975.65**	**70,355.16**
(CIF - COF)								
Cash Flow	**-349,751.60**	**60,433.37**	**61,642.04**	**62,874.88**	**64,132.37**	**65,415.02**	**66,723.32**	**68,057.79**
Discounted difference	-349,751.60	57,969.66	56,718.51	55,494.37	54,296.65	53,124.78	51,978.20	50,856.37
Net Present Value (NPV)	**-349,751.60**	**-291,781.94**	**-235,063.43**	**-179,569.06**	**-125,272.40**	**-72,147.62**	**-20,169.41**	**30,686.96**
Amortisation in years:							**7,4**	

Table 8-9: Investment calculation - Alternative 3

Alternative 3 - GOM ATOS Scan Box								
Required rate of return:	*Interest rate: 4.25%*		*Inflation rate: 2%*					
End of Year (EOY)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Cash Out Flow (COF)								
Initial investment	-425,000.00							
Set up costs	-15,000.00							
Costs of additional departments	-2,000.00	-2,040.00	-2,080.80	-2,122.42	-2,164.86	-2,208.16	-2,252.32	-2,297.37
Total COF	**-442,000.00**	**-2,040.00**	**-2,080.80**	**-2,122.42**	**-2,164.86**	**-2,208.16**	**-2,252.32**	**-2,297.37**
Cash In Flow (CIF)								
Saving costs - external labour	€ 53,996.40	55,076.33	56,177.85	57,301.41	58,447.44	59,616.39	60,808.72	62,024.89
Rejection costs	€ 7,252.00	7,397.04	7,544.98	7,695.88	7,849.80	8,006.79	8,166.93	8,330.27
Total CIF	**61,248.40**	**62,473.37**	**63,722.84**	**64,997.29**	**66,297.24**	**67,623.18**	**68,975.65**	**70,355.16**
(CIF - COF)								
Cash Flow	**-380,751.60**	**60,433.37**	**61,642.04**	**62,874.88**	**64,132.37**	**65,415.02**	**66,723.32**	**68,057.79**
Discounted difference	-380,751.60	57,969.66	56,718.51	55,494.37	54,296.65	53,124.78	51,978.20	50,856.37
Net Present Value (NPV)	**-380,751.60**	**-322,781.94**	**-266,063.43**	**-210,569.06**	**-156,272.40**	**-103,147.62**	**-51,169.41**	**-313.04**
Amortisation in years:								**not amortised after eight years**