



SPECIFICATION AND DESIGN OF A MEASURING SYSTEM FOR SPRING SYSTEMS IN COLD FORM TOOLING António

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ISEP – School of Engineering, Polytechnic of Porto

Mechanical Engineering Department



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Dissertation presented to ISEP – School of Engineering to fulfil the requirements necessary to obtain a Master's degree in Mechanical Engineering, carried out under the guidance of Doctor Raul Duarte Salgueiral Gomes Campilho and Doctor Francisco José Gomes da Silva, Adjunct Professors at ISEP – School of Engineering, Polytechnic of Porto.

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Nanos gigantum humeris insidentes

KEYWORDS

Springs systems, measuring system, tool dies, tests on springs systems, cold forming.

ABSTRACT

Spring systems are components on which science rarely focuses. Their universality, operating dynamics and low acquisition costs are factors that delay research. The fact that science does not document and present results on this topic forces and encourages companies to develop their own methods, research and results.

Measuring equipment represents a key element for the continuous improvement of a process with actual performance data of process components. An accurate performance indication of a component makes a significant difference in the final quality of the product. In this thesis, the principle of measurement for spring systems as well as the respective machine design are presented.

Practical cases related to metal forming processes were analysed to define machine requirements. It was decided to aim for a machine working the dynamic regime, with testing force capacity up to 30 kN and measuring displacement until 10 mm. A positioning system for tool die motion was also analysed, without compromising the required accuracy.

This dissertation reflects a solid basis for the design of the machine, since practical cases were analysed to adjust and validate the system face the real needs. A group of experts was also heard to ensure that the system complied with the requirements needed in the field. The results allow to guarantee a good process control for a type of mechanical system on which the scientific documentation is very limited.

PALAVRAS CHAVE

Sistemas de molas, Sistemas de medição, Ferramentas de conformação, Sistemas de teste de molas, Deformação a frio.

RESUMO

Os sistemas de molas são componentes nos quais a ciência raramente se concentra. A sua universalidade, dinâmica operacional e baixo custo de aquisição, são fatores que desmotivam a investigação em torno deste assunto. O facto de a ciência não documentar e apresentar resultados sobre esse tópico, força e incentiva as empresas a desenvolverem seus próprios métodos, pesquisas e resultados.

Os equipamentos de medição representam um elemento-chave para a melhoria contínua de um processo, com dados reais de desempenho dos componentes do processo. Uma indicação precisa do desempenho de um componente faz toda a diferença na qualidade final do produto. Nesta dissertação, são apresentados o princípio de medição para sistemas de molas, bem como o respectivo projeto de máquinas.

Foram analisados alguns casos práticos relacionados com processos de conformação de metais, para definir as características necessárias para o equipamento. Estabeleceu-se como requisitos uma máquina que trabalhasse em regime dinâmico, com capacidade de teste de força até 30 kN e admitindo deslocamentos da mola até 10 mm. Também foi analisado um sistema de posicionamento para o movimento das ferramentas, sem comprometer a precisão necessária.

O documento reflete uma base sólida para o projeto da máquina, uma vez que foram analisados casos práticos para ajustar e validar o sistema perante as necessidades reais. Foi ainda ouvido um grupo de especialistas neste assunto, para garantir que o sistema cumpria com os requisitos necessários na prática. Os resultados permitem garantir um bom controlo de processo para um tipo de sistema mecânico sobre o qual a documentação científica é muito limitada.

LIST OF SYMBOLS AND ABBREVIATIONS

List of abbreviations

3D	Three Dimensional
AFM	Atomic Force Microscopy
ASTM	American Society for Testing and Materials
BS	British Standards
CAD	Computer Assisted Design
CNC	Computer Numerical Control
Cr	Chromium
DIN	Deutsches Institut für Normung
FIB	Focused Ion Beam
FEM	Finite Element Method
FMEA	Failure Mode Effect Analysis
IEEE	Institute of Electrical and Electronics Engineers
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light-Emitting Diode
LFM	Lateral Force Microscopy
LVDT	Linear Variable Differential Transformer
MEM	Micromachine Electro Mechanical Systems
M.O.	<i>Morfologisch overzicht</i>

NDT	Non-Destructive Test
PLC	Programmable Logic Controllers
SEM	Scanning Electron Microscopy
ROI	Return of Investment
Si	Silicon
SPM	Strokes per minute
SPS	Strokes per second
TEM	Transmission Electron Microscopy
V	Vanadium
GR&R	Gage Repeatability and Reproducibility

List of units

Hz	Hertz
m	Meter
mA	MilliAmpere
mm	Millimetre
MPa	Mega Pascal
N	Newton
Pa	Pascal
rad	Radian
s	Second
W	Watt
μm	Micrometre

\$	Dollars
----	---------

°	Degree
---	--------

List of symbols

b	Distance between torque and force point
-----	---

C	Spring index
-----	--------------

Cl	Clearance
------	-----------

d	Wire or bar diameter
-----	----------------------

D	Diameter
-----	----------

D_i	Internal diameter
-------	-------------------

D_o	Outside diameter
-------	------------------

E	Modulus of elasticity
-----	-----------------------

F	Force
-----	-------

G	Modulus of elasticity in shear
-----	--------------------------------

h	Height
-----	--------

HL	High Limit
------	------------

K	Spring Rate
-----	-------------

K	Factor
-----	--------

k_f	Flow stress
-------	-------------

k_{fm}	Mean stability factor
----------	-----------------------

k_w	Deformation resistance
-------	------------------------

k_{wm}	Mean deformation resistance
----------	-----------------------------

L	Spring's length
-----	-----------------

L_f	Free length
L_s	Solid length
LL	Low Limit
M	Moment of force
MP	Mechanical power
N	Number of coils
O	Occurrence
p	Pitch
P	Force/Load
P_r	Relative pressure
P_x	Penetration
S	Severity
t	Thickness
T	Torque
U	Energy
V	Volume
W_{id}	Referenced deformation work
x	Physical position
δ	Linear Deflection/Slope range
ε	Relative deformation
η_f	Forming efficiency factor
Θ	Angular Deflection
σ	Normal stress

τ	Shear stress
ϕ	Deformation
%GR&R	Trust level of measurement

GLOSSARY OF TERMS

Active Coils	Coils that are affected by the load application
Angular relationship of ends	Relative position of the loops or hooks of extensive springs between each other
Buckling/Bending	Lateral or bowing deflection of compression springs when suffering compression. Related with slenderness ratio (L/D)
Close end	Section where the pitch is reduced, zone where the spring can be fixed, beginning and end zone for a spring
Close and ground end	Identical to close end with an ending difference, grounded structure to provide support for the spring
Close-wound	Adjacent coils touch each other
Cut-off	Value reference for the roughness of a surface, mechanical filter
Deflection	Wave of the spring when a load is applied or removed
Elastic limit	Allowed stress on a material without permanent stain
Endurance limit	Material's maximum stress to operate indefinitely (for a given minimum stress) without failure
Extrudates	Material obtain from extrusion
Free angle	Angle between edges of a spring when load is not applied on it.
Free length	Total length of the spring without forces being applied on it.
Hysteresis	Loss of mechanical energy during cyclical loading and unloading of a spring, capacity to restore all absorbed energy
Inactive coils	Coils that are not affected by the load application
Loops	Wire shapes at the end of the spring to provide force and attachment application

MATLAB	Software used to programme receiving data into mathematical functions or graphs.
Mean coil diameter	Outside wire diameter minus wire diameter, Inner diameter plus wire diameter
Modulus in shear or torsion	Stiffness coefficient used for extension and compression springs
Modulus in tension or bending	Stiffness factor used for torsion and flat springs
Open end, not ground	Constant pitch on each end the of coil at the end of a compression spring
Open end ground	Equal to " <i>Open end, not ground</i> " followed by a grinding operation at the spring's end
Permanent set	Plastic behaviour of a material, elastic recovery is not possible
Pitch	Number of coils per measurement unit, the distance between adjacent active coils
Rate	Load changes per unit of deflection
Slenderness ratio	Spring length per mean coil diameter
Spring index	Usual to helical springs. It variates according to the form of the spring
Strain	Relation between length variation and original length
Stress	Relation between force and a predetermined area
Stress range	Difference between the maximum and minimum operating stress
Squareness of end	Angle between the compression axis of the spring and a normal plane at the end of the spring.
Squareness under load	Equal to " <i>Squareness of end</i> " with the spring beneath load

Total number of coils Number of active coils plus the number of inactive coils

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INTRODUCTION

1 INTRODUCTION

1.1 Framework

Springs represent one of the oldest and more used components to be used in mechanical engineering applications. The fact that springs are constantly used in traction and compression, with energy absorption capabilities, makes them a key element for machine design. In order to improve these elements lifespan, it is important to understand and control the springs' behaviour over time.

Although the use of springs dates back to ancient times, these components still represent the main component with the ability to retain and accumulate energy. Moreover, springs are also known for high strength capacity, when subjected to in-service loads (concentrated forces and torsion).

In metal forming and tool die applications, helical and disc compression springs are typically used. Under this scope, the springs' mechanical properties and usage conditions are essential for the process, since the cutting and plastically deforming operations are highly dependent on the springs' conditions.

The use of measuring devices in general is largely increasing due to Industry 4.0, allowing having significant improvements in a work environment in which competition and knowledge increase daily. As a result, daily tasks in product fabrication are improved through quantitative and qualitative measuring processes, leading to a better final product quality.

1.2 Objectives

The objective of this thesis is to present a case study report of a force-displacement measuring system for spring systems used in cold forming tooling on a conceptual level. The scope of the measuring system is to evaluate and control critical spring system conditions. Critical spring systems are systems seen as important for the metal forming process. In order to accurately assess the spring systems' conditions, the measuring system should be able to reproduce as faithfully as possible the in-service working conditions of the springs.

1.3 Methodology

For the elaboration of the thesis, Philips proposed the following objectives:

1. Inventory of functional and technical requirements (for example: range of spring forces, range of measuring distances, range of tool dimensions);
2. Research on measuring and actuation principles and solutions;
3. Define/describe measuring cycle;
4. Develop concepts for a measuring system including human interface; take safety requirements into account;
5. Evaluate concepts using evaluation tools and propose best concept;
6. Define boundaries for measurement results of spring systems: when spring system is ok, or when it is not ok.

If the duration of the internship allows:

7. Create mechanical drawings of the measuring system and define requirements for a database.

Planning is a key element for every project, and a proper planning helps in obtaining the project's goals in a more efficient and fast manner. Lean Six Sigma is one of the methods that can be used to plan and control project stages and, thus, it was considered in this work. To better understand this method, information is presented in Appendix 1 regarding the considered tools.

The different project stages were planned using the Define-Identify-Design-Optimize and Validate (DIDOV) technique, whose high level overview is presented in Figure 1.

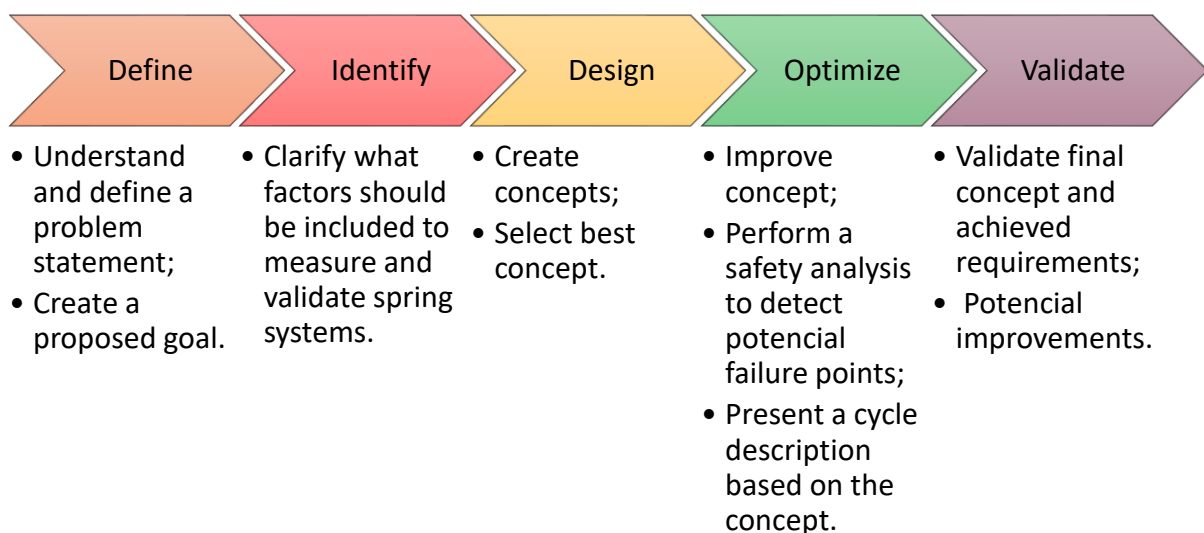


Figure 1 –DIDOV phases and tasks

1.4 Structure of the report

Chapter 1 (Introduction) presents, on a high level, the framework of the present work, objectives and methodology to achieve the proposed goals.

Chapter 2 (Background) presents an overview of different thesis-related subjects, which are considered relevant for the work being developed. The topics will support some of the principles used, and include cold form principles and elements, a general description on spring systems, as well as the measuring principles.

In Chapter 3 (Thesis development), the practical evaluation of solutions and a case study about the problem found in the company are presented. This chapter will report the company history and philosophy, the requirements descriptions for the measuring device, as well as concept's selection and measuring cycle description. Payback for the device was also analysed with a proposal for elements to use on a next project phase.

Chapter 4 (Conclusions and proposals of future works) presents a summary of all the conclusions gathered from the previous work. Some recommendations will be given to directly apply or to further investigate the topics approached during the elaboration of this report.

1.5 Welcoming company

This thesis was elaborated on the tutelage of Philips in the Netherlands and ISEP in Portugal. Eng. Albert van der Marel, Eng. Marcel Pol and Eng. Mark Kiewit assisted the elaboration of the study inside Philips during a period of seven months.

BACKGROUND

2 BACKGROUND

2.1 Cold forming

2.1.1 Principle

The processes related to the manufacturing are quite dissimilar and abundant (Table 1). As mentioned in DIN 8580 [1], manufacturing processes can be divided into six large groups: coating, modifying material property, primary shaping, material dividing, joining and forming.

Table 1 – Types of manufacturing processes (adapted from DIN 8580 classification [1])

Create cohesion	Preserve cohesion	Reduce cohesion	Increase cohesion
Shape changing			
	Metal forming	Cutting/Dividing	Joining
Primary shaping	Modifying property		Coating
	Rearrangement of material particles	Elimination of material particles	Addition of materials particles

Forming [2] is a mass holding process where the body changes the original shape. Bulk metal forming (Figure 2) and sheet metal forming (Figure 3) are two main groups of metal forming. Bulk metal forming works with higher volume to surface sections, while sheet metal uses near relations between volume and the material surface. Contrarily to bulk metal, a sheet form presents an initial thickness close to the final thickness. Some authors consider rolling of thin sheet, a sheet metal forming. However, since there is thickness variation, it will be considered a bulk metal process on this report.

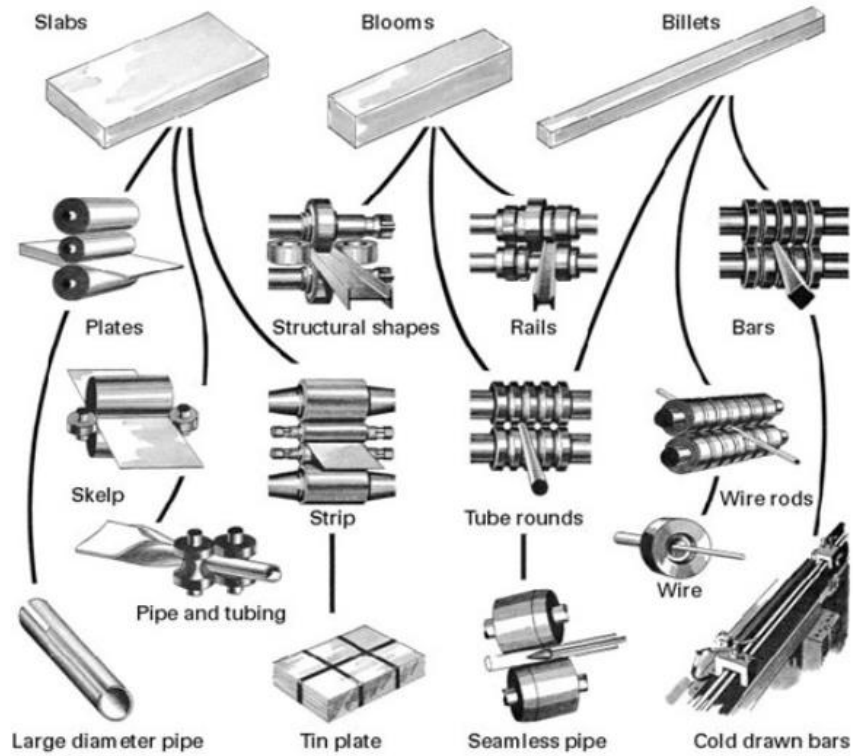


Figure 2 – Bulk metal forming processes [3].

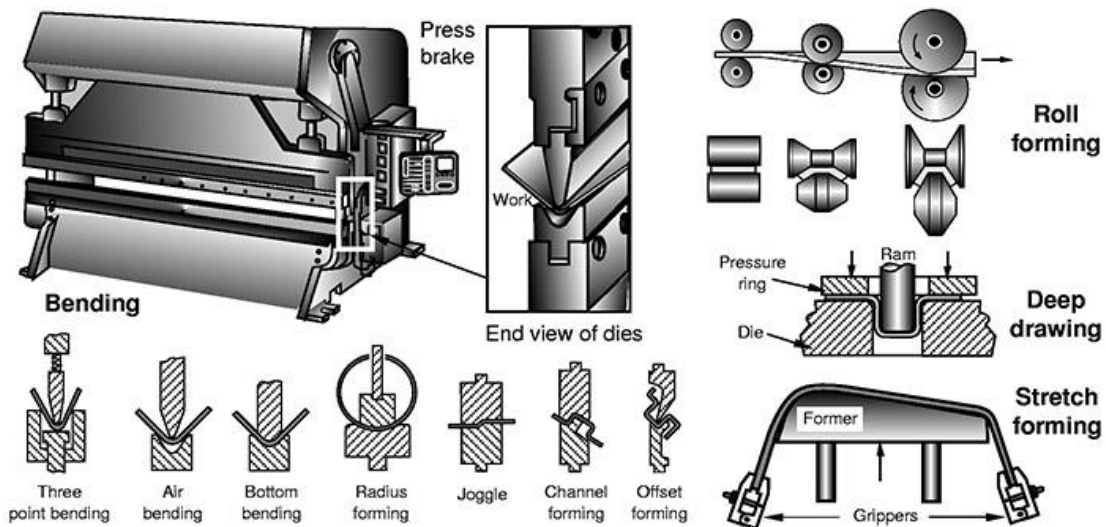


Figure 3 – Sheet metal forming processes [4].

Forming can also be divided into five large groups (Figure 4) according to the type of the loads used. According to this classification, forming can be separated in forming under compressive conditions, forming under compressive and tensile conditions, forming under tensile conditions, forming by bending and forming under shearing conditions.

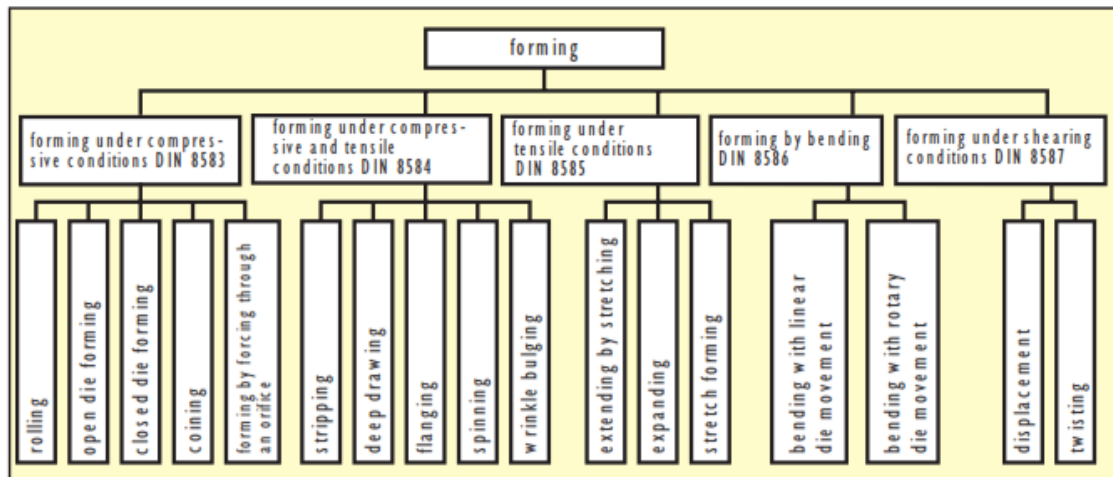


Figure 4 – Forming classification [5]

To assist a further analysis of each process variation, Appendix 2 was added.

Looking specifically to cold forming, cold forming is defined [6] as the process of forming new shapes to the material (typically metal alloys) keeping temperature near to room temperature. Under this transformation, is typical to obtain better properties, such as hardness and material strength of the transformed metal. This process is performed at high speeds and high pressures. The complexity of the process is related to the decreasing number of steps needed without loss of final product quality or loss of production capacity speed. Figure 5 shows the different stages of sheet transformation. Each step requires continuous analysis, to not only ensure the quality of the final product, but also to understand whether it is possible to combine steps, change the bending ratios, the thickness of the product between different stages and the conditions of the material surface, for example.

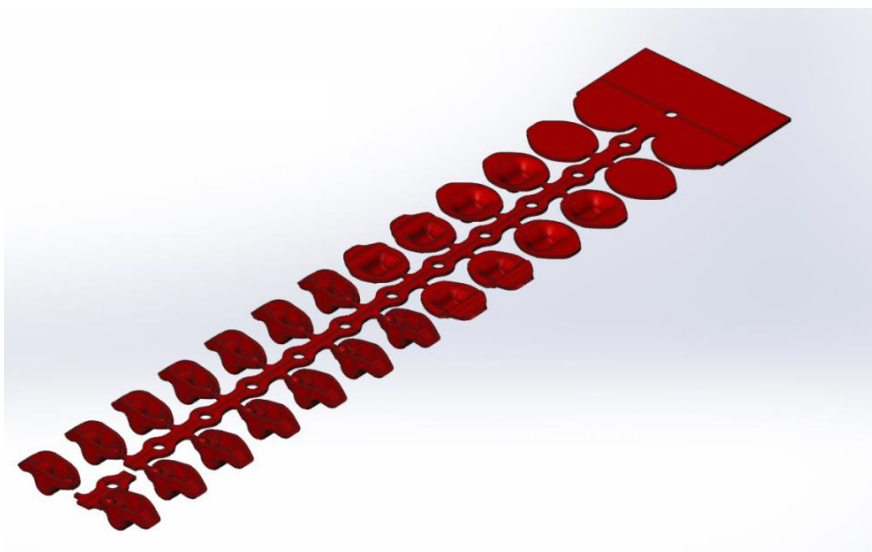


Figure 5 – Different phases of metal forming process[7]

2.1.2 Elements

Cold forming is essentially formed by three components:

- Presses;
- Tool dies;
- Product.

2.1.2.1 Press

Presses are the “body” for the cold forming process. Presses are usually designed to be universal and allocate different types of dies, even though is also possible to build presses for specific types of work applications.

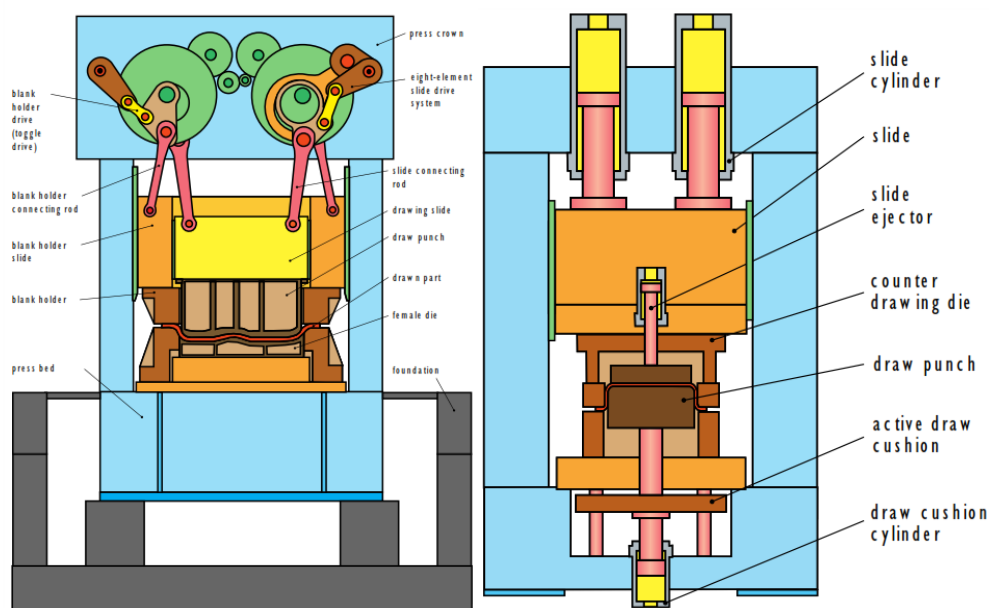


Figure 6 – Drawing examples of presses [5]

Figure 6 illustrates two different types of presses. An eccentric press presents circular wheels (rotational movement) to produce the necessary force, while hydraulic presses present actuation cylinders (linear movement) to produce the same procedure.

2.1.2.2 Tool dies

Tools (Figure 7) are another essential part of metal forming processes and operations. The word die can be used under two different meanings. The word can be used in a general way, which is referent to the entire press toll or can be used in a more specific method, where the word only is referent to the machined part to receive the blank, being the top part named punch.

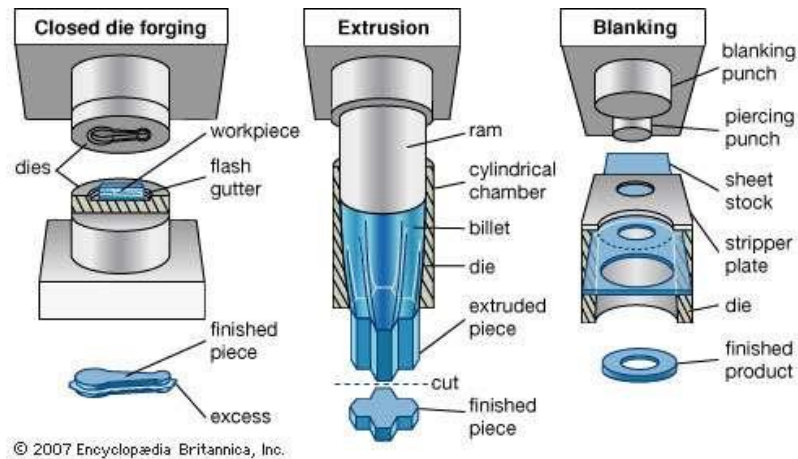


Figure 7 – Tool die [8]

The tools are assembled to the die set (Figure 8). The die set can be seen as the connection between the press and the tool. Using bolts, the edges of the tool are clamped to the press borders and using guideposts. The tolerances are set (four guideposts are normally the number used to ensure quality to the die) with the dependency between posts since if one is not correctly dimensioned, the tool may not be able to do a proper forming. This system helps to ensure quality as well as prevents material waste [9].

After the part drawing, the next step will study how the scrap strip should be cut to have a careful material use and reduce waste. 75% of scrap strip use is usually the minimal goal according to Paquin [10].

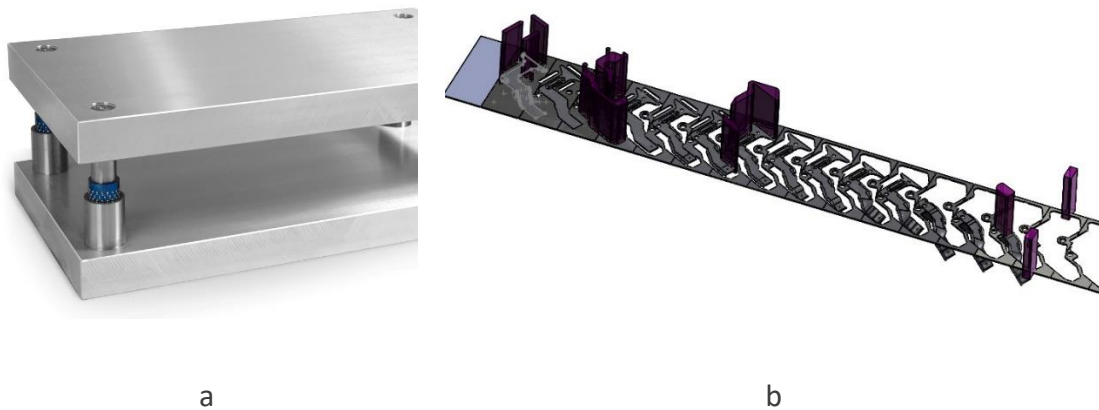


Figure 8 –Standard die set (a) [11] and a scrap strip sequence (b) [12]

To have a proper cutting tool, a suitable assembly (Figure 9) should be constituted by:

- Blanking punch;

With the desired shape, the blanking punch is the part responsible to remove the blank from the scrap. Flange systems are used for a fast removal when essential maintenance is necessary.

- Piercing punch;

Piercing punch is used to facilitate the blanking punch function. It makes desired forms on the strip to be punched more controllable. The strip can be held to the piercing punch and, in that case, a stripper should be used.

- Punch plates;

These plates are used to absorb and retain the impact as well as have a special shape to facilitate the clamping process to the metal strip.

- Pilots;

Pilots are used to make sure that the metal strip is correctly positioned during the forming process.

- Back gage;

Another system to ensure a correct cutting position and assist the operator to start the forming process.

- Finger stops;

Finger stops are used to assist every step made through the tool sequence. They can also be used to control the finish quality.

- Automatic stops;

As the designation indicates, these components are responsible to automatically stop the metal strip on a specific position.

- Stripper plate;

The stripper plate is responsible to remove the remaining material produced.

- Fasteners;

Fasteners are used to connect the parts allowing the possibility to remove parts for maintenance, replacement or process changes.

- Die set.

The frame to support the components assembly and a quality control insurance.

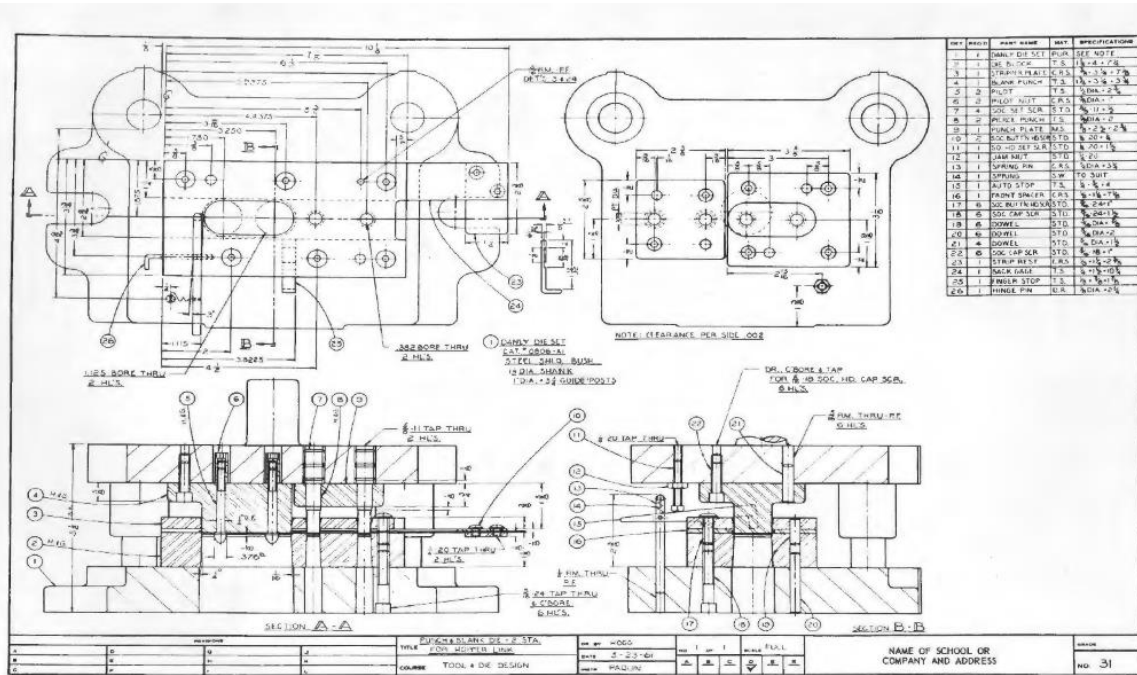


Figure 9 – Tool complete draw [10]

As is possible to see, tool dies are complex components for the metal forming process. Figure 10 presents another drawing example. Both figures highlight the design requirements of these systems. The design of the tools can take years to be mastered, requiring a high knowledge about the process, material used and equipment. The greatest difficulty is to accumulate so many sub-systems (pilots, punches, sensors for example) in a space so limited.

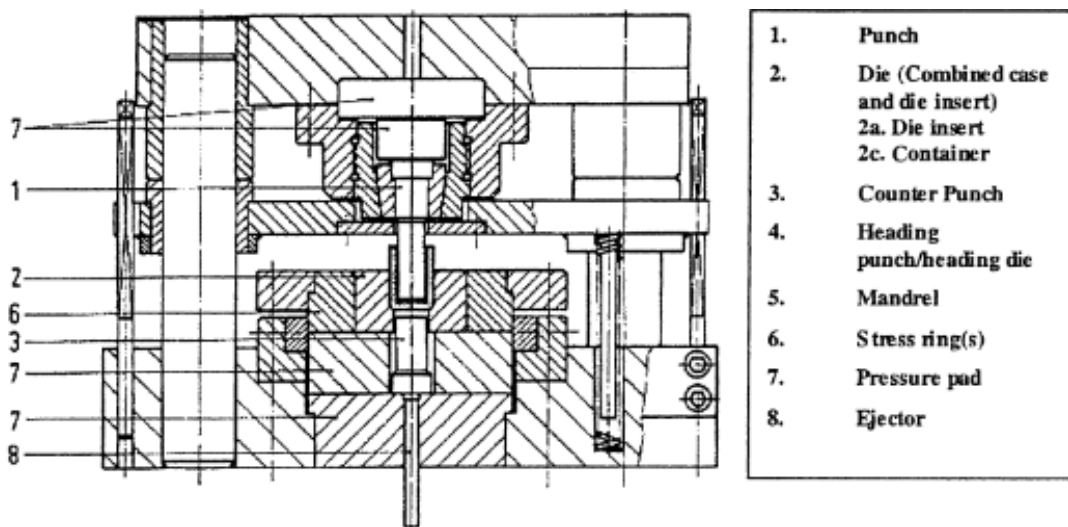


Figure 10 – Tool complete draw 2 [13]

An example of the exploded view for a tool die is presented in Figure 11.

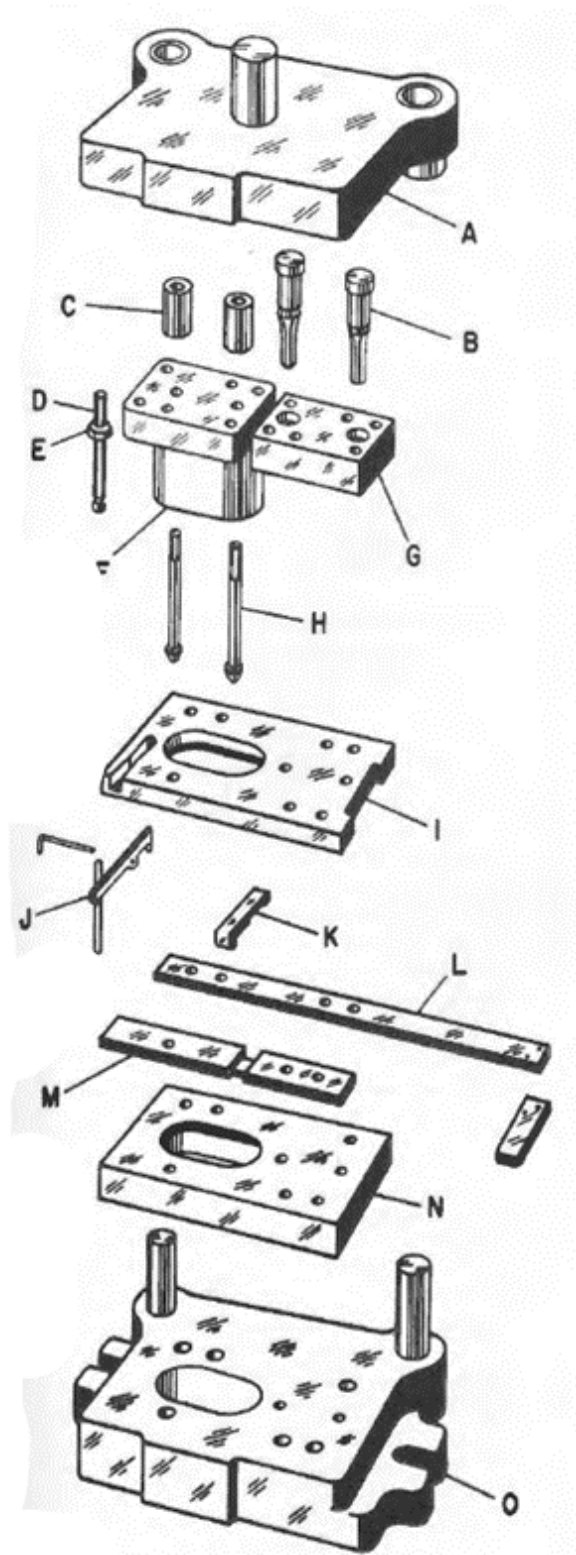


Figure 11 – Punch holder (A), Piercing punch (B), Pilot nut (C), Square head set screw (D), Jam nut (E), Blanking punch (F), Punch plate (G), Pilot (H), Stripper plate (I), Automatic stop (J), Finger stop (K), Back gage (L), Front spacer (M), Die block (N), Die holder (O) [10]

2.1.2.3 Product

The product can be compared to the "running blood" of the process. Like blood, the product runs through the system (presses and tool dies). Without it, the functioning of the system makes no sense, like a human body without blood. The product is continuously being produced having a quality control in the order of nanometers.

For this study case, shaving machines are the final product obtained. Shaving machines (Figure 12) are complex products with detailed sub-assemblies. Looking at a simple shaver it is possible to separate the main body from the shaving heads. Inside of the shaving heads, there are even smaller components with different functions:

- Support;
- Guide;
- Cut;
- Rotate;
- Cover.



Figure 12 – Product phases and exploded view [14]

The essential elements to be controlled are the cap and the cutter (Figure 13).



Figure 13 – Cutter on the left and cap on the right [14]

The cap makes direct contact with the human skin during shaving, thus, it is important for this component to present a good quality finish to avoid cuts on the customer's face. The cutter, as the name implies, is responsible for cutting the hair. In this component angles of bending given to the blade as well as its sharpness are essential for a proper well function.

The industry evolution and customer demand obligate that these elements evolve and become more reliable (Figure 14).

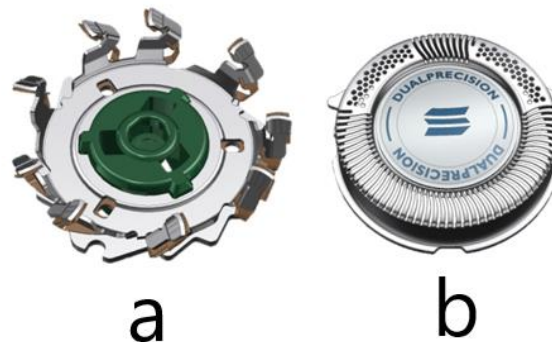


Figure 14 – Modern cutter (a) and cap (b) [14]

To maintain and understand the level of quality, it is important to understand the necessary elements for the final quality check of the product. Each component of the tool is essential for metal forming.

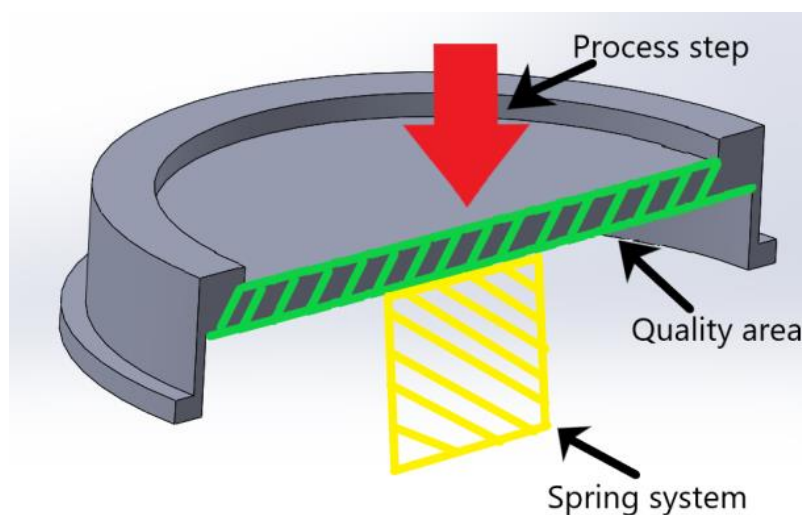


Figure 15 – Importance of spring systems (self-elaboration)

Spring systems (Figure 15), inside tool dies, are the necessary balance for the final quality of the product. If the spring systems do not promote the adequate stiffness to the tool die, the results will not be desirable. Spring systems are comparable to a “human heart” being responsible for “pumping blood” for the entire body (process). Speeds, forces and displacements are all dependent on these components.

2.2 Spring systems

2.2.1 Introduction

Spring systems, as a mechanical component, are rarely analysed by science (scientific publication). Appendix 3 presents a summary of scientific articles that can be related, although records were not found for these components under cold forming process application.

Spring systems for cold forming (Figure 16) are any system that acts inside the tool dies with a spring acting in it. These systems can act individually or simultaneously, when more than one spring is on the system. Independent spring systems can also act at once for the same process step; those are called simultaneous spring systems. Combinations are parallel, in series or a combination of both. It is important to understand that these systems rarely act alone (with only one spring system involved).



Figure 16 – Spring systems example (self-elaboration)

Within a tool, there are many different mechanisms based on spring systems, from the pilots to the guide strips, cutting components or shape modifiers. These spring systems represent a crucial function to obtain a high quality in the final product.

Figure 17 shows an example of a tool dies used in the factory. As is also visible, spring systems are placed between the upper plate (plate with technical elements) and up fixing bed (plate used to connect the die to the press). On the bottom is also possible to have springs, although this is not the case presented in the figure.

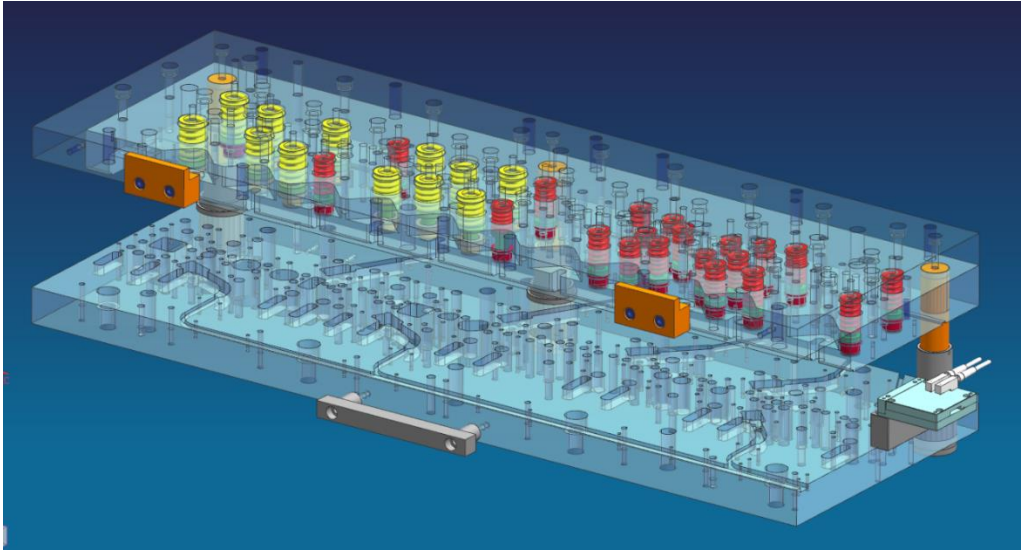


Figure 17 – Spring systems inside a tool die [15]

Figure 18 highlights disassembled parts that are used to create spring systems.



Figure 18 – Spring systems parts (self-elaboration)

2.2.2 Types of spring used for cold forming applications

When spring systems are disassembled, it is possible to make an individual analysis of the springs used in this process.

For the cold forming process, two types of springs are used for the creation of spring systems, both being used on a compression principle. Figure 19 presents an example of used springs as well as some of the spring properties.



Price group	C
d (mm)	1.60
Dm (mm)	10.00
Nw	3.50
C(N/mm)	19.08
Sn(mm)	8.70
Ln(mm)	9.80
F(N)	165.99
Min. Bus[mm]	12.25
Max. Axis	7.94
Acc. to tolerances	DIN 2089-1/EN 13906-1
Du (mm)	11.60
Lo(mm)	18.50
musicwire or stainless steel	VST
Nt	5.50

Figure 19 – Example of springs used to create spring systems (Tevema D12400) [16]

On the figure it is possible to see the following parameters:

d	Wire diameter	Materials: Music wire Din 17223 C / No. 1.1200 / EN10270-1:01 DH >2: EN10270-1:01 SH
Dm	Mean coil diameter	
Di	Inside diameter (Dm - d)	
Du	Outside diameter	Stainless steel wire Din 17224 / X10CrNi 18-8 no. 1.4310 / AISI 302 / EN10270-3:01 Din 2095-2 / Din 2098-2
Nw	Number of active coils	
Lo	Free length	Tolerances
Ln	Loaded length	Production: Coiled Righthand Ends 0,2 till 1,0 mm squared and unground 1,0-10 mm squared and ground
Fn	Load at Ln in Newton	
Sn	Compression at Fn	Surface treatment: The springs are oiled. Against an additional price it is possible to supply them with other surface treatment. However these are not on stock.
C	Rate	
Min.Bus	Hole size	Temperature: Music wire max. +80°C Stainless steel wire max. +250°C
Max.As	Rod	

Figure 20 – Typical spring parameters [16]

2.2.2.1 Helical springs

Helical springs represent the most common configuration known to ordinary people. The name has origins on the word coil, which is related to the fabrication process to obtain these springs. These springs can present different design configuration (Figure 21) although, under cold forming processes, the constant pitch configuration is the only one used.

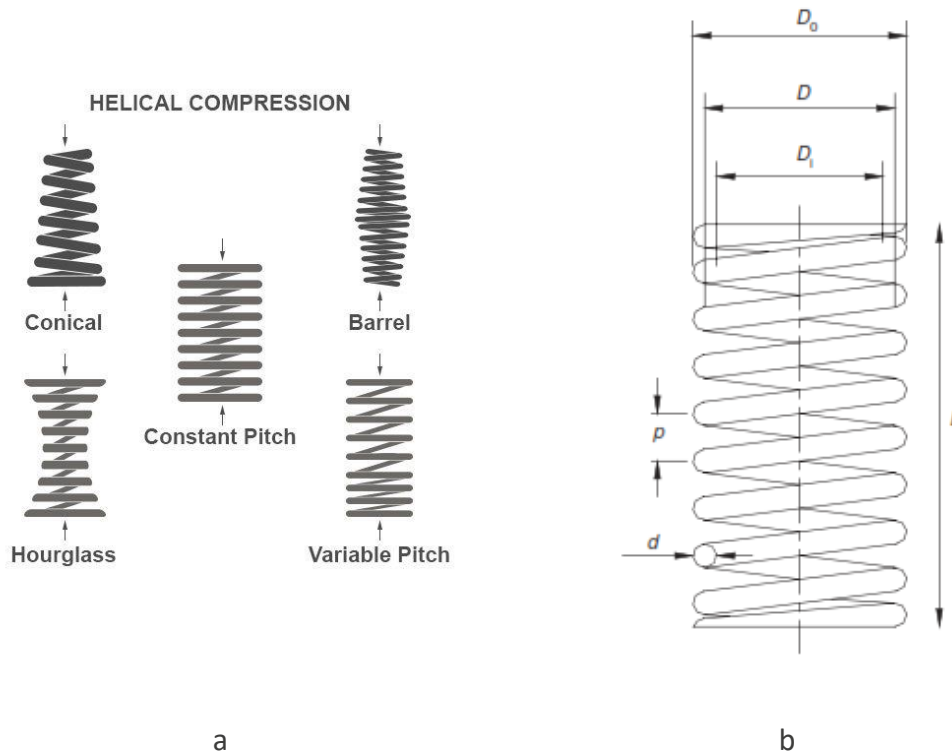


Figure 21 –Types of helical compression springs (a) [17] and a draw with parameterization indicators (b) [18]

The typical parameters to design these types of springs are wire diameter (d), mean diameter (D), free length (L_f) and pitch (p). It is also possible to design the spring replacing the pitch for the number of coils (N). During compression, there are different stage phases (Figure 22). The first one is the free length, and it represents the real length when there is no load acting on the spring. The second phase is during preload, which happens with the first deformation ($\delta_{initial}$). The operating length is obtained during the maximum working load and it represents the shortest distance possible for working stage. The last stage is called, the solid length, and it represents the stage where the spring no longer works as an elastic body. The coils are compressed and touch each other and represent the last stage where is possible to apply load without spring's crushing. On helical springs, two types of loads can occur, direct stress and torsional shear stress. Spring's index (C) for this model is given by:

$$C = \frac{D}{d} \quad (1)$$

where D represents mean coil diameter and d represents wire diameter. The ideal C is between 4 and 12. Values lower than 4 are difficult to fabricate and if the value is higher than 12, the springs are predisposed to buckling. Using internal or external supports, it is possible to reduce buckling effect on the exchange of possible force resistance by the spring. From here it is possible to construct a graphic with slenderness factor (ratio between L_f/D) at one axis and with the deflection to its free length (δ/L_f) at the other.

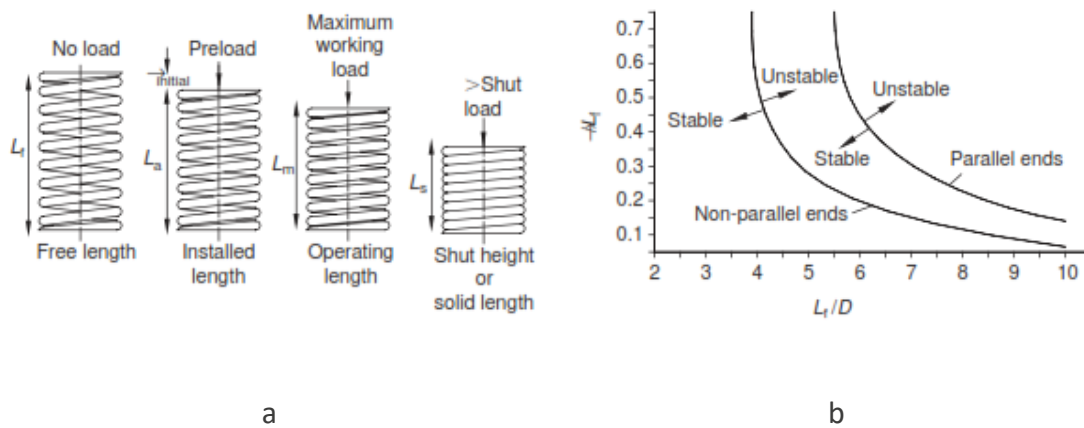


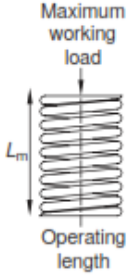

Figure 22 – Diverse lengths during compression (a) and spring’s capacity to work based on buckling effect (b) [18]

Failure for these springs is typically connected with unevenly-weighted assemblies. Bend and break are direct consequences of these imbalanced systems.

Table 2 relates theoretical lengths with the practical spring system work use on the tool dies.

Table 2 – Theoretical length and practical use for spring systems analysis for the process (self-elaboration)

Comments	Load on the spring
<p>Only used when the spring system is disassembled.</p> <p>Also used for visual inspection.</p>	
<p>Condition of the spring for which the spring system is assembled on the tool die without no force being applied on it.</p>	

Comments	Load on the spring
<p>Spring condition when the spring system is mounted on the tool die with a full course of applied punch.</p>	
<p>No use for the cold forming process.</p>	

Helical springs are divided according to the colours on them. According to ISO 10243 [19], the following code should be taken into account by suppliers (Figure 23).



Figure 23 – Capacity loads and respective colours [20]

Some functions inside tools require higher forces, being possible to use grey or brown depending on the supplier (Figure 24).



Figure 24 – Special springs colours [21]

2.2.2.2 Disc springs

Belleville spring washers present a conical shape, to provide tension when flattened. Even with deflection limitation, they are very useful for some cases principally because they present non-linear force-deflection properties. They are used in cases where compressive capacity is mandatory. Height (h) and thickness (t) represent an important ratio for the spring's compression (Figure 25).

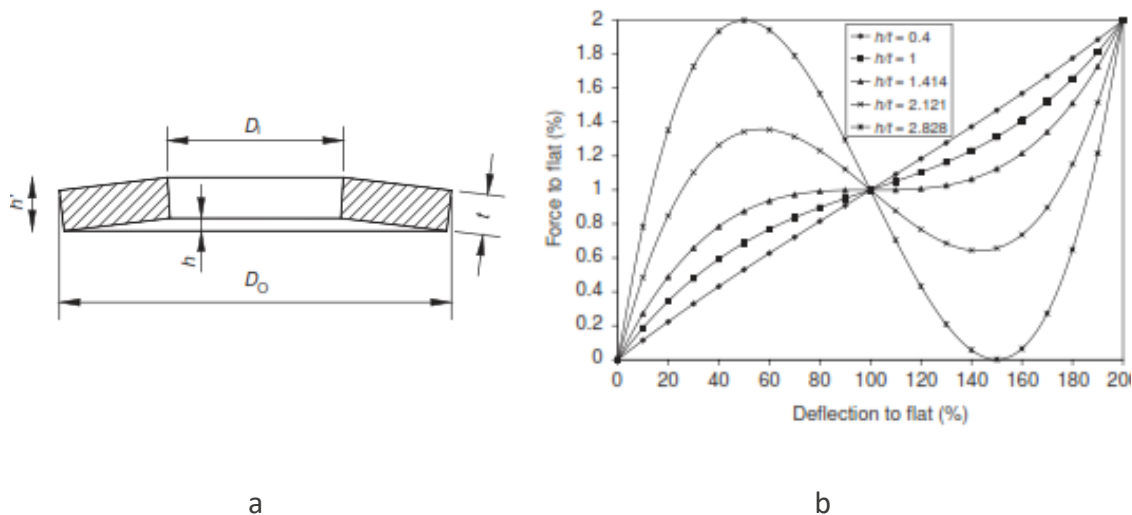


Figure 25 –Typical dimensions used in Belleville design (a) and force deflection graphic for a Belleville spring ($E=270\text{GPa}$ and $\mu=0.3$)(b) [18]

With the increase of the h/t ratio, force to deflection behaviour increases its non-linear tendency. For values higher than 1.414 (h/t ratio), the behaviour becomes bimodal with a better work region definition and more than one deflection adjustment. In these cases, there is also a central region where the force becomes constant resulting in deflection neutrality. To stop this natural compensation, a small force can be set. Higher force applications may result in advanced deformation and unpredictable performance. The stress critical points are located at the outside and inside diameter edges.

To increase the deflection values, Belleville springs are combined in different combinations (Figure 26). The parallel configuration allows increasing tolerated total force, but the deflection will be identical to a single Belleville spring. On the other hand, using a series formation, the deflection will increase, but the total force permitted will be equal to a single Belleville spring. Series-parallel systems try to join both characteristics. To use these configurations, a support method is necessary. Inserting the spring into a hole or using a rod to adjust them are the most common methods, although the available load decreases due to friction.

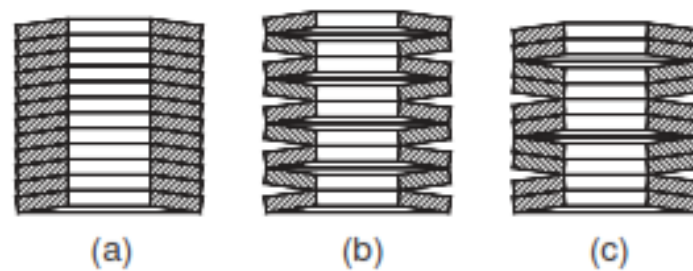


Figure 26 –Belleville usual spring combinations: parallel (a), series (b) and series-parallel (c) [18]

2.2.2.3 Differences between the disc and helical springs on spring systems

The major theoretic difference between these systems is the relation between force load capacity and displacement of the spring. Figure 27 presents that difference for both springs. Helical springs are able to perform long displacements, while disc springs support higher forces being typically used with another disc spring. The spring used is then based on the spring system function.

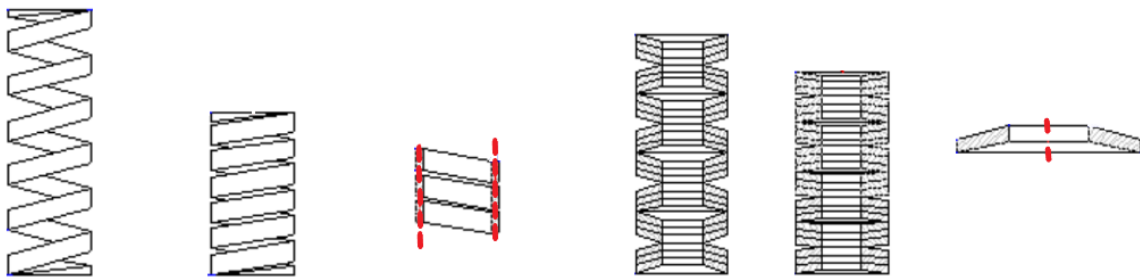


Figure 27 – Force and displacement relation (adapted from MITCalc [22])

Other important points are [23]:

- Disc springs require a larger diameter housing compared with helical springs for the same application;
- Helical springs require a longer housing length to be used compared with disc springs for the same application;
- Disc springs are easier to control over bending and concentric alignment due to the larger diameter and short length;
- Disc springs are also more versatile to be assembled on systems, since disc springs can be rearranged for displacement capacity (parallel arrangement) or load capacity (series arrangement).

2.3 Measuring principles

A mechanism is always exposed to different factors that increase or decrease life cycles.[24, 25] For a constant and desirable equipment function, it is important to

control and remain system conditions equal. The input and output should vary the less possible. Meadows [26] presented a method to think in systems in general. Meadows proposed to separate complexed systems into smaller systems with less complexity and study then by parameter input and output result. By making these smaller associations is easy to understand the behaviour of complex systems. Figure 28 represents the in principle, where clouds represent linked systems, inflow the input to the test, the stock is the system to understand and the outflow is the result obtained.



Figure 28 – “Thinking in system “principle [26]

Following this method, it is possible to divide every factor that influences spring systems (Table 3).

Table 3 – Properties affecting spring systems (self-elaboration)

Parameters	Comments
Operating rate	Range for which the spring is properly working. Connected with spring constancy rate, force applied and travelled displacement
Fatigue	Expected cycles for a system to fail
Temperature	Temperature influence over the spring systems. Ambient temperature is used for the process
Wear/Tear	Thought chemical analysis, measure elements concentration to validate or exclude spring system capacity to operate

The decision about which factor to use to measure and evaluate spring systems, should be the property that produces more “outflow”. “Inflow” inputs are reduced if this method/principle is applied.

A wide range of properties affects springs, being these factors well documented by suppliers or standards. Unfortunately, most of them are excluded for a spring system analysis since springs are not the only component of a spring system.

2.3.1 Practical analysis

During a week, via mentor guidance, a maintenance team tried to provide the most relevant information on used spring systems. The idea of this analysis was to restrict properties and decide which properties are important to be inside the scope for a measuring device.

During that week, some tools (e.g., 7278 142 4500 system) were opened to analyse and better understand spring systems conditions. Table 4 summarizes and makes a general analysis of the gathered information.

Table 4 – Collected information (self-elaboration)

Picture	System	Comments
	<p>High diameter helical springs</p>	<p>High signs of wear and tear Identical wear pattern between different springs Earlier break than expected (preventive maintenance)</p>
	<p>Shorter diameter helical springs</p>	<p>No signs of tear and wear were detected Springs cycles are according to preventive maintenance cycles</p>

Picture	System	Comments
	<p>Disc springs</p>	<p>Behaviour is identical for shorter or higher diameter springs</p> <p>High signs of tear and wear</p> <p>Unpredictable pattern</p> <p>Springs system acting simultaneously present different conditions for the same number of cycles</p>
		<p>Spring systems with a higher diameter; create high corrosion signs inside tool dies.</p> <p>These higher diameter systems are also the mechanisms responsible for the product quality.</p> <p>From this earlier analysis, it is also possible to detect that larger diameter spring systems are possible presenting hysteresis higher than expected.</p>
	<p>Spring system housing</p>	

Picture	System	Comments
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Spring break

In some systems, springs were broken before the expected time.

Production lines are highly affected by these cases (minimal of 8 hours stop).

Same rules are used to implement this mechanism, spring break should not be a problem.

Those cases were only documented on higher than 40 mm diameter springs.

Counted cycles control

A software is used to control and count spring cycles.

Once the recommended cycles are achieved, maintenance is performed.

The software presents an expected estimation for the fatigue spring cycles.



Other notes

Use of microscopes assists on visual inspection.

A big tool inspection can take until 6 hours.

Forces and displacement values for these systems are not measured when at assembled conditions.

After this analysis, Table 3 was updated (Table 5) with comments related with observed factors.

Table 5 – Methods to evaluate properties affecting spring systems (self-elaboration)

Parameters	Comments
Operating rate	<p>Tests were performed for systems similar to Figure 16 outside of the dies.</p> <p>Some reports were made (Appendix 3) over force and displacement behaviour for springs. The advantage of these methods is that they provide quantitative data.</p>
Fatigue	<p>Cycles are counted to predict spring systems failure.</p> <p>The method presents a good control capacity but also proves to be not very efficient since some springs were found broken earlier than expected.</p>
Temperature	<p>Temperature applied over spring system are according to suppliers working principles.</p> <p>Tool dies complexity can make difficult to measure temperature.</p> <p>The study of Schleicher [27] ,for example, present smaller variations for 200°C temperature experiments. For the analysed spring systems working temperatures are not even close to that (room temperature).</p>
Wear/Tear	<p>Most observed springs presented marks of wear, equal patterns were not found, especially on disc springs.</p> <p>Wear was not found for all the spring systems.</p> <p>Many reports where made (Appendix 3) about measuring wear and tear, even though most of them presented non-definite conclusions. Measures in this topic are wide-ranging, being possible to act in chemical fields, tribological fields, photographic analysis, etc.</p> <p>This type of study is also used for testing similar or continuous conditions of materials leading to a pattern. Since spring systems are wide (different spring types, diameter, length, etc..) with different functions, it will be difficult to create a universal pattern.</p>

2.3.2 Principle to validate spring systems

After the conditions observed, it is possible to set a principle to validate spring systems:

- Collecting force and displacement values over time, a graph shall be created with boundaries for each spring specific configuration. Initially, values will be compared with theoretical expected values. Boundary curves are going to be shortened with time by experience use, production demands, etc. Figure 29 represents the designs expected for the graphs;
- The red line represents evolution and area decreasing of the control graphic with time. This process of sharpening graph form will increase trust on the measurement as well as define better spring systems hysteresis;
- The test needs to be performed dynamically to emulate conditions found overproduction.

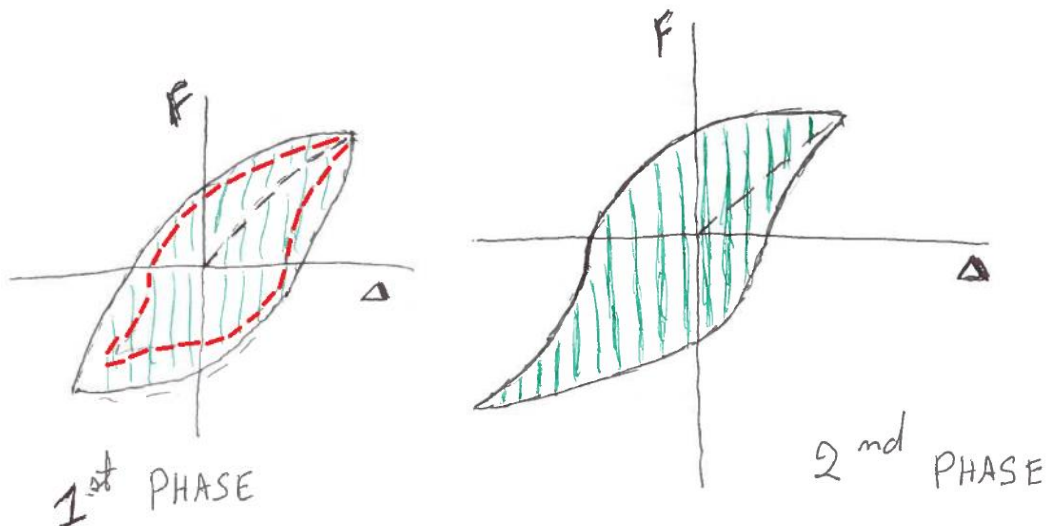


Figure 29 –Expected graphs (self-elaboration)

2.3.2.1 Hooke's law

Robert Hooke stated that the force or load is directly connected with displacement movement. Small displacement conditions (typical for springs) are important, since under this condition, the material returns to the original initial position. This relation between force and displacement is applied under pure material elastic behaviour [28].

Deformation force may act as stretching, compressing, squeezing, bending or twisting on solid parts [29]. For a spring, there are two major factors to consider for a correct perception force (F) and spring constant (k). The following relation gives the physical position (x):

$$F = kx \quad (2)$$

When deformation surpasses Hooke's law principles the material will not be able to return to the original position. It is also possible to have the formula on a negative relation:

$$F = -kx \quad (3)$$

In this case, force concept loses some of the sense into it, $-kx$ represent the spring's return equation until origin point. It is also possible to express Hooke's law in the form of stress and strain. Stress and strain are normally proportional for small stress imposition. Figure 30 shows the three typical stages. Number 1 represents the ideal scenario, 2 represents a spring with decreasing stiffness characteristics and number 3 progressive load capacity (typical on disc springs).

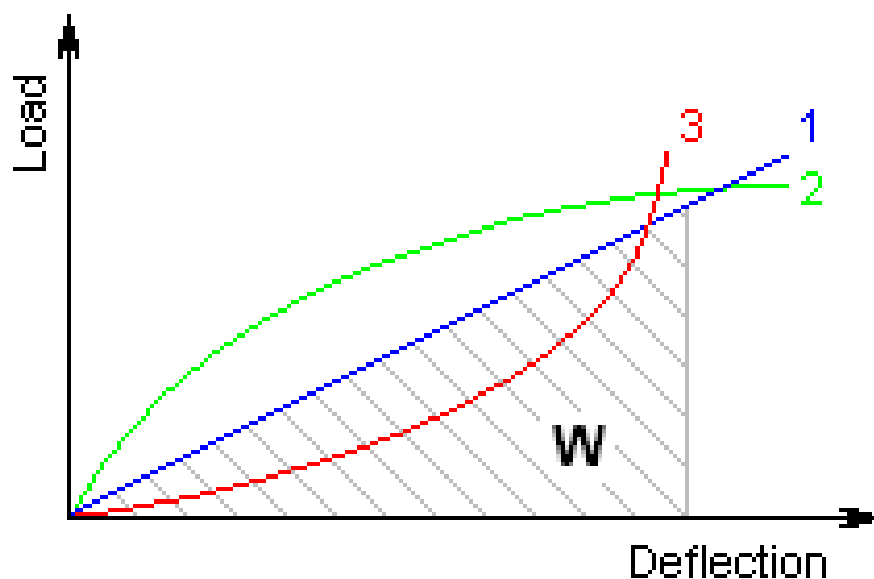


Figure 30 –Different types of spring's behaviour [22]

2.3.2.2 Hysteresis effect

Hysteresis is a word with high relevance for all the systems that need to be described over quantitative values. Diverse areas like science and engineering use them to understand and simplify systems analysis.

Hysteresis can be described as the variation of physical properties based on its own historical result (Figure 31). A lot of models can be used on Hysteresis, and some of them are more typical on engineering fields, like Maxwell, Boltzmann, Madelung, Prandtl, Masing, Volterra, von Mises, Saint-Venant, Tresca, Ishlinskii, while Zadeh, Desoer, Arbib, Falb, Kalman models are more used for mathematical areas [30]. Identically to Meadows [26] philosophy, most of the times hysteresis is used with an input value that will lead to a measured output conclusion value. The increase of inputs testing samples will lead to an algorithm capable of relating outputted and inputted values.

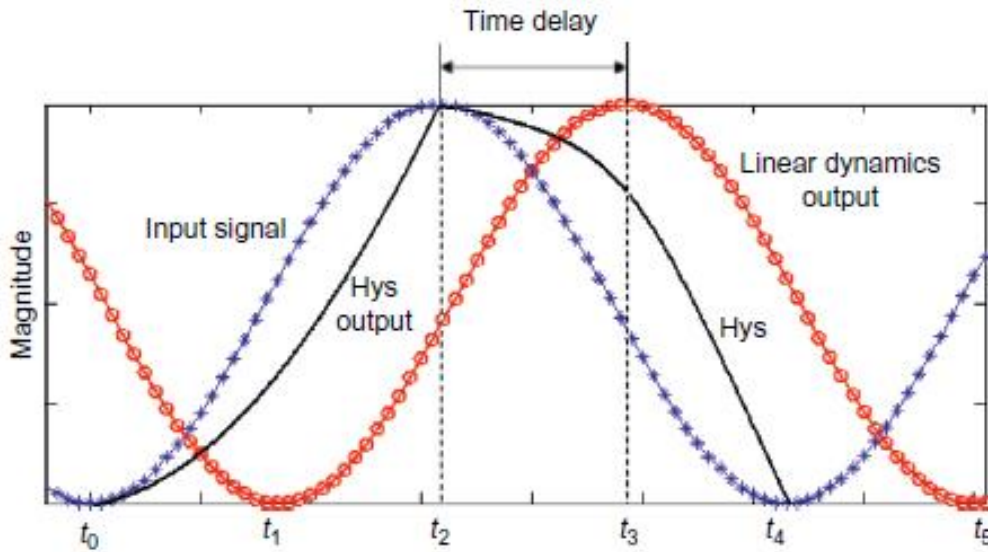


Figure 31 –Hysteresis principle [31]

The area of hysteresis curves represents the variation of energy for the propriety to be analysed.

Elastic hysteresis is particularly related to the phenomenon of dynamical cycle loading/unloading relation over a material of elastic behaviour. With time increase, energy storage capacity changes, affecting the system capacity to deal with elastic loads and unloads over time for this case (Figure 32).

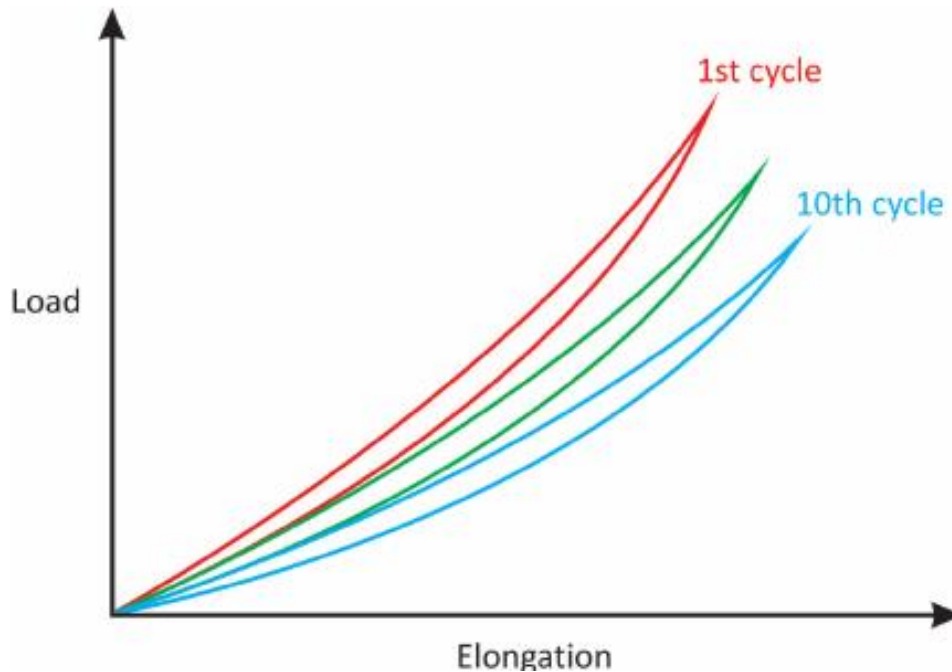

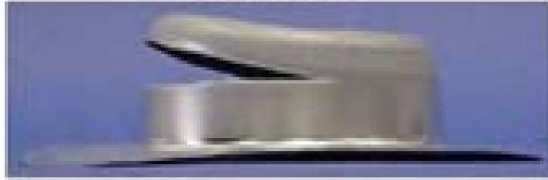



Figure 32 – Hysteresis effect over Hooke's law [32]

Looking at spring systems specifically, the change of force or displacement capacities will affect product quality (Table 6).

Table 6 – Cause-effect for the process [33]

Cause	Effect	Name
Operating rate surpasses acceptable values of force and displacement.		Wrinkling
		Tearing
Operating rate fails to reach acceptable values of force and displacement.		Springback

2.3.2.3 Hypothetical example

Springs can be validated under different methods for operating conditions. One example is the Almen–Laszlo's equation [34] that is used to calculate disk springs behaviour. Another example implemented in DIN 2095 [35], which specifies the parameters that need to be covered to have a spring with a good quality to be used in cold forming processes.

For spring systems, a more practical approach must be applied since documentation is inexistent.

Picking up two spring examples observed from spring systems, and combining stroke and force per each system with the spring catalogue information from the supplier, the following data was obtained (Table 7):

- Theoretical stoke allowed by the spring system;
- Theoretical loads allowed by the spring system;
- Tolerances for load and stroke according to spring supplier.

Table 7 – Example data [36]

Example	Initial Stroke	Final Stroke	Distance Tolerance	Initial Load	Final Load	Operating Tolerance
	mm	mm	%	N	N	%
24 mm spring	5.5	8	1	226.76	283.47	10
63 mm spring	12.9	19	1	10879	15998	10

With the tolerances obtained from the supplier, it is possible to obtain the area where spring systems should operate (Table 8).

Table 8 – Points obtained from Table 7 values (self-elaboration)

Point	24 mm spring		63 mm spring	
	Displacement (mm)	Force (N)	Displacement (mm)	Force (N)
Initial Stroke + Distance tolerance/ Initial Load + Operating Tolerance	5.555	294.436	13.029	11966.9
Final Stroke + Distance tolerance/ Final Load + Operating Tolerance	8.08	311.817	19.19	17597.8
Final Stroke - Distance tolerance/ Final Load - Operating Tolerance	7.92	255.123	18.81	14398.2
Initial Stroke - Distance tolerance/ Initial Load - Operating Tolerance	5.445	204.084	12.771	9791.1

With these four points, it is then possible to build a graph that represents the working region.

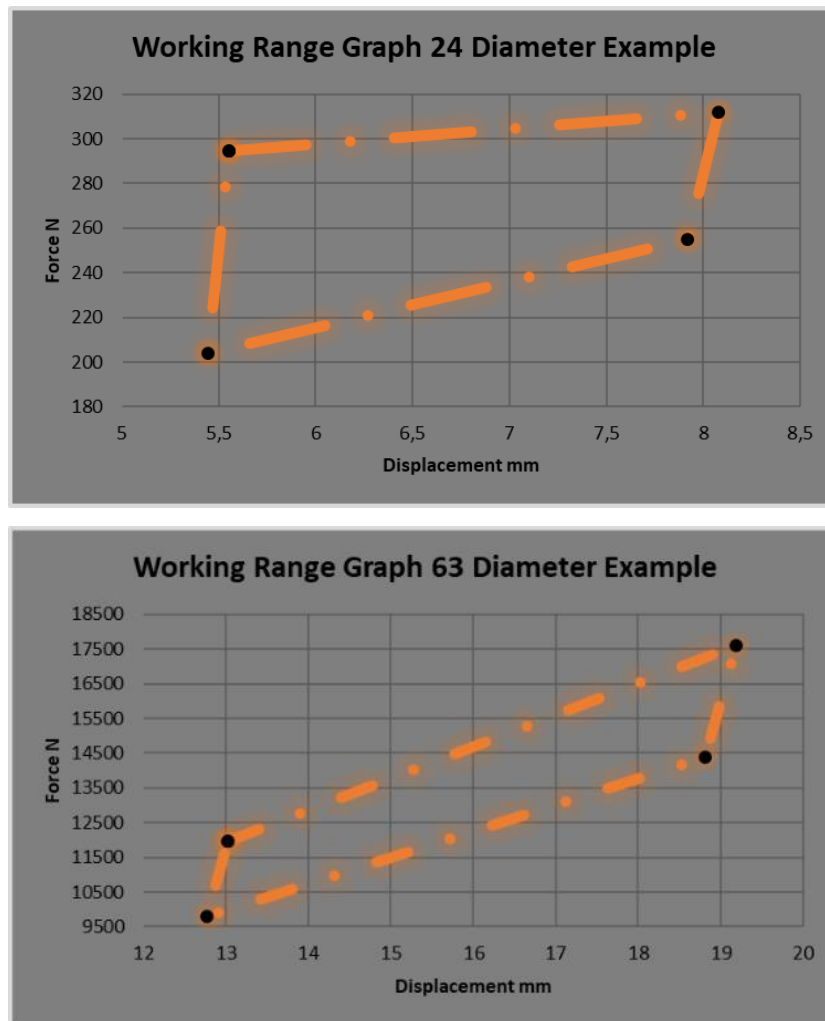


Figure 33 –Working area (self-elaboration)

Figure 33 shows that the curves will diverge depending on which spring system is used. This theoretical map matches what was found on maintenance week. Springs with bigger diameter have a minor area to release elastic stress than shorter diameter springs. The stress that is accumulated has a more critical range to operate in the second case (63 mm diameter). Even with different values for force and displacement, it is perceptible witch spring case is worst. This graphical shape difference may be showing part of the problem.

Residual stress is a critical factor for failure in springs [23, 37]. If with time this value is increasing due to the high number of strokes, this may be the cause for the problem of spring systems. Figure 34 shows how the residual stress may variate. The yellow line represents the initial residual stress already on the spring due to the pre-tension configuration and other factors such as small deformations, cracks, contacts, etc. With this initial line and adding the load required to perform tools stroke, there are two

possible scenarios. The first one (line green) is when the stroke is inside of spring work specifications and the release of it still has a range for unexpected factors. The second one is worst: the red line is already at the boundaries of the spring, and small variations will break the spring. The yellow line can also increase with cycles performed inside of the tool, but that evolution can only be truly obtained from measurements.

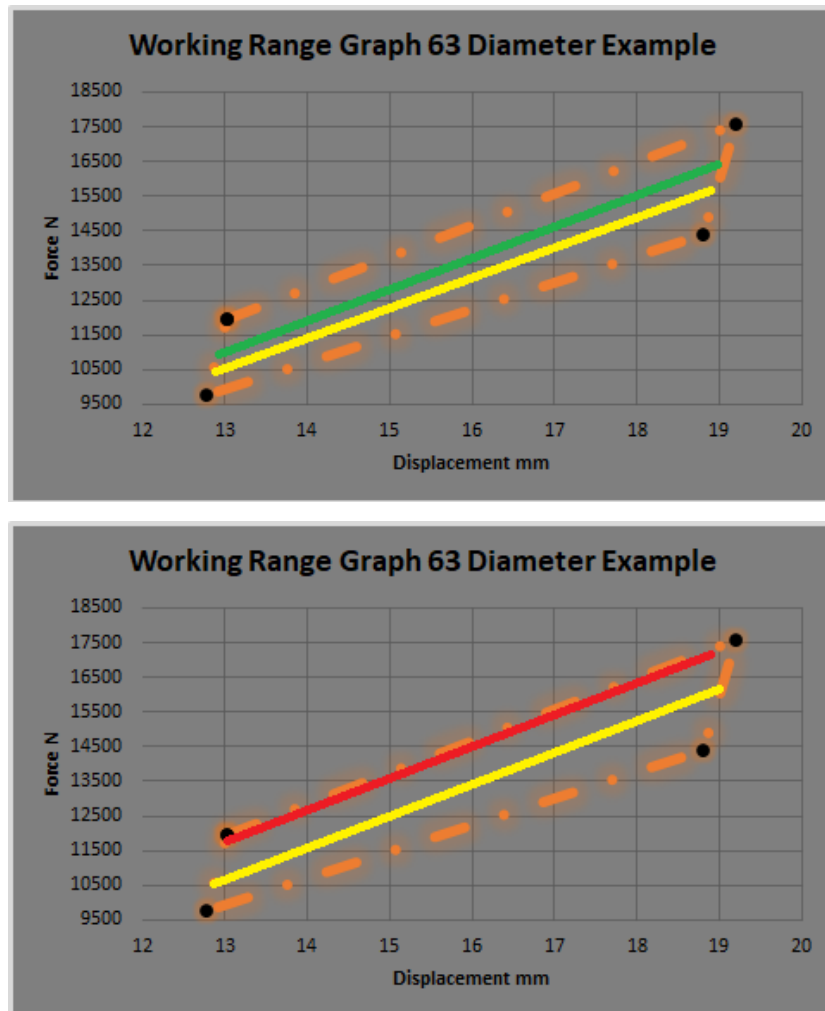


Figure 34 –Residual stress factor (self-elaboration)

This graphical representations and curves definition are the major principle for the definition of the life conditions for the spring systems. The principle can be compared with regular compression tests. The main differences are that: since more than one test is performed, the results are not entirely focused on material properties, fatigue principle is added with historical data and residual stress and elastic accumulation behaviour will be measurable with the difference between the slops. The dynamic behaviour will also add another important factor to the analysis (hysteresis).

THESIS DEVELOPMENT


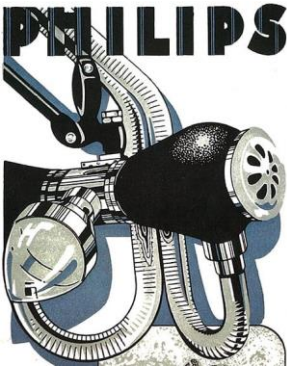
3 THESIS DEVELOPMENT

3.1 Welcoming company characterization

3.1.1 Philips history

The company assisting this study is Philips. Koninklijke Philips N.V. is a Dutch company focused on healthcare area. Gerald Philips, with the help of his father, Frederik, founded the company around 1891 in a humble factory at Eindhoven. Gerald was making studies on carbon filaments, so it is not surprising that first Philips products were based on that. Table 9 presents a review on Philips history.

Table 9 – Philips history evolution [38]

Years	Description	
<p>1891 – 1915</p> <p>“From light revolution to product evolution “</p>	<p>Principal company focus was based on making carbon-filament lamps. In 1912, the company enters on Amsterdam Stock Exchange.</p>	
<p>1915 – 1925</p> <p>“Innovation and diversification: X-rays and radio reception”</p>	<p>In 1918, the company starts studies on the x-ray tube. This is the first step for the company to start to investigate innovative topics and research fields. In the 25th anniversary, the company receives a royal recognition. Is also during this period that the company reaches external markets.</p>	

1925 – 1940
 “The first radios, televisions and electric shavers”

In 1927, Philips became the world largest manufacturing on radios and radio tubes. The first medical x-ray equipment production was introduced in 1933. At 1938, the first television is introduced and one year late the first electric shaver.



1940 – 1970
 “A succession of technology breakthroughs”

1949 is the year in which the company introduces Philips Synchrocyclotron, allowing research investigation on tumours evolves by enabling malignant tumours treatments. It 1963, Philips introduced the compact audio cassette.



1970 – 1980
 “Continued product innovation for images, sound and data”

During this period, and because of energy management, some discoveries were made to energy saving lamps. The high demand for image, sound and data also allows the introduction of the optical disc and compact disc.



1980 – 1990
 “Technological landmark: the Compact Disc”

Working in collaboration with Sony, the launch of the compact disc marks another import point of Philips development.



1990 – 2000
 “Far-reaching changes and new successes”

In 1997, again with Sony, the DVD is launched, but the most important landmark was Philips different approach to healthcare. The company invests on new medical and clinical processes.



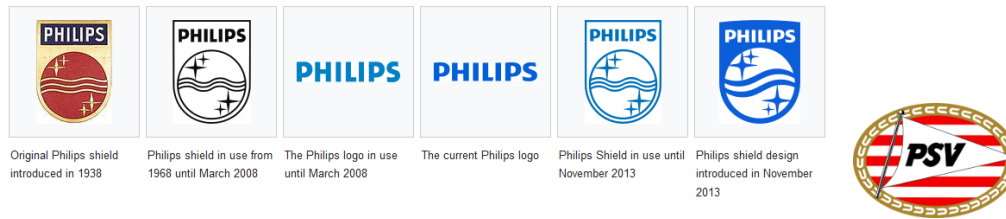


Figure 35 – Philips logo evolution and PSV banner [39]

Philips initial headquarters were in Eindhoven, being then moved to Amsterdam. The contributions made by Philips to Eindhoven are well marked on history with the biggest sign left on the city being PSV (Philips Sport Vereniging, Figure 35) and the research headquarters still located there.

3.1.2 Philips nowadays

Since the beginning of the 21th century, Philips has already done major developments [38]. Philips nowadays employs around 105.000 people across 60 countries. The company is leader in healthcare and invested in protocols all around the world to equip and work on smart hospitals. The consumer lifestyle also plays a huge part, from smart tooth cleaners to more advanced shavers.

Nowadays, the company can be divided in two major actuation areas:

- Philips consumer health and well-being.

This part can be seen as the daily use equipment. Represents almost every technology founded and distributed by Philips. From shavers to televisions, almost every product pass through this group of the company.

- Philips professional healthcare.

Earlier company days related with x-ray research connect Philips with professional healthcare, it is possible to connect Philips with this area, which is the most “recent” side of the company and is now growing into advanced medical equipment and smart medical care.

3.1.3 Drachten and Philips

Drachten factory initiated working in 1950 with 40 employers to produce electric shavers. With time passing, Drachten has become Philips Consumer Lifestyle, largest factory. At 2014, 80 million shaving heads where produced. Developments, research and innovation on shavers all pass through this location. One of the most recent accomplishments obtained on this factory was the production of Philips’s OneBlade (Figure 36).



Figure 36 –OneBlade shaver [40]

3.1.4 NPI

New Product Introduction (NPI) is responsible for the introduction of new processes, support development/improvement of already implemented processes and assist technical support group in hard solving production problems. NPI is divided into different groups with a specific goal or area of investigation. In the present case, the hosting team was NPI Metal Forming. The organogram is presented in Figure 37.

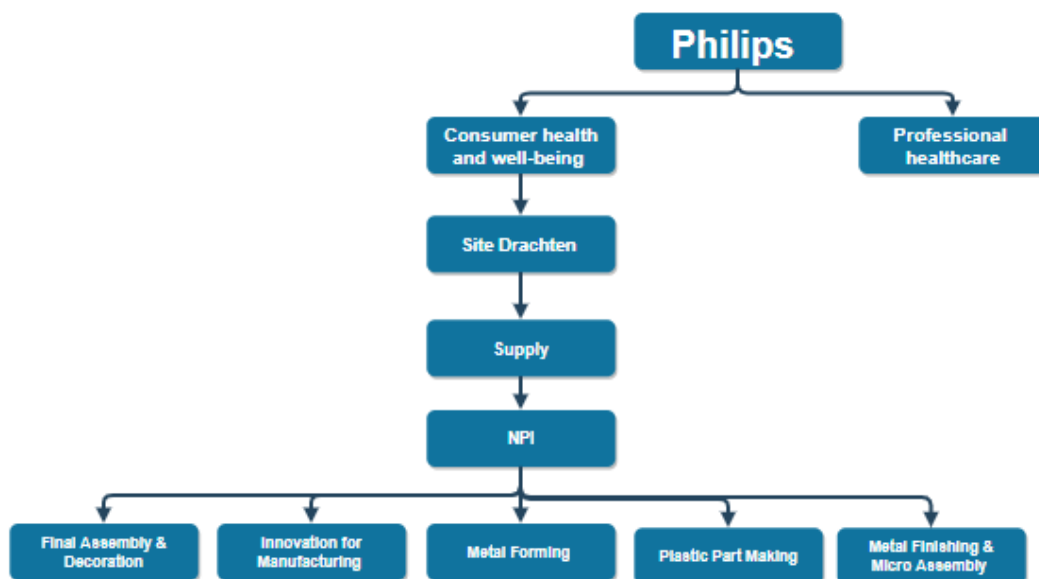


Figure 37 – NPI Organogram

3.2 Practical problem statement and proposed goal

With the previous information it is possible to introduce and state a problem as well as to propose a solution/goal for the faced problem. This proposal was made based on SMART methodology. To understand more about this method, Appendix 4 was added to the document.

Problem environment: At this stage, the control performed on spring systems is based on periodical maintenance cycle, based on visual inspection of the springs after a certain amount of system cycles. No spring measurements are being performed. This method takes a lot of time since the complete tool needs to be disassembled in order to observe the status of the springs. Then every spring is individually analysed, which costs a lot of time. The preload forces for every springs system are not analysed leading, to an unclear definition of initial conditions when tools enter the production lines. Tests to spring systems can be performed, but the systems are outside of the dies, which leads to different conditions than the ones found when the spring system is assembled, especially because boundary conditions (e.g., die housings) are not taken into account. Tests are also not fast enough to be comparable to production lines speeds. Another important factor is that even with theoretical calculations and proper spring system assembly some springs break sooner than expected. Finally, even though forces and displacement are obtained via theoretical calculation, real values are not known, as well as the spring system hysteresis behaviour values.

Business Opportunity: Specify and design a measuring system for spring systems inside tool dies

Research question: How should a measuring machine be to validate spring systems inside tool dies?

Proposed goal: Present the best concept for the measuring machine taking into account safety as the principal design factor, presenting also a measuring cycles description and an evaluation boundary principle. Machine technical requirements should be obtained from different study cycles for relevant factors. The principle desirable in chapter 2.3 will be used as the support for the measurement principle as well as for the evaluation criteria.

The project complexity leads to sub-questions, questions that are also connected with critical points for this assignment.

To assist and guide the lecture of the third chapter, as well as highlight some of the major question thoughts, Table 10 is presented.

Table 10 – Sub-questions per chapter

Chapter	Sub-Questions
3.3	What stakeholders are interested on the assignment? What could they win with a measuring machine?
3.4	What technical requirements are needed for the machine? What type of historical data can be used to set technical requirements?
3.5	What type of functions needs to be performed by the machine? What type of elements can be used to cover needed functions? What concepts can be created with possible elements?
3.6	How every concept matches needed functions?
3.7	What concept should be taken a reference to be optimized?
3.8	Is there any specific function that can still /need to be optimized?
3.9	What should be the final concept based on optimized functions?
3.10	How to improve safety on the concept?
3.11	How can the final concept be described? How does it look like?
3.12	How can the measuring cycle be described (step by step)?
3.13	How can a database be built?
3.14	How much would it cost?
3.15	Is it possible to validate the concept with existing elements?

3.3 Stakeholders analysis

To understand which departments should be involved, a stakeholder’s analysis was made to involve teams with direct interest on assignment proposition (Figure 38). Each stakeholder has its own need and will be shortly described.

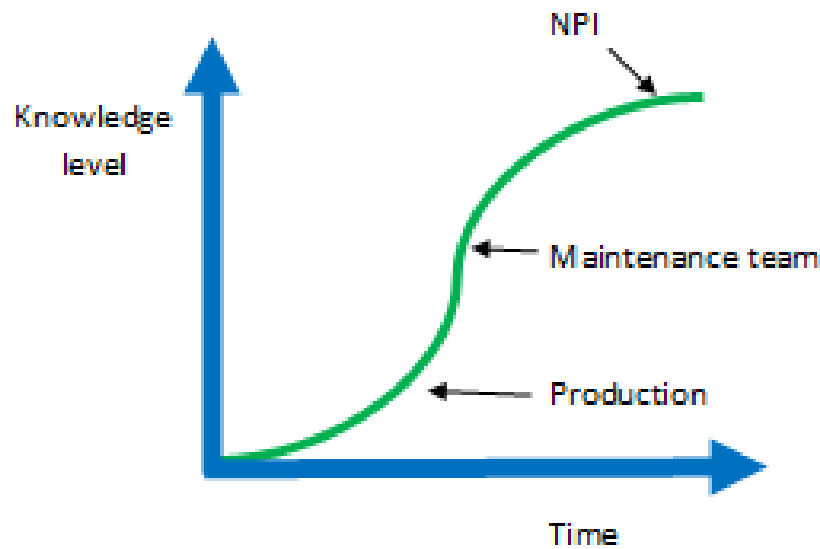


Figure 38 – Stakeholders analysis (self-elaboration)

Production will benefit from a machine because production line stops due to spring break shall be reduced and workflow for tool maintenance gains even a higher level of control. Knowledge level will have a high impact initially but, with time, new gains are not expected.

Maintenance will benefit with some time evaluation for the machine, even though an early project implementation for the machine will provide relevant data. With time improved knowledge will be gained and maintenance services will be more efficient.

NPI will benefit on a long run analysis. Initial results will not be secure enough to implement new “rules” for tool design and testing standards but, with time, data obtained from the machine will allow creating, testing new tool design, inspect new mechanism implementation, and even prevent spring systems hysteresis inside tools dies.

3.4 Technical requirements

3.4.1 Historical data collection (theoretical values)

Spring system properties are based on force and displacement values. These value variations represent the real process capacity to form bend or cut a sheet. The force range and the displacement range are then defined by the spring system.

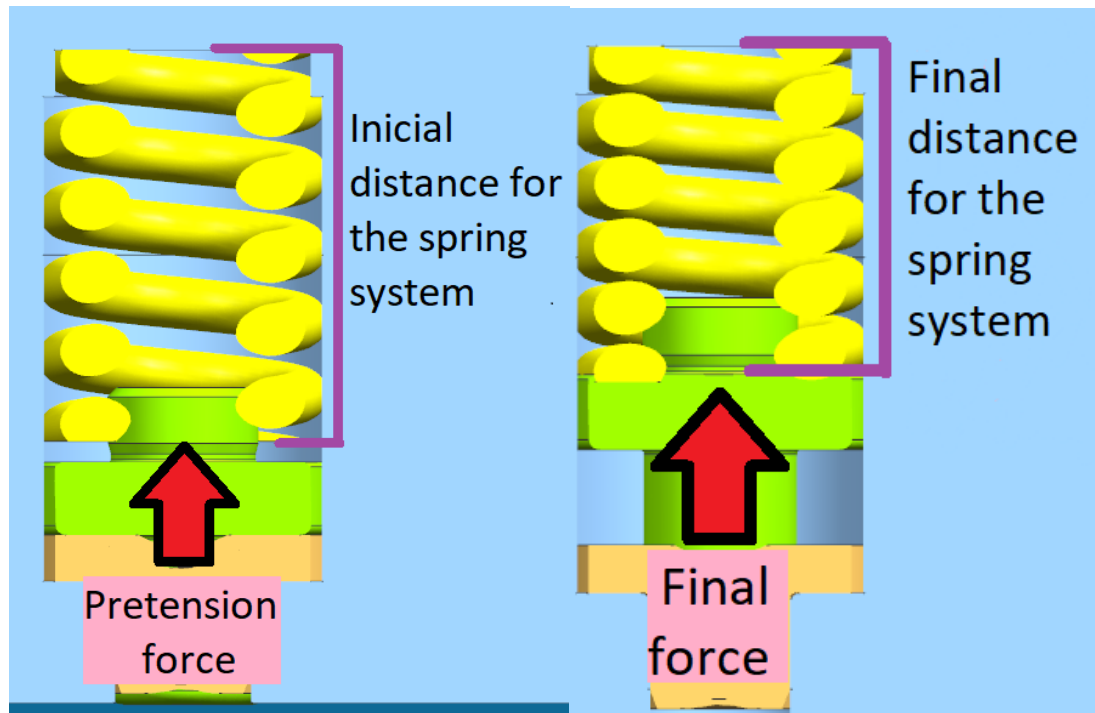


Figure 39 – Force and displacement variation for a spring system

Figure 39 presents a situation for a single spring acting but, as it was already mentioned, these systems are rarely acting individually in cold forming dies. A more realist approach is presented in Figure 40.

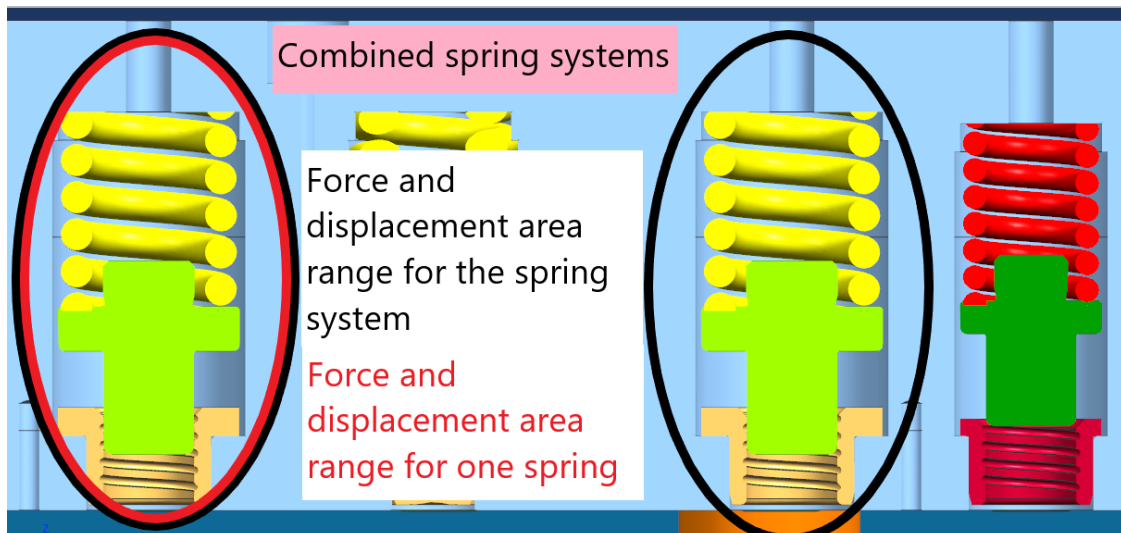


Figure 40 – Combined spring systems

Technical requirements were collected from technical drawings inventory. Collected data reflect the required force and range, displacement variation, diameter of springs and maximum housing spring length. The selection process was based on tools with the highest forces and tools with the highest dimensions. Die tools used were (according to Philips Drachten database):

- 7822 142 4500,
- 7822 142 4800,
- 7822 142 4900,
- 7822 142 50000,
- 7822 142 7100,
- 7822 143 17000.

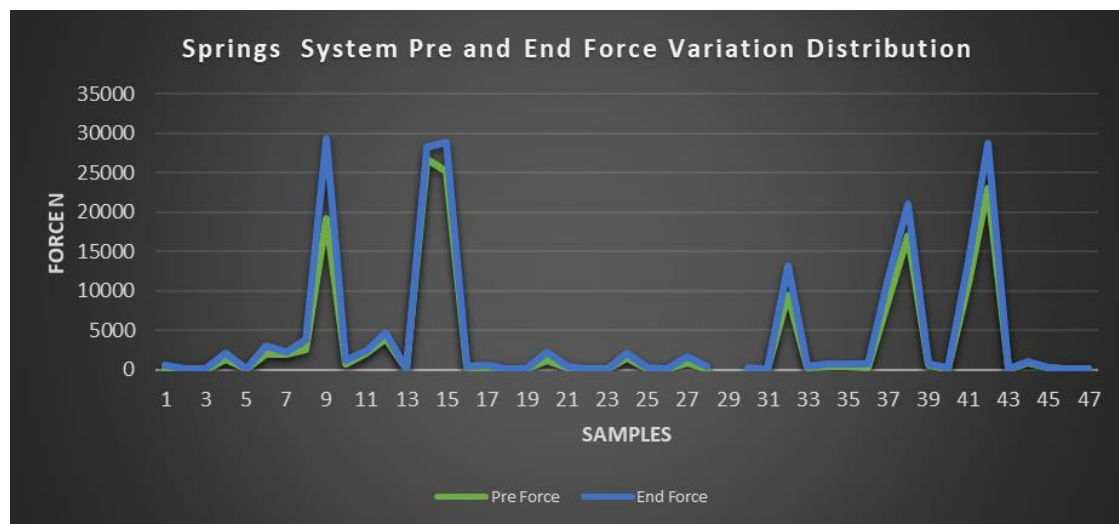
Sample		Pre (N)	P Distance (mm)	End (N)	E Distance (mm)	Total P (N)	Total E(N)	Force Range Spring	Displacement Range	Force Range Sytems
9.5*76	1	15	72.4	55.7	60.9	150	557	40.7	11.5	407
9.5*51	2	15	44.4	38	32.9	60	152	23	11.5	92
ema D11	3	9.5	8.5	16.7	7	19	33	7.2	1.5	14
12.5*51	4	95	41.6	149.5	36.2	1330	2093	54.5	5.4	763
12.5*51	5	170	40.1	273	33.4	104	167	103	6.7	63
31*64	6	1489.5	47	1932	41.9	1967	3018	442.5	5.1	1051
20*64	7	325	52.3	507.4	47.3	2030	2211	182.4	5	181
24*76	8	1320	62.8	1920	58.8	2640	3841	600	4	1201
63*76	9	9600	64.6	14652	58.6	19200	29304	5052	5.9999999999999999	10104
19.5*76	10	750	63.4	1227.6	55.4	750	1228	477.6	8	478
24*51	11	1034	36	1171.8	34	2064	2344	137.8	2	280
20*44	12	2000	39.6	2361.6	38.8	4000	4723	361.6	0.8000000000000004	723

Figure 41 – Table used example

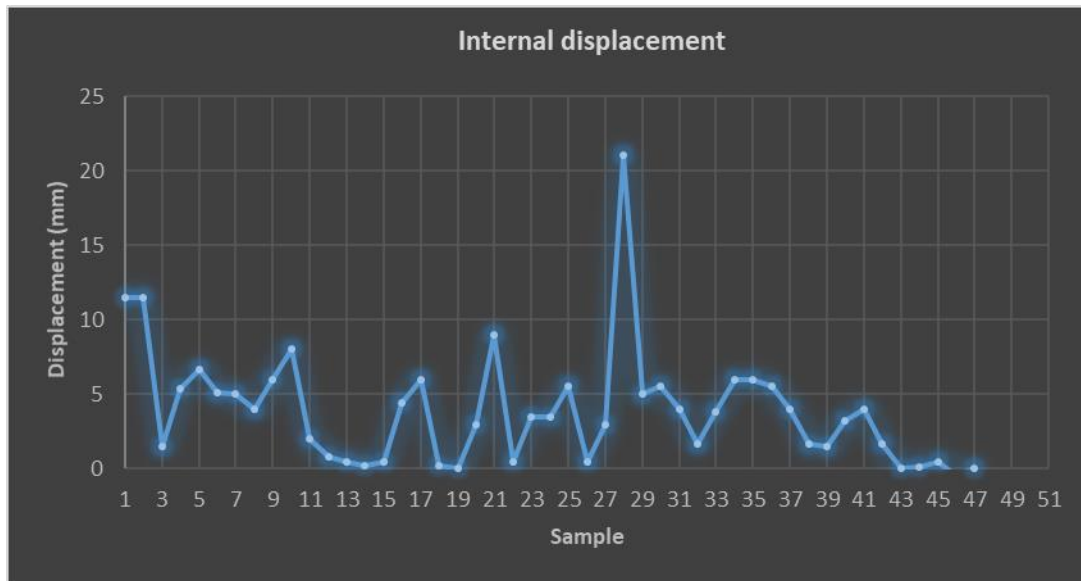
Figure 41 shows an example of some of the information collected. Appendix 5 was added to assist columns meaning as well to present full data on a larger dimension to assist further analyses.

From the collected data, different graphs are produced for easier interpretation. A total of 47 different spring systems samples are analysed and combined to perform this investigation (Table 11).

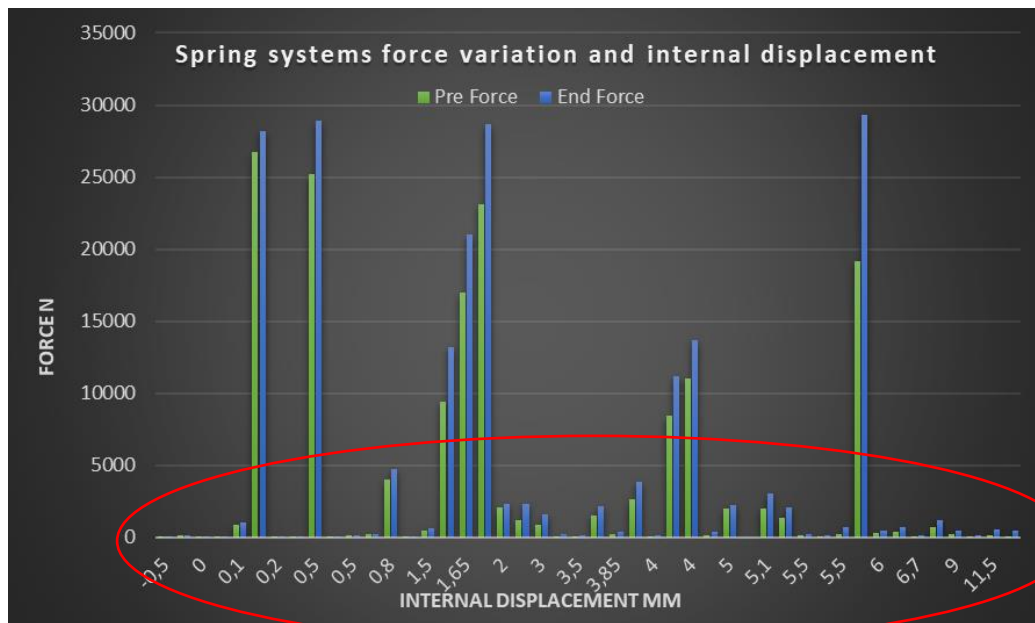
Table 11 – Data analysis and parameters establishment



- Forces between 0 to 30 kN for analysed spring systems;
- Higher force variation is located at sample 9 (10 kN of force variation);
- Samples 29 did not present historical data.

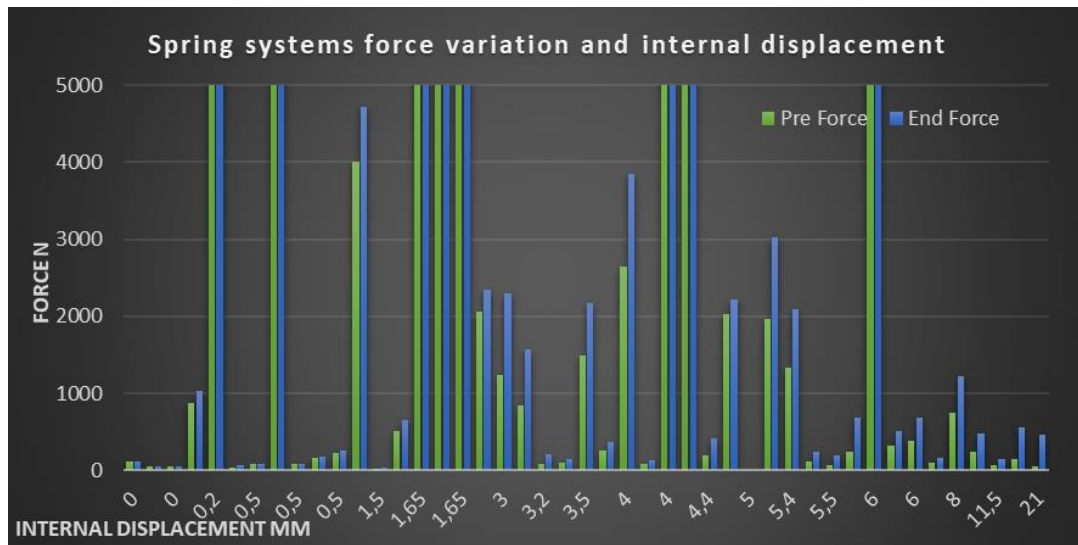


- Displacement for the spring system inside the tool dies.
- Located between 0 and 21 mm.



- Combining the two previous graphics, operating rate can be analysed.
- The higher forces sample are located in displacements from 0.2 mm to 6 mm.

- Zooming the red highlighted area



- Most of the springs systems have minimum forces of 1 kN.
- For these systems the displacement is located between 0 and 10 mm.

After discussion with the involved stakeholders, values for force and displacement during the measuring cycles aimed for:

- 1 to 30 kN.
- 0 to 10 mm.

The major reasons where:

- Small force spring systems do not present any detected problems;
- These spring functions are secondary when compared with high force spring systems, not having a direct influence on the product quality;
- One of the objectives is to prevent springs from breaking, which only happens in high force spring systems.

3.4.2 Accuracy

Accuracy is another relevant topic to be defined; a bad accuracy definition will lead to a low trust measurement device. Collected historical data and using gage repeatability and reproducibility (GR&R) method, the desired sigma was obtained from the following equation:

$$\%GR \& R = \frac{6 * \delta}{HL - LL} \tag{4}$$

Trust level (GR&R) was aimed at 10%. Since theoretical values are known, for no stroke and a full stroke applied, these values represent the high limit (HL) and the low limit (LL).

Table 12 presents force and displacement values already ordered from the most demanding accuracy until the lowest. Appendix 6 was added to provide more information about this method and data used.

The equation allows to define on which level values should be collected to ensure a proper repeatability and reproducibility to obtain a certain trust level (10%).

Table 12 – Accuracy study

Propriety				Comments
Force				
Initial force (N)	Final force (N)	Force difference (N)	Sigma (N)	
50	44	6	0.1	
46	46	0	0	
80	88	8	0.1333333333	
75	86	11	0.1833333333	
104	167	63	1.05	
60	152	92	1.5333333333	
866	1030	172	2.8666666666	
2030	2211	181	3.0166666666	<ul style="list-style-type: none"> • First value above 1 kN of force was selected (red circle); • Accuracy tolerance for the sensor should be 1 kN ± 3 N:
321	514	193	3.2166666666	
187	408	221	3.6833333333	
248	479	231	3.85	
Displacement				
Initial point (mm)	Final Point (mm)	Displacement (mm)		
45.9	45.9	0		
9.8	9.8	0		
9	9	0		
2	1.9	0.1		
27.4	27.2	0.19999999999999		
11	10.8	0.19999999999999		
14.5	14	0.5		<ul style="list-style-type: none"> • Minimal displacement (yellow circle); • Accuracy tolerance should be around 1 mm ± 1 μm; • This value would be difficult to obtain since, for this calculation, temperature, material deflection, pressure and vibration, were not considered; • A new aim was obtained (red circle); • Accuracy tolerance was targeted at 1 mm ± 8 μm.
27.6	27.1	0.5		
14.5	14	0.5		
14.5	14	0.5		
14.5	14	0.5		

3.4.3 Motion influence

Since the aim is to predict and analyse spring systems behaviour identical to their use in presses, the dynamic behaviour will be adopted. To turn the values more nearer to the presses, information was collected with the speeds of the production lines (Table 13).

Table 13 – Speed in presses

Part	Line	Speed
Cap	Line 1	CONFIDENTIAL
	Line 2	
Cutter	Line 2	
	Line 3	
	Pressto	
X	Line X	

Based on press working principle (eccentric press), the following equations were used to define presses' working parameters:

$$\text{Angular velocity} = 2 \times n \times \pi \tag{5}$$

$$\text{Crank angle} = \frac{\text{angle} \times 2 \times \pi}{360} \tag{6}$$

$$\text{RPM} = \frac{2 \times n \times \pi}{60} \tag{7}$$

With n representing the number of rotations for the press eccentric and the angle representing the theoretical angle for the press rotation location. Figure 42 may assist this parameters interpretation.

A closer to reality calculation, were performed adding to the previous equations, elements also critical for presses analysis.

Press operational values where based on real production parameters. The angle used is 90 degrees, because that is the point where the speed is highest. Figure 42 shows the mechanism principle and design properties.

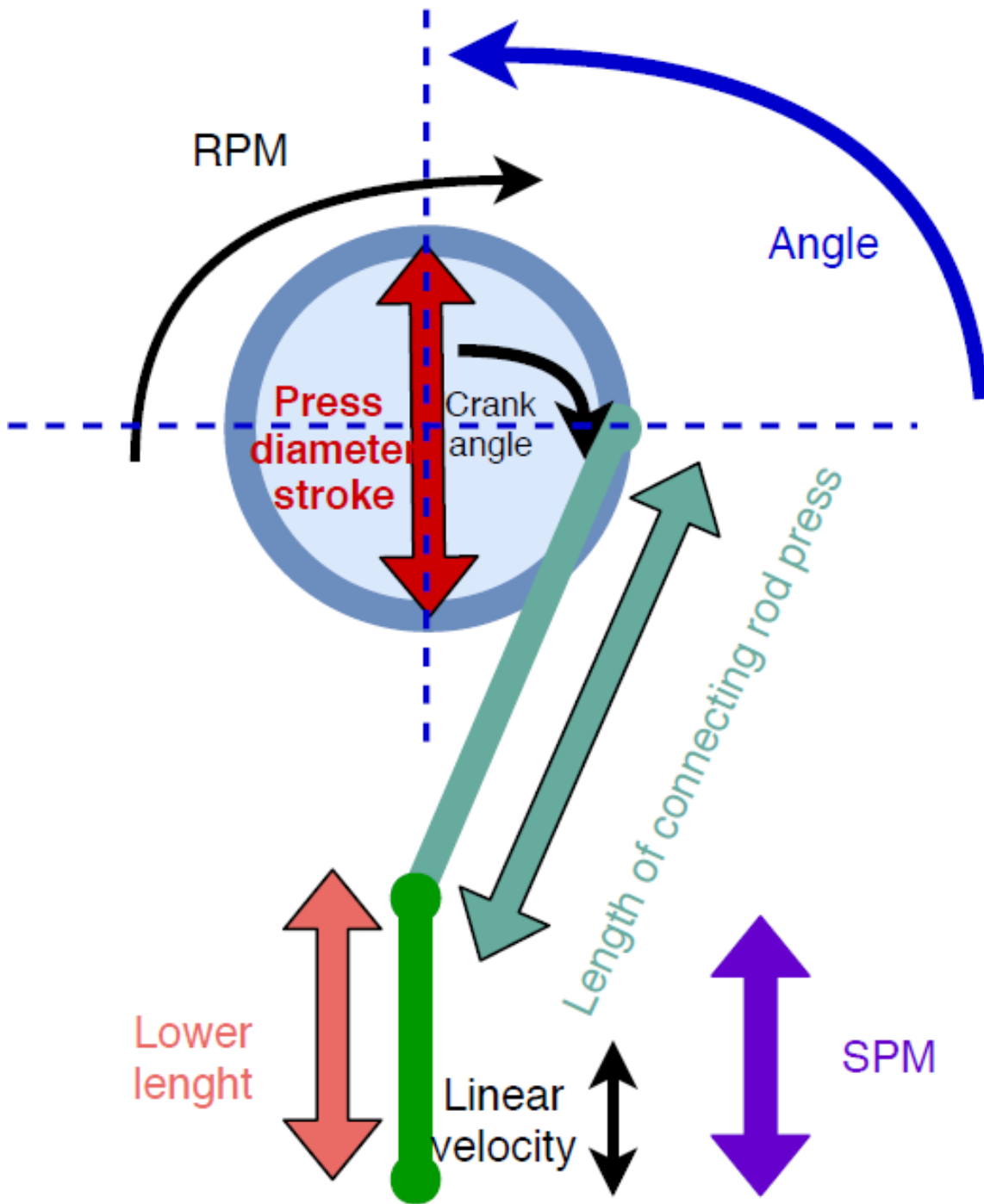


Figure 42 –Mechanism principle and important variables

Based on machine principle, conditions were set to predict linear changes.

Table 14 presents the inputted values that were used as an example. From technical experience by professionals on presses, the lower length was used as half of the press diameter stroke.

Table 14 – Press mechanism inputted values

Proprietary	Value
Press diameter stroke	40 mm
Press speed	X SPM
Length of connecting rod press	0.2 m
Angle Position	90°
Frequency	Y RPM
Crank angle	1.5708 rad
Lower length	20 mm

The linear velocity in the presses is obtained by:

$$v = \frac{RPM \times Lower\ length \times \sin (crank\ angle) + lower\ length}{(2 \times Length\ of\ connecting\ rod\ press) \times \sin (2 \times crank\ angle)} \times 3.6 \quad (8)$$

Previous considerations lead to the results presented in Table 15.

Table 15 – Velocity results

Press diameter (mm)	Velocity (m/s)
40	0.5236
	0.2513
	0.1257

With these values, it is possible to see that, at the highest point, linear motion is approximately 0.5 m/s. Looking also at minimal speeds that are achieved at presses, velocity should be around 0.125 m/s. Since the measuring displacement is short (0 to 10 mm), a 60 SPM velocity was aimed (0.1257 m/s) since:

- The measuring cycles need to be dynamic and continuous without no loss of contact between the measuring device and the spring system;
- Displacement is too short to gain higher speeds at so short travelling range;
- The displacement is different between systems, which does not allow a specific and single travelling configuration;
- 60 SPM does not reflect the real value for production lines, but is valuable as a starting reference point to collect data.

3.4.4 Technical inputs summary

After collecting all the information, Table 16 was created to resume all relevant inputs.

Table 16 – Inputs collected

Input	Values
X1 – Measuring displacement range	0 to 10 mm
X2 – Measuring force range	1 to 30 kN
X3 – Displacement sensor tolerance	±8.33 µm (maximum)
X4 – Force sensor tolerance	±3 N (maximum)
X5 – Actuation speed	0.1257 m/s (minimal) 60 SPM
X6 – Largest half tool dimension analysed	388 × 1425 × 100 mm ³ (important for the dimensions needed for the measuring device and needed space for tool-free movement)
X7 – Maximum tool weight	630 kg (total tool mass that needs to be moved)
X8 – Alignment space	±1 mm (scale needed to ensure that every point on the tool surface is measurable, obtained from mechanical drawings analysis)
X9 – Tools should not be damaged	Elements in the tool should be preserved. Even spring systems should not be broken although in some cases were springs degradation is high, break may happen.

To make easier to understand the importance of these three last parameters, Figure 43, Figure 44 and Figure 45 illustrate the importance of these properties for an accurate positioning and alignment.

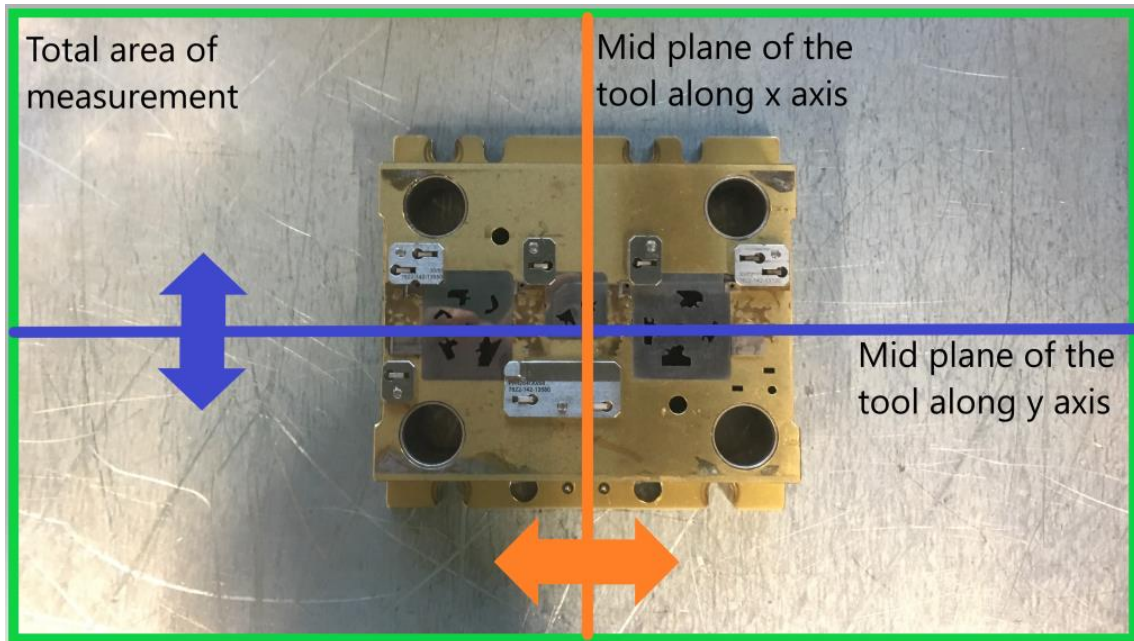


Figure 43 –Importance of x and y movement freedom

- The green box represents the area needed to perform the measurement;
- The arrows represent x and y movement that should be performed by the die tool or the measuring device;
- Movement for alignment is performed in the x and y axes

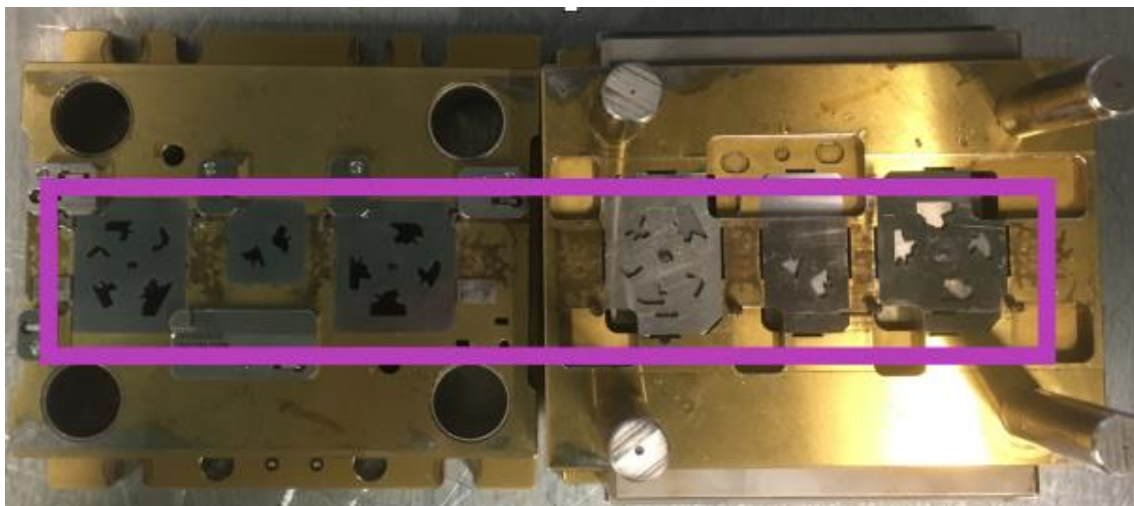


Figure 44 –Tool disassembled showing both top and bottom spring systems mechanism surfaces

- Tools are analysed separately by bottom and top part assemblies to have access to the spring system surface;
- The purple rectangle represents the total area for the entire tool section analysis

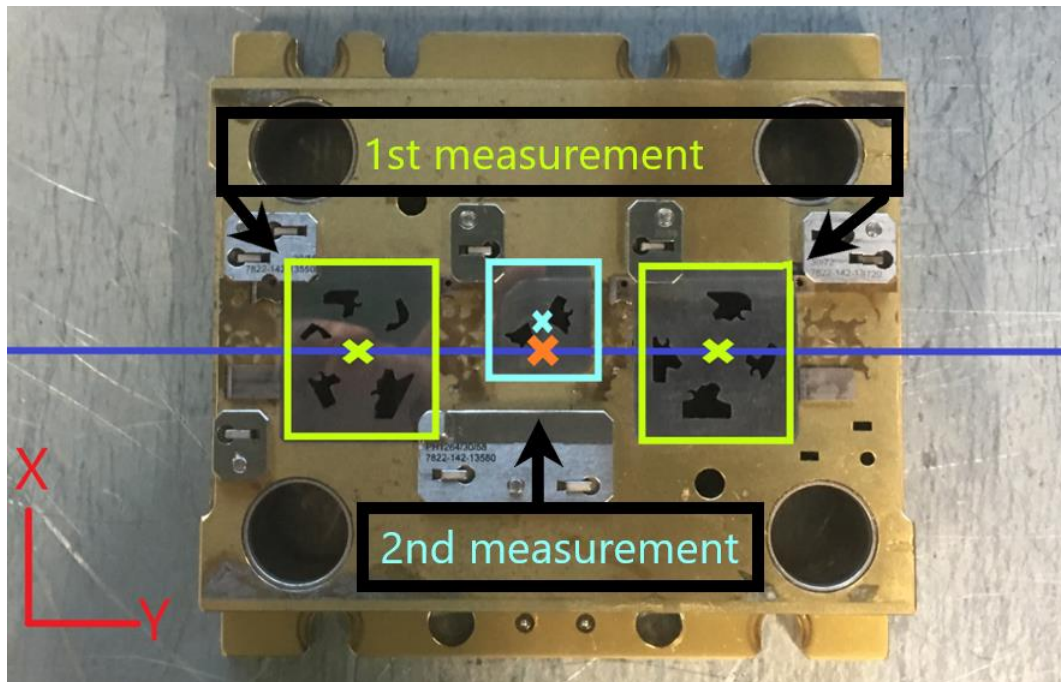


Figure 45 –Importance of 1 mm of space alignment

- Figure 45 presents a typical die tool central component;
- With two spring systems (green box and blue box);
- The boxes represent the activation area for each spring system;
- Rarely these components are aligned on the same central plane (blue line);
- The green cross represents the individual centre per spring for the green box system;
- The orange cross represents the point to have force location for the green box spring system, even though the systems should be activated in the green boxes. Figure 46 presents that principle representation.

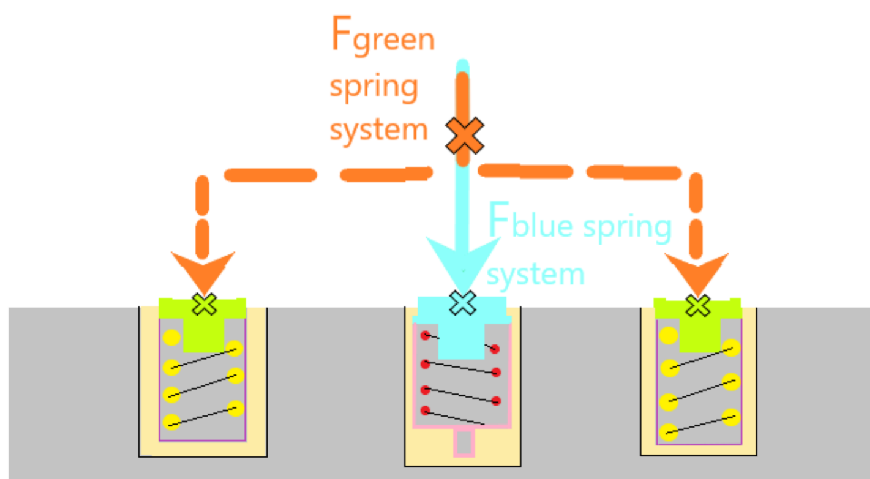


Figure 46 –Force representation for Figure 45 spring systems

- The reason to have 1 mm of alignment is to ensure that the centre of the spring system is activated during measurements. If that is not ensured, then the probability of having the spring break or escape will compromise operator safety.
- It is also important to consider that the large weight of these components makes manual movement difficult

Figure 47 represents a Kano diagram (a simple way to include other parameters that are not so easily to measure in this phase) with topics to be included in the equipment (blue boxes) and future improvements analyses (green boxes). Future improvements are not mandatory for the project but, if any of them are achievable during the project, they will be added to machine design.

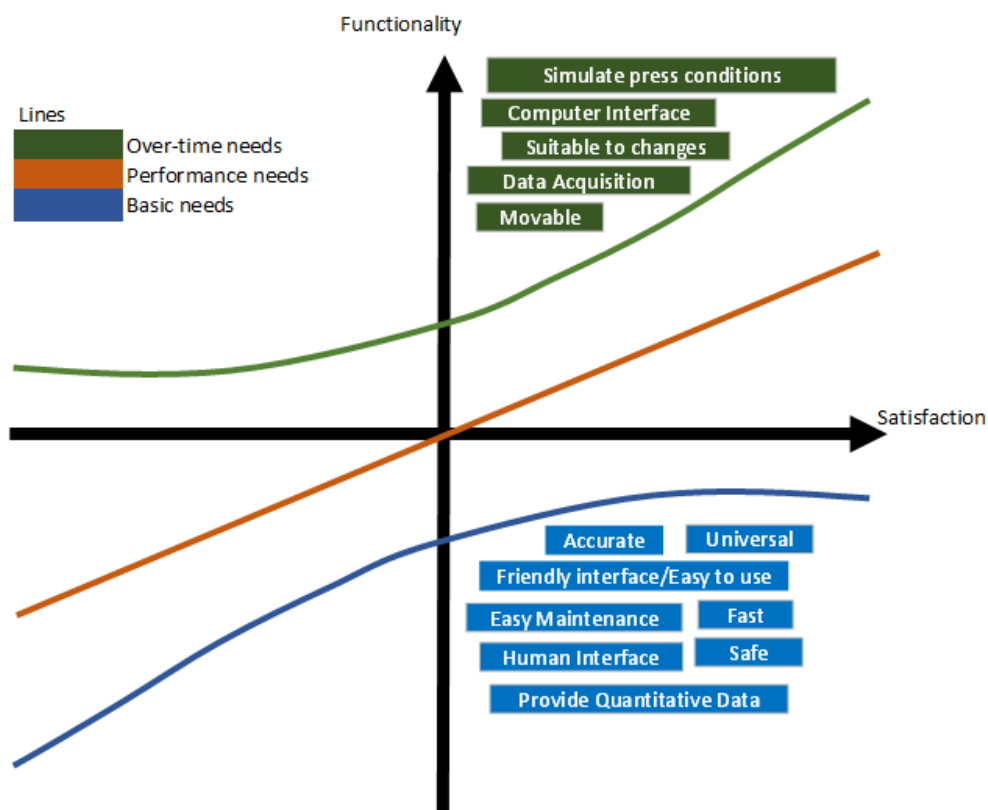


Figure 47 –Kano diagram

3.5 Concept generation

From the requirements list to start a drafting idea’s phase, the following questions arise:

- How should the tool be placed in the machine?
- Should the tool die be moveable or fix relative to the measuring machine?
- Should the measuring machine be moveable or fix relative to the tool?

- How can the alignment between the tool and the measuring machine be ensured?
- Should the testing speed allow velocity variation or should the velocity always be the same?
- Which mechanism will produce speed, force and displacement during the test?
- Which type of sensors should be used for measuring force and displacement?
- Are sensors accurate enough according to the required accuracy for a proper testing?
- How is data collected?

Collecting some of the critical points obtained from previous chapters and possible answers for the concept machine, a “*Morfologisch overzicht*” or Morphological overview (M.O.) was achieved (Figure 48). The idea for the M.O. is to think and combine possible practical scenarios for the machine design. The big advantage of this concept is the fast and easy perception for the reader. Many concepts can be created and inputted options can always increase. To present and have a proper M.O., some brainstorm and review meetings should be performed for a higher trust on available options (Appendix 7).

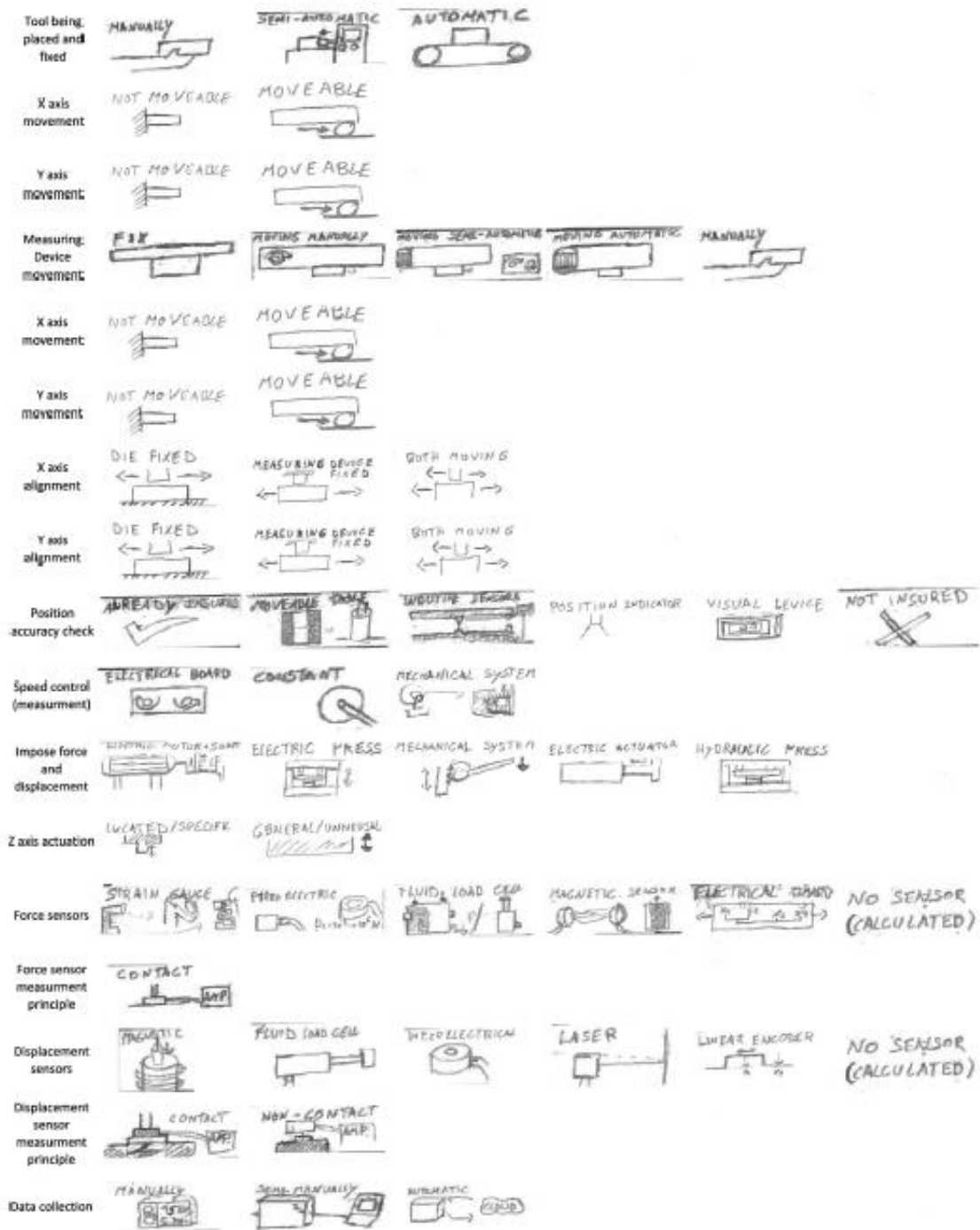


Figure 48 – “Morfologisch overzicht”

To aid in selecting the principles and values capacity for sensors, some scientific papers were consulted [41, 42], books [43, 44] and the OMEGA technical handbook [45]. Figure 49 represents two tables with relevant information related to the selected sensors.

Force							
Sensor	Requirements	Strain Gauge	Piezoelectric	Fluid Load Cell	ElectroMagnetic Sensor	LVDT	Electrical Board
From (N)	1 kN	0.1	0.0015	500	0.01	0.01	System dependent
To (kN)	30 kN	0,1	120000	500000	1000	1000	
Accuracy (%FS)	10	0.2-1	0.3-1	0.25-5	0.5-2	0.5-2	
Displacement							
Sensor	Requirements	Magnetic	Fluid Load Cell	Piezoelectric	Laser	Strain gauge	Linear Encoder
From	0 mm	1 μm	0.5 mm	10 μm	Nanometers	10 μm	Nanometers
To	10 mm	500 μm	500 mm	10mm	Meters	500 μm	Meters
Resolution (nm)	8.33 μm	0.49	5	2.4	0.49	23	6
Accuracy (%FS)	10	1	0.25	0.1	1ppm	1	5ppm

Figure 49 – Reference values for sensors

From the force table (Figure 49):

- Force sensors present a wide range of application;
- Looking at force requirements, most of the sensor applications are suitable;
- Electrical board’s sensors are single case scenarios; therefore an estimation value is difficult to obtain.
- One of the factors that makes force sensors not being the most concerning technology to be used, is the high internal use and existence of this equipment.

From the displacement table (Figure 49):

- Displacement sensors are more targeted depending on measuring scale;
- Resolution for the displacement sensors was also taken into account since this parameter is critical and has a high demand for test quality;
- Even though some sensors may not fulfil the requirements necessary in this stage, it is more important to ensure diversity and different working principles.
- This table represents an overall study at displacement sensors;
- Some special application can be also performed to change “standard” measured values by the sensors although they increase costs.

After setting and analysing possible alternatives and adding them to the M.O. some paths were formulated to create and produce machine evaluation concepts (Figure 50).

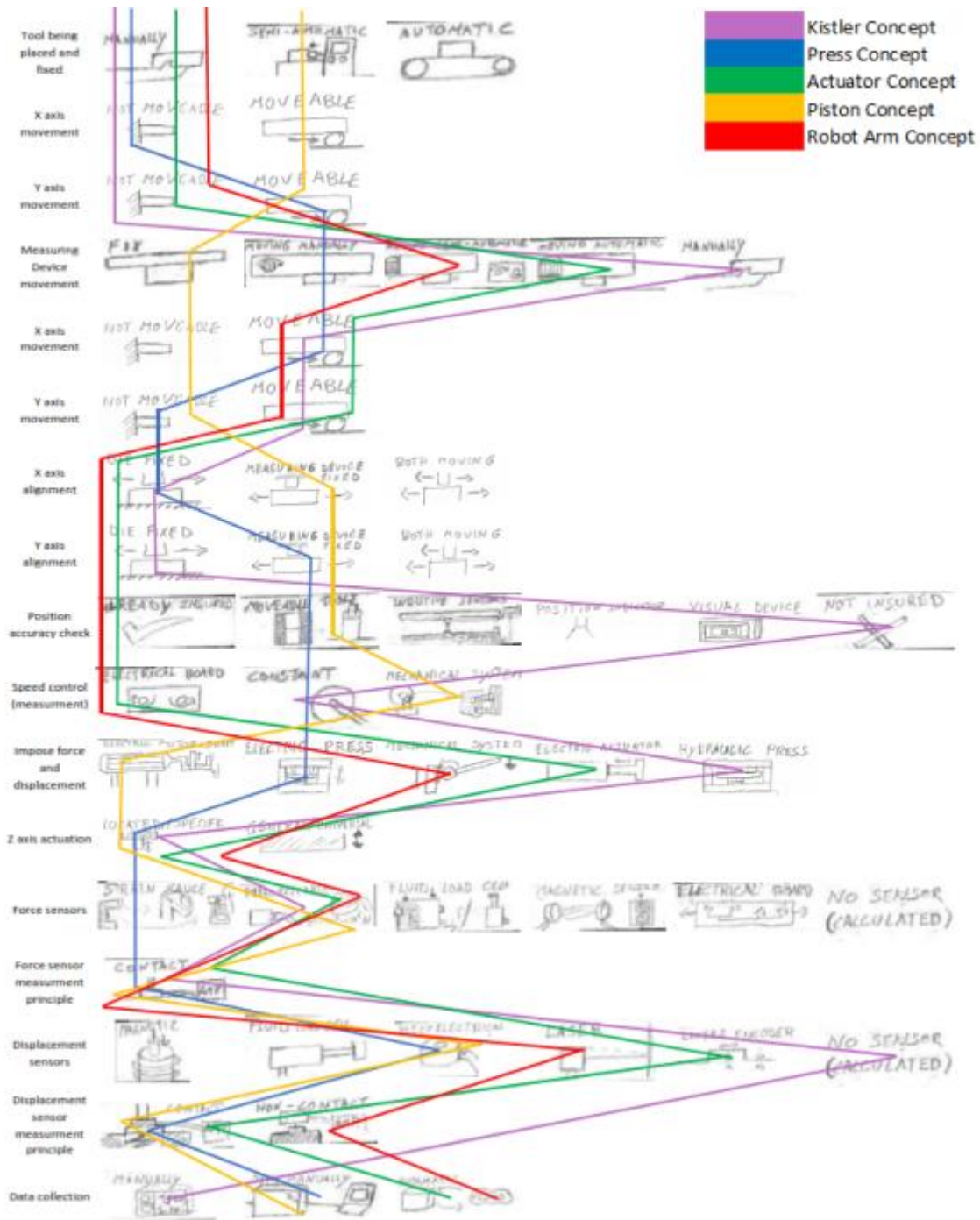


Figure 50 – “Morfologisch overzicht” paths

3.6 Review concepts

After the generation of concepts, these were revised to avoid omissions of systems as well as to gain consciousness about their functioning for future evaluation. The following sub-chapters (3.6.1 to 3.6.5) will present a high level look at them. Further information can be found in Appendix 8.

3.6.1 First option – “Kistler concept”

This first concept (Figure 51) was elaborated only to use internal resources. The following notes can be taken into consideration from it:

- Only internal resources are used;
- The press is hydraulic;
- Low speed;
- Machine design is not needed;
- Stiffness and robustness ensure accuracy;
- The movement is fully performed by the measuring machine;
- Only force sensor is used;
- Displacement is determined based on force values;
- Big time for setup configuration;
- Inspired on Sadílek [46] work.

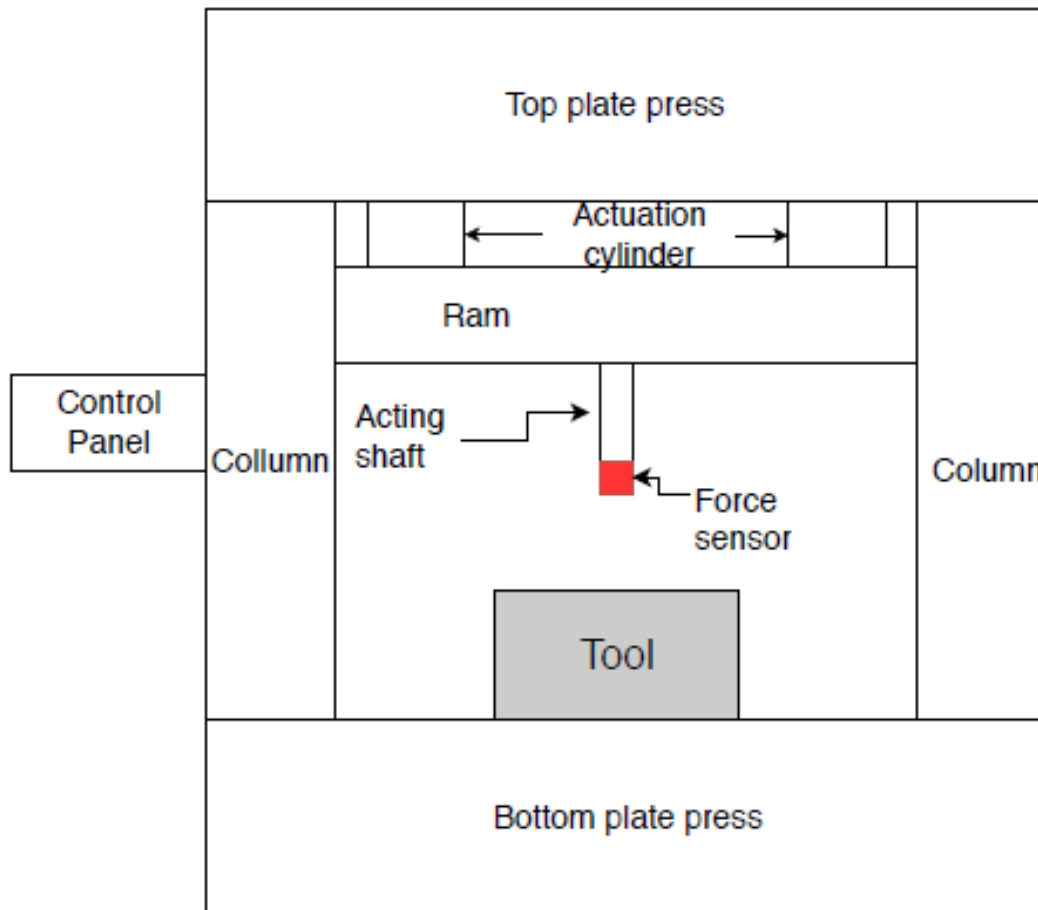


Figure 51 – Kistler concept

3.6.2 Second option – “Press concept”

This second concept (Figure 52) uses an eccentric servo-electric press. Notes can be summarized to:

- Use of a servo-electric press;
- Speed identical to production lines;
- High stiffness and robustness to ensure accuracy;
- High cost compared with other concepts;
- Bottom plate of the press needs to be specially made to allow die tool movements;
- Positioning system is divided between the tool and the measuring device;

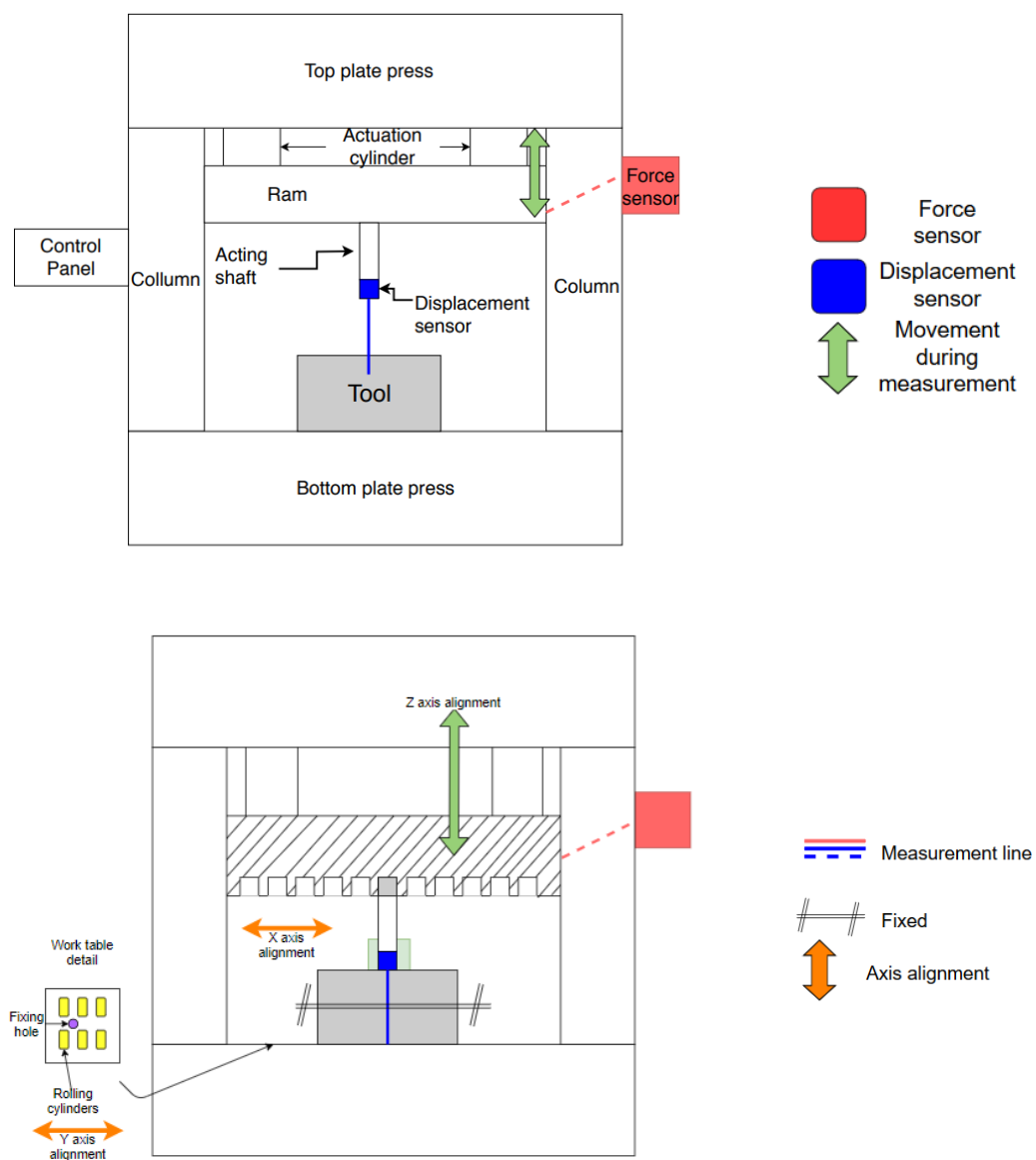


Figure 52 – Special press concept design

3.6.3 Third option – “Actuator concept”

This third concept (Figure 53) uses an actuator to emulate a working press principle. These devices usually already present internal sensors. The following notes recapitulate concept major ideas:

- Use of a servo electric actuator;
- Use of actuator internal sensors;
- Cheaper alternative to a press;
- Fully automated;
- Use of a gantry system;
- Displacement measurement relative to the tool surface.

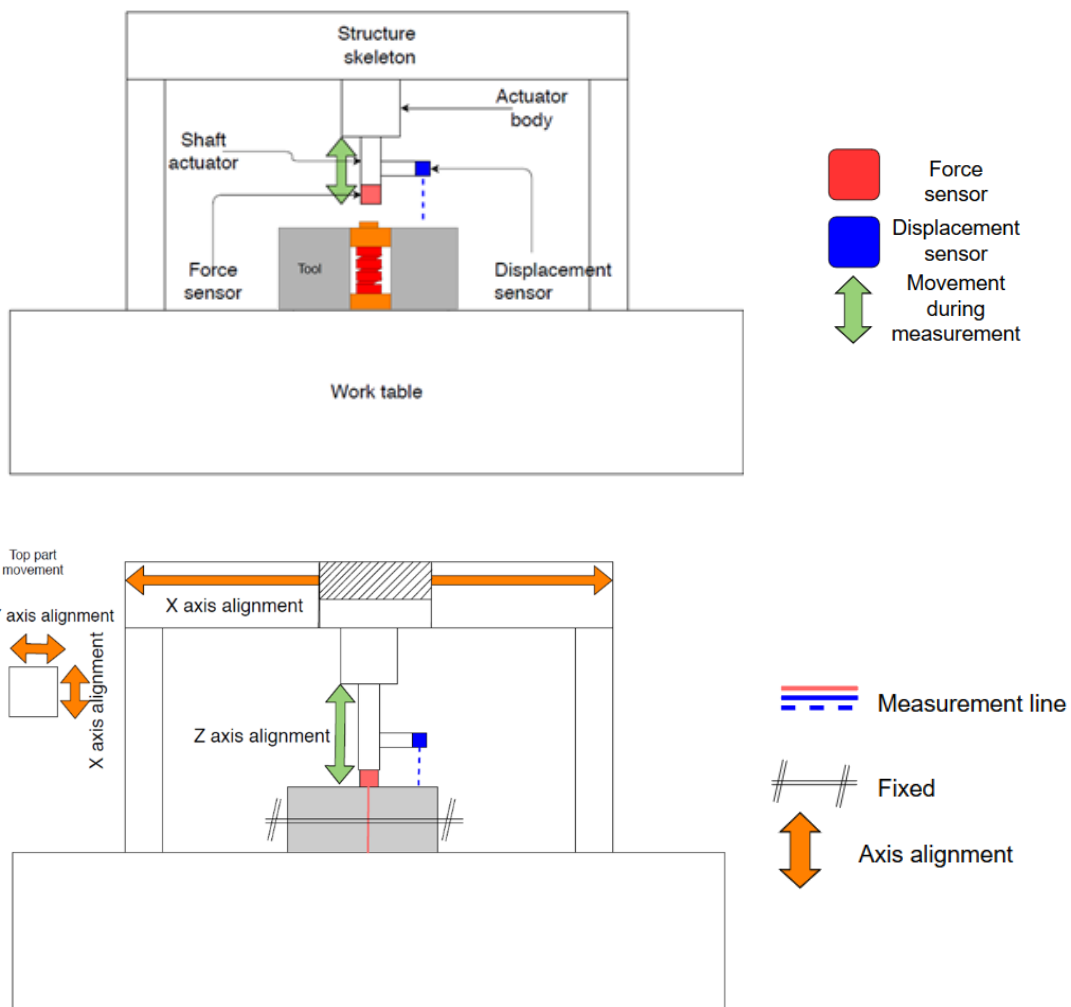


Figure 53 – Actuator concept

3.6.4 Fourth option – “Piston concept”

In this fourth concept (Figure 54) a motor and a shaft are combined to emulate a press. This concept is an experimental idea with the following’s thoughts behind it:

- Under dimensioning of a press;
- Create the working principle for a press with integrated sensors (Figure 55);
- Particular solution (market options are not available);
- Speeds identical to production.

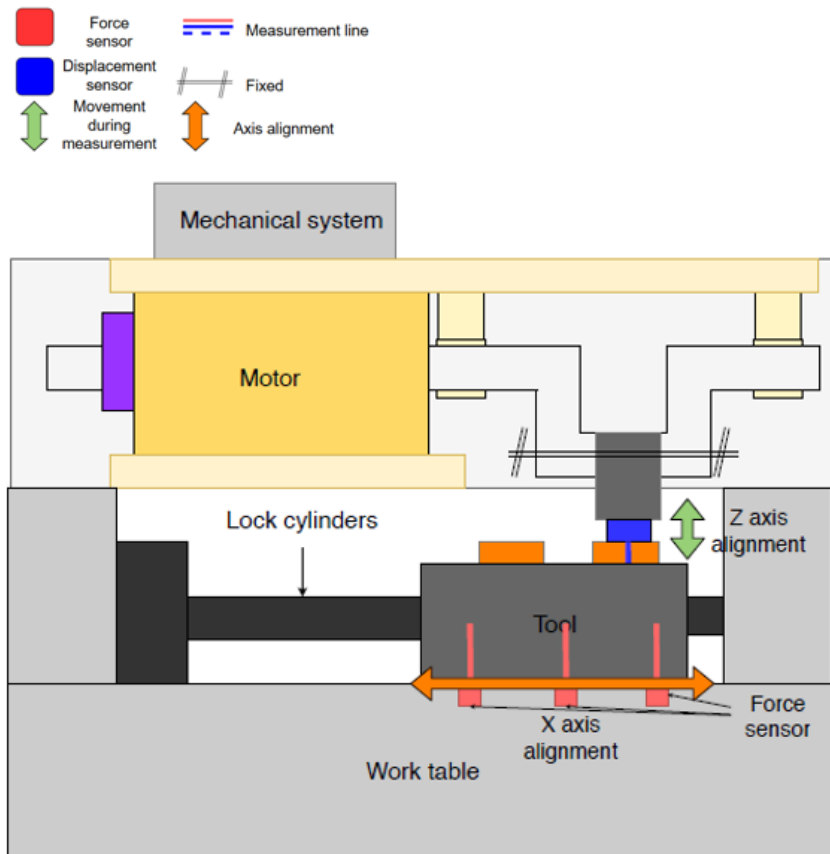


Figure 54 – Piston concept

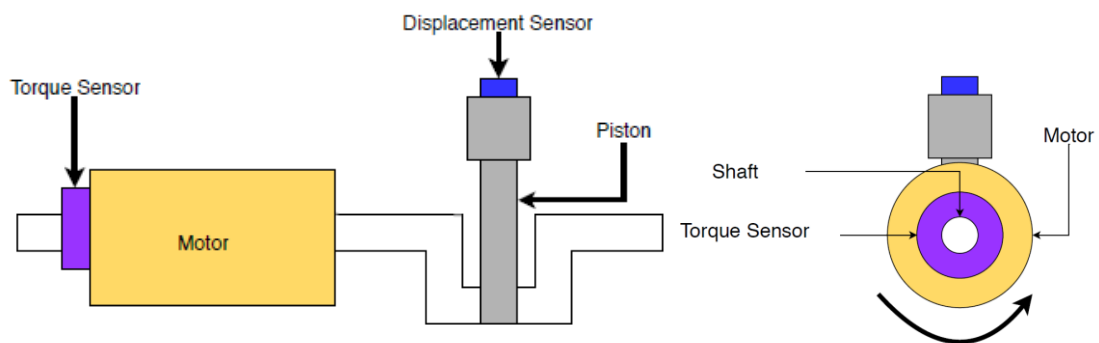


Figure 55 – Piston machine principle

3.6.5 Fifth option – “Robot arm concept”

For the fifth concept (Figure 56), a robot arm is used to push and force the spring systems inside the dies with force superiors to human capacity:

- Use of a robot arm;
- Easy reachability for the three acting axes;
- Complex to automate for the desired application;
- Speeds are limited;
- High cost.

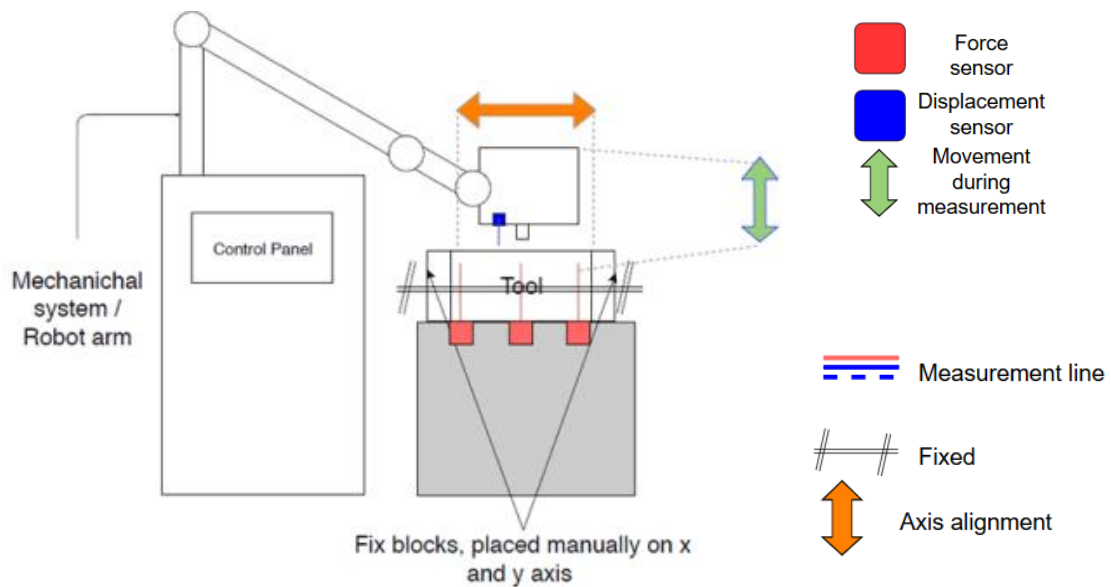


Figure 56 – Robot arm concept and arm example

3.7 Concept selection

To do a proper decision on the concept to adopt, Table 17 represents the chosen parameters and motivations behind it. The first property is based on technical requirements (3.4.4). The remaining properties are not as measurable but also reflect important parameters some of them already discussed in a previous chapter.

Table 17 – Evaluation parameters

Property	Question marks	Motivation
High Measurement Accuracy	How well does the concept measure and how trustful is the data?	Since a measuring device is desirable, accuracy during measurement needs to be evaluated for which concept.
High Safety	How safe is the machine to use?	Ensure safety for everyone using the machine is also an important topic to reduce workplace accidents.
Low Cost	How much does it cost?	An overall look at the full expense on the device (initial investment, cost per operation, training costs, etc).
Low Time	How much time does the machine take to perform a measurement?	Total time to use the machine.
Project Feasibility / Availability	There are already solutions for it on the market?	An existing solution decreases the time of the project and also assist full machine design.
Low Maintenance/Fatigue	When will the machine fail? How much maintenance does the device need?	Machine operability is important, so working breaks need to be reduced and decrease as much as possible. Maintenance should also be easy to perform.
Universal	How universal is the machine for different force and displacement ranges?	A universal machine is suitable for all spring systems.
High Robustness	How reliable is the structure?	To ensure high force application and reduce elements bending, shear and tear. Accuracy for the sensors can also be affected by a low robustness.
Friendly interface/Easy to use	How easy it is to use the machine?	A friendly human interface should be implemented. This will allow having a large number of people using the machine.

By mentor suggestion, a Pugh matrix was elaborated (Figure 57). More information about Pugh matrix method and template used can be found in Appendix 9. The following rules were implemented:

- Piston concept was locked as the standard concept;
- The standard concept represents the principle behind presses (crank and piston principle);
- Key stakeholders were challenged to fulfil a personal evaluation;
- Notes to evaluate concept could be “++”, “+”, “S”, “-”, “--”;
- “++” represents the highest score and “--” the lowest;
- The notes are given relative to the standard concept;
- Importance rating column was left open to allow personal choice of the most important properties.






Pugh Matrix							
Solution Alternatives							
		Importance Rating	Piston	"Kistler"	Press	Actuator	Robot arm
Concept Selection Legend							
Key Criteria							
Measurement Accuracy			S				
Safety			S				
Cost			S				
Time			S				
Project Feasibility / Availability			S				
Maintenance/Fatigue			S				
Universal			S				
Robustness			S				
Friendly interface/Easy to use			S				
Sum of Positives			0	0	0	0	0
Sum of Negatives			0	0	0	0	0
Sum of Sames			9	0	0	0	0
Weighted Sum of Positives			0	0	0	0	0
Weighted Sum of Negatives			0	0	0	0	0
TOTALS			0	0	0	0	0

Figure 57 – Pugh matrix template

At the end, the values were analysed to ensure results conformity. The results were then combined, and a graph was created to simplify results interpretation and analysis (Figure 58).

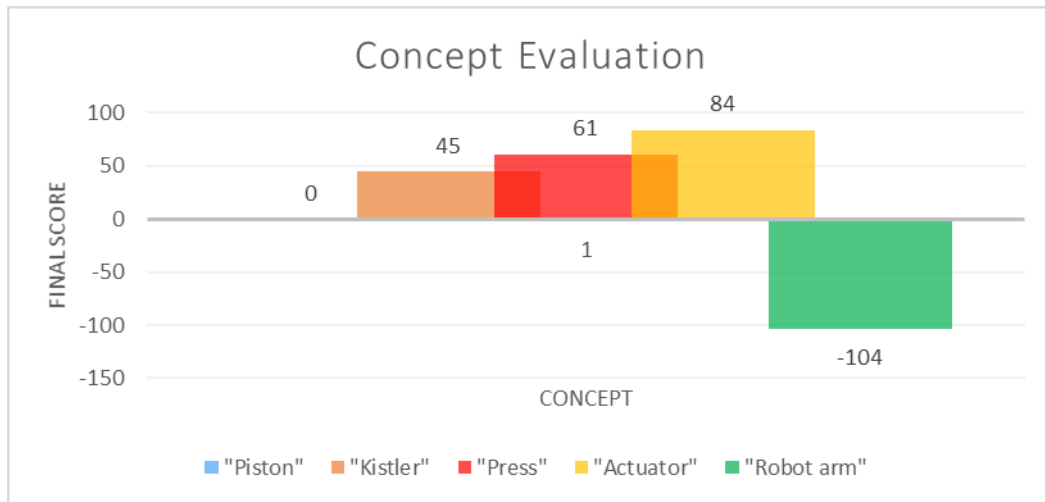


Figure 58 – Pugh matrix concepts score

Following, the conclusions were also pointed out:

- The press structure can be difficult to adopt for the sensors and for the tool moving system;
- The press is also a mechanism more difficult to control on safety;
- The press is also more expensive than an actuator;
- The actuator is the most versatile system;
- The actuator can be automated;
- The actuator achieves desirable speed;
- The actuator concept must be optimized for the design and principle of critical components.

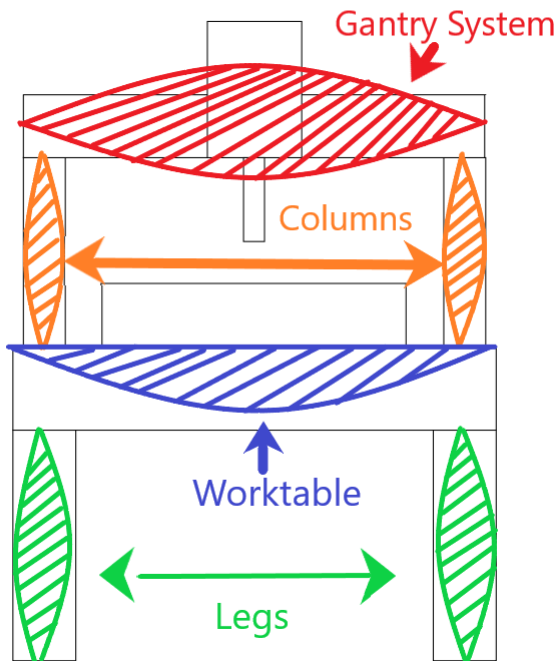
3.8 Optimizing concept

From the actuator concept, some questions are still open:

- Does an internal displacement sensor on the actuator ensure accuracy?
- What alternatives can be used externally to measure displacement instead?
- Do gantry systems support 3 tonnes of force under dynamic use?
- Is it safe to use a gantry system with such high forces?
- What positioning mechanism can be used instead?

3.8.1 Displacement external sensor

Displacement is the key element for proper measurement because the offset will be used to control the measuring range due to short travel.



The dynamic movement will produce deflection and bending (represented by the coloured areas).

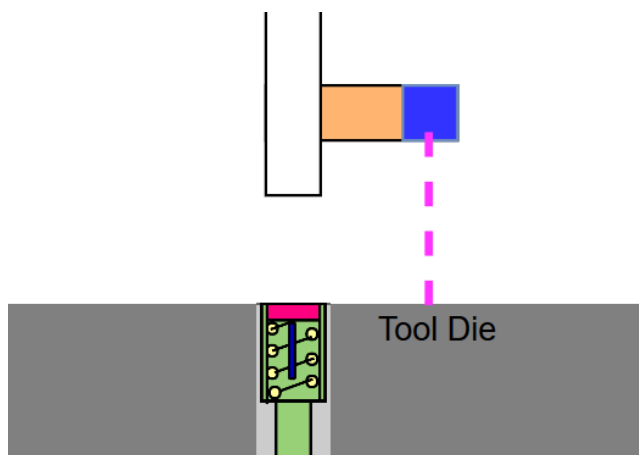
To prevent errors during the measurement, the full system deflection would need to be lower than 1 μm .

This deflection constraint would make the system heavy, highly costly due to the use of high Young's Modulus alloys, highly time-consuming for design optimization, and the occurrence of fatigue in the structure could lead to wrong measurements.

The use of an external sensor can solve that problem since fewer elements need to be controlled.

Figure 59 – Structure deflection and bending

Figure 59 presents the consequences of using an internal sensor. As an alternative, if an external sensor (Figure 60) is used, the topics that need to be covered are presented.



The connecting body between the actuator cylinder and the displacement sensor (orange rectangle) needs to be designed to support vibration, bending and weight influence.

The system to measure the displacement relative to the tool surface (pink line) needs to be higher than 10 mm, to ensure that during measurement blank points do not occur.

Figure 60 – External displacement sensor

Since for this system only Linear Variable Differential Transformer (LVDT) and Laser sensors are suitable for work application, Figure 61 was created to summarize the main characteristics for both options.

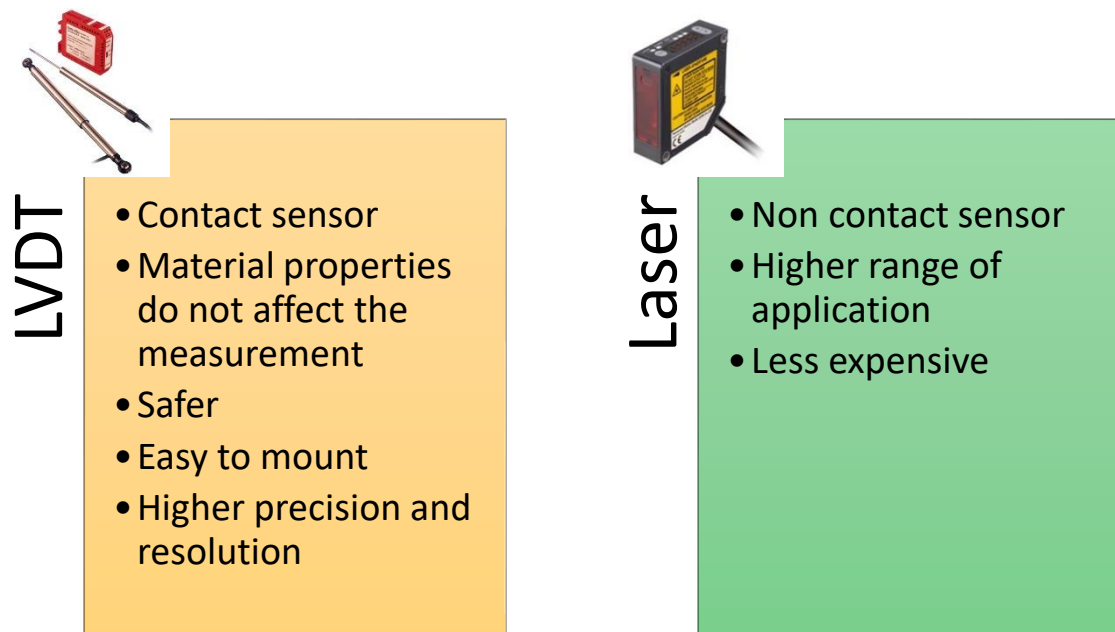


Figure 61 – External sensor options and respective advantages [47, 48]

After presenting the proposal to the stakeholders, it was decided to move forward with an LVDT sensor, since:

- A contact sensor prevents errors;
- It is easier to detect contact sensor errors;
- The measurement range is shorter;
- Safety should have a higher impact than cost.

3.8.2 Positioning mechanism

After looking deeper into the market options for gantry systems capable of holding 30 kN of force, no system was found with such characteristics due to force requirements. It was decided to do a second study only about the positioning system with an actuator and an external sensor on it.

The major points to be achieved by this mechanism are:

- Movement on x and y axes;
- If the movement is performed on the actuator, it needs to support forces of 30 kN (minimal) and have control mechanisms to ensure a fixed position during measurement;
- If movement is performed on the tool, the dimensions of the bigger tool are locked at 1425(l) × 388(w) × 100(h) [mm³] and the weight is locked to 630 kg (total tool weight);
- Alignment space of 1 mm;
- Aimed floor space :3 m × 1.5 m.

Looking for similar machines, compression testing machines usually only have movement in one axis (Figure 62). The most near to desirable functions would be a computer numerical control (CNC), although conventional systems do not have such high forces acting (Figure 63).



Figure 62 – Compression testing machine [49]



Figure 63 – CNC milling machine [50]

Using the dimensions of the tool, some sketches were made to facilitate analysis in the positioning system options.

Following chapters (3.8.2.1 to 3.8.2.6) will present summary tables (Table 18 to Table 23) where the main ideas behind motion and positioning concepts are discussed.

3.8.2.1 Concept 1 – “Measuring tank”

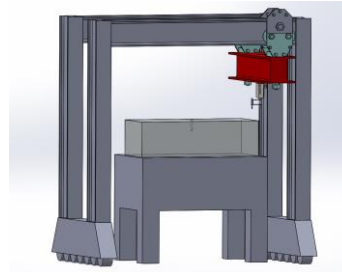
Identically to a tank the structure is robust, heavy and moveable.

Table 18 – Measuring tank summary table

Movement alignment was based on cranes used in ships.

Measuring device is the only moveable element (X and Y axis).

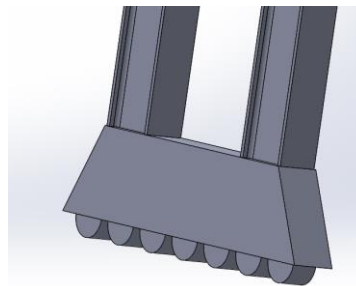
Tool is easily reachable.



X alignment is performed manually by the operator pushing the device.

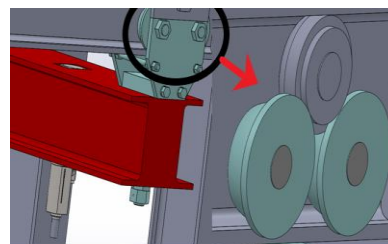
Wheels must have a break to prevent movement once the alignment is obtained.

Railways can also be used to ensure more control of this movement.

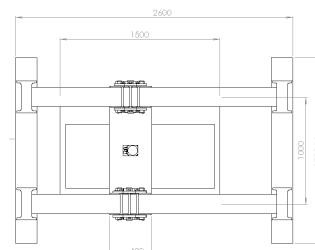


Y alignment is assisted by a motor ensuring higher precision and accuracy.

To prevent the beam fall due to the dynamic movement, a “planetary gear system” was created.



Dimensions for the concept (a higher resolution picture can be found in Appendix 10).



3.8.2.2 Concept 2 – “Neo”- a futurist approach with automated systems

A futurist approach with automated systems.

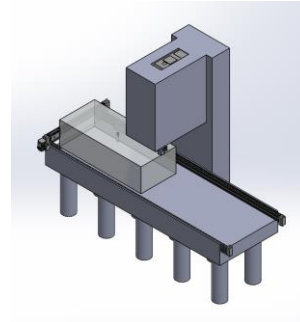
Table 19 – Neo summary table

Based on CNC.

Worktable is the only element moveable for X and Y axis.

Tool is easily reachable from one side.

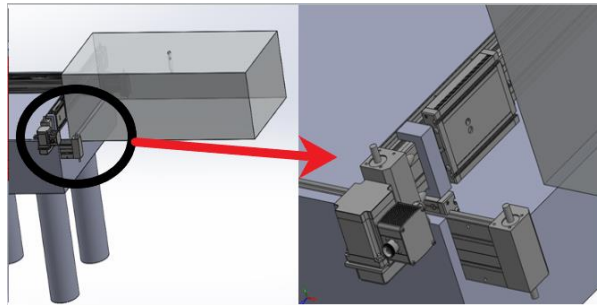
The actuator tower is fixed to the centre of the table.



The tool is fixed to a double linear guide unit.

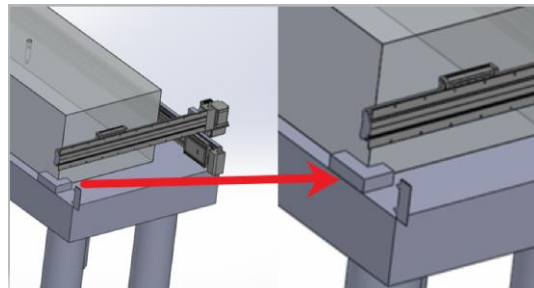
The linear unit is connected with a motor to ensure a high control on tool positioning.

Automated.

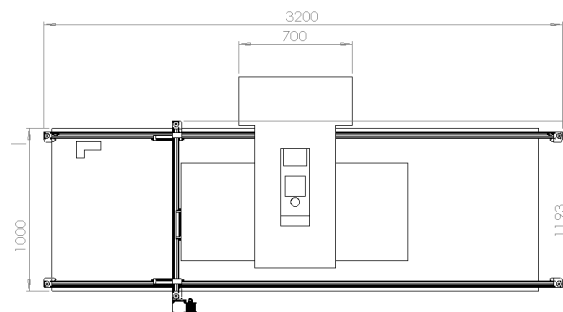


The first movement is to position the tool against a physical control point.

This point is the reference point to then create fully automated functions to test all spring systems.



Dimensions for the concept (a higher resolution picture can be found in Appendix 10).



3.8.2.3 Concept 3 – “Drive thru” – Like on a drive thru, a car is moved and the service is performed.

Like on a drive thru, a car is moved, and the service is performed.

Table 20 – Drive thru summary table

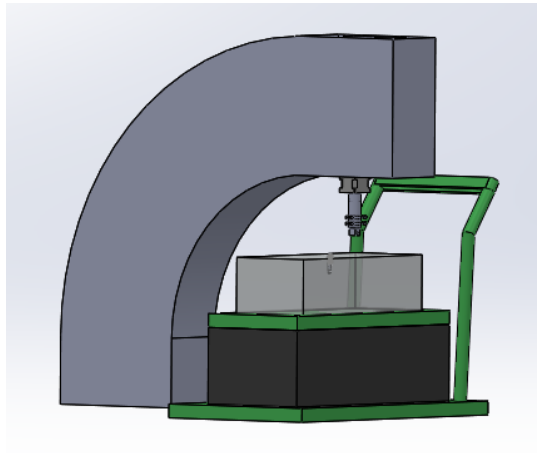
Based on drive thru.

The green car is the only element moveable for X and Y axis.

The tool is easily reachable from one side.

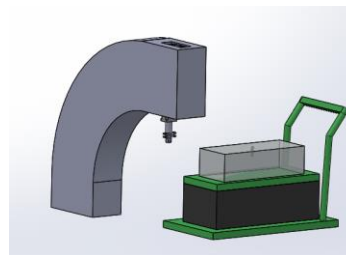
The actuator is fixed on a space with enough space for the car reachability.

Flexible and virtually cheap because the car is not only applicable to this machine use.



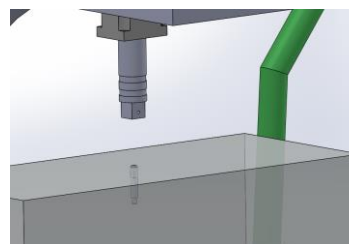
The tool is moved until matches the actuation tower.

An air system identical to a hovercraft is used under the car to make movement easy.

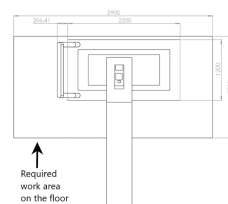


The positioning is fully manual.

After being positioned, air can be released to make the car unmoveable.



Dimensions for the concept (a higher resolution picture can be found in Appendix 10).



3.8.2.4 Concept 4 – “Bowie” – Under pressure the tool is moved

Under pressure the tool is moved (hydraulic system).

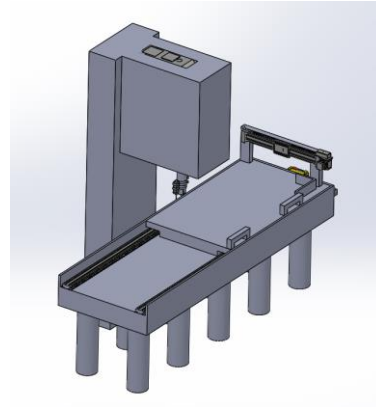
Table 21 – Bowie summary table

Based on Philips 7822 142 2480 system.

The working table is the only element moveable for X and Y axis.

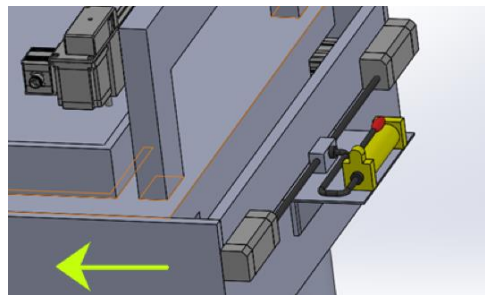
The tool is easily reachable from one side.

The actuator is fixed on table centre.



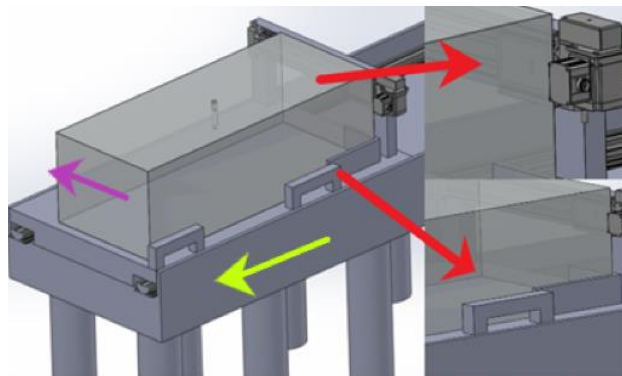
The tool is moved semi-assisted with guide rails.

A hydraulic pump system is used to lift cylindrical rollers to allow movement on the arrow direction.

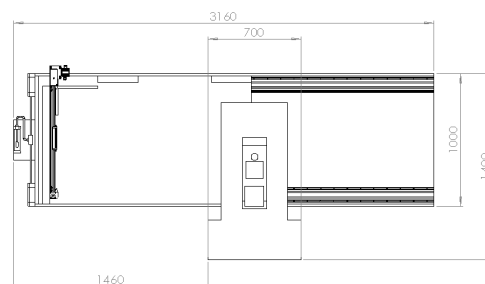


A linear guide unit moves the tool on the remaining direction (purple arrow). This movement can either be semi-manual or automated.

Handlers assist tool movement on the lime green arrow direction.



Dimensions for the concept (a higher resolution picture can be found in Appendix 10).



3.8.2.5 Concept 5 – “Mermaid” - Like a mermaid the systems is a hybrid that divides movement on two different systems

Like a mermaid the systems is a hybrid that divides movement on two different systems

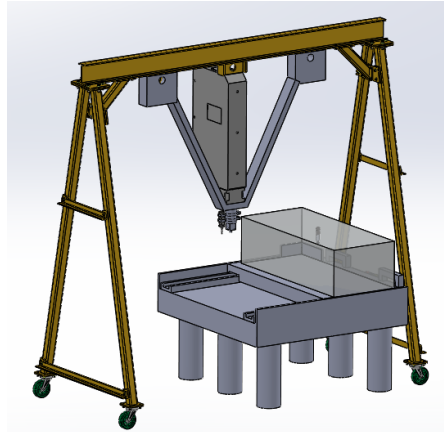
Table 22 – Mermaid summary table

Division of movements between both elements.

The working table is moveable for X direction.

The actuator is moveable for Y direction.

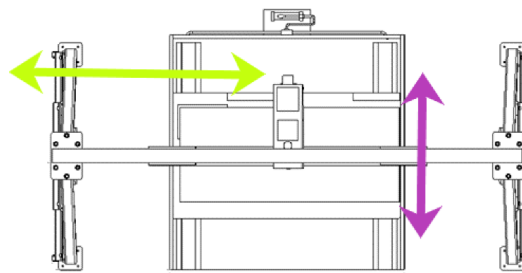
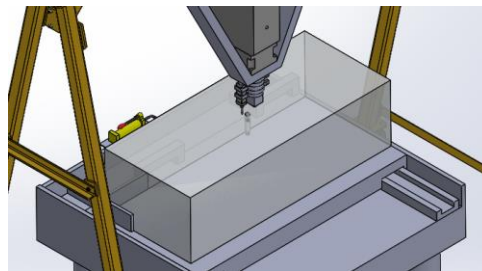
The tool is easily reachable.



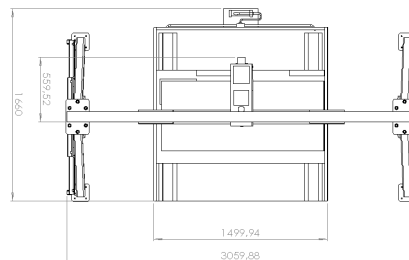
Positioning is dependent on the operator capacity and the matching between two elements (table + crane).

A hydraulic system is used to lift the tool and move it on purple arrow direction.

The crane with the attached actuator is moved on the lime green arrow direction.



Dimensions for the concept (a higher resolution picture can be found in Appendix 10).



3.8.2.6 Concept 6 – “Vegas”- Go all in and combine all elements in a worktable.

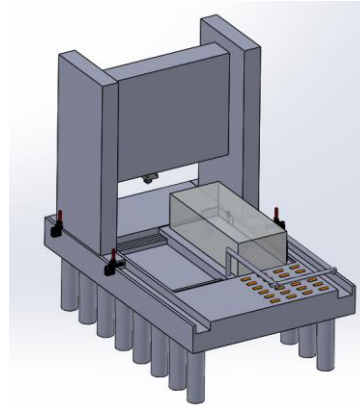
Go all in and combine all elements in a worktable

Table 23 – Vegas summary table

Single machine.

Movement for x and y axes is performed in the bottom region of the measuring device.

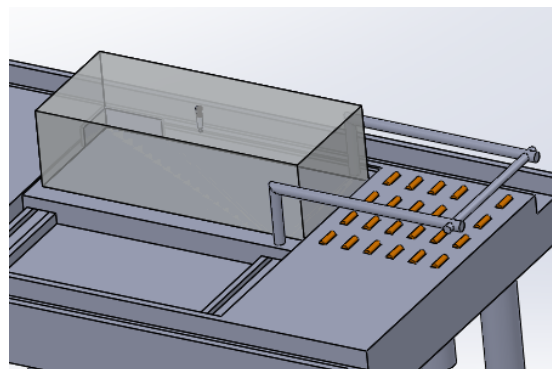
The tool is difficult to reach, and accessibility is low when compared to other concepts.



Tool is placed on the table being pushed until the central area assisted by the orange rollers until it matches a control position.

The central region presents a surface moving under a linear guide unit.

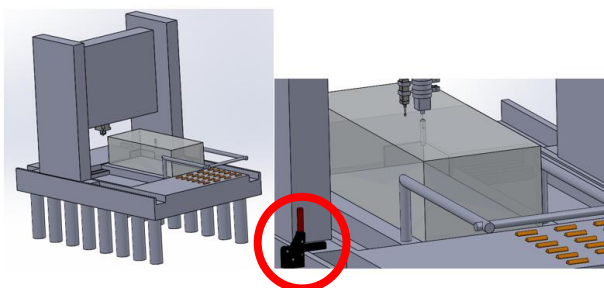
Automation is possible.



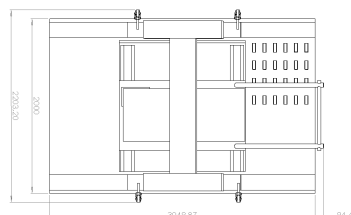
The tower with the actuator is also moveable under a linear guide unit.

Automation is possible.

Clamping tools (red circle) can be used to ensure more safety and prevent frame fall.



Dimensions for the concept
(a higher resolution picture can be found in Appendix 10).



3.9 Optimized concept selection

To meet the expectations for the final draw of the machine, as well as to have a universal decision on the motion system, a Pugh matrix (Figure 64) was elaborated and filled by the stakeholders. This second evaluation is a key factor for the final optimized machine concept. More information about this project stage can be found in Appendix 11



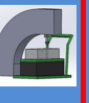
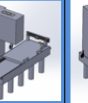
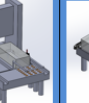
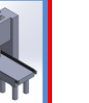
Pugh Matrix							
Solution Alternatives							
Key Criteria	Importance Rating	Mermaid	Tank	Drive thru	Bowie	Vegas	Neo (automated tool positioning)
							
Positioning accuracy	5	S	-	-	+	+	++
Vertical system stiffness	4	S	-	+	+	++	+
Surrounding independency (wall/floor)	5	S	S	S	++	++	++
Size	3	S	+	+	++	+	++
Safety	5	S	S	++	+	+	++
Investment	1	S	S	+	+	S	-
Positioning time	2	S	S	-	+	+	++
User friendliness	4	S	S	++	+	+	++
Sum of Positives		0	1	7	10	9	13
Sum of Negatives		0	2	2	0	0	2
Sum of Sames		8	5	1	0	1	0
Weighted Sum of Positives		0	3	26	37	37	52
Weighted Sum of Negatives		0	9	7	7	7	0
TOTALS		0	-6	19	30	30	52

Figure 64 – Pugh matrix results on positioning system.

From the meeting, the following conclusions where drawn:

- Neo is the reference concept, but both Bowie and Vegas top points should be added to the final machine concept;
- Bowie is non automated, presenting a less complex system and lower investment;
- Vegas fixed frame is the best option, allowing a reduction of contact points for the machine with the floor;
- The actuator frame needs to be unmoveable, to prevent and decrease the red zone (less safe zone). That way it is also possible to divide safety into more steps: an initial step about positioning safety and a second cycle for the measurement (Figure 65);



Figure 65 – Red area for a fixed actuator vs red area for a moving actuator

- Another factor to have a fixed frame is the fact, that during research, none of the analysed compression testing machines presented movement. The closest system to take as a reference would be a CNC, although these systems usually do not operate on the dynamic system or either on this range of compressive forces. This “historical” factor reinforces the principle to have a fixed actuation frame.
- The positioning system should be as simple as possible. Factors like operator training, operating costs, system complexity and a number of elements need also to be taken into account.
- The machine concept principle should allow future automation, but in this stage semi-assisted movement should be performed.

3.10 FMEA – Failure Mode Effect Analysis

Safety is the most important factor for the measuring machine. FMEA can be used to predict and analyse possible failures including safety (more information about this tool is available in Appendix 12). The FMEA performed can be found on attached documentation. From an initial analysis, some counteractions were taken to prevent failure:

- Add a more secure control mechanism (light/laser pointer) to match a small engraving on the tool surface;
- Create a barrier to restrain tool movement range;
- Add a pressure control system to inspect pressure inside the hydraulic mechanism.

3.11 Final Concept

The final design (Figure 66) of the machine must feature a machine with a table having movement in the x and y axes with the ability to move all the tools, and a fixed structure with movement in the z axis. The desired size for the machine is 3 meters by 1.5 meters, with 4 meters in height, and with capacity of alignment space of 1 mm. The mobile system needs to be as simple as possible. Tool should not be damaged with movement. A servo-electric actuator is used to execute the requested force (up to 30 kN) and displacement (displacement from 0 to 10 mm) for the measuring cycle. Looking at the sensors, the force sensor can be a sensor incorporated into the actuator, since the accuracy of the Newton scale is more than sufficient for the range of forces being used by the machine. Although most actuators can meet the technical requirements, the displacement sensor must be external and measured relative to the tool surface to avoid the influence of deflection and bending (minimum reach of 15 mm and resolution of 8.33 μm). A PLC board with displacement input and number of cycles must be connected with the actuator to move it on the z axis and assist the measurements. The PLC can

then send the collected data to a computer over an IP connection. The data are then analysed and compared with historical data.

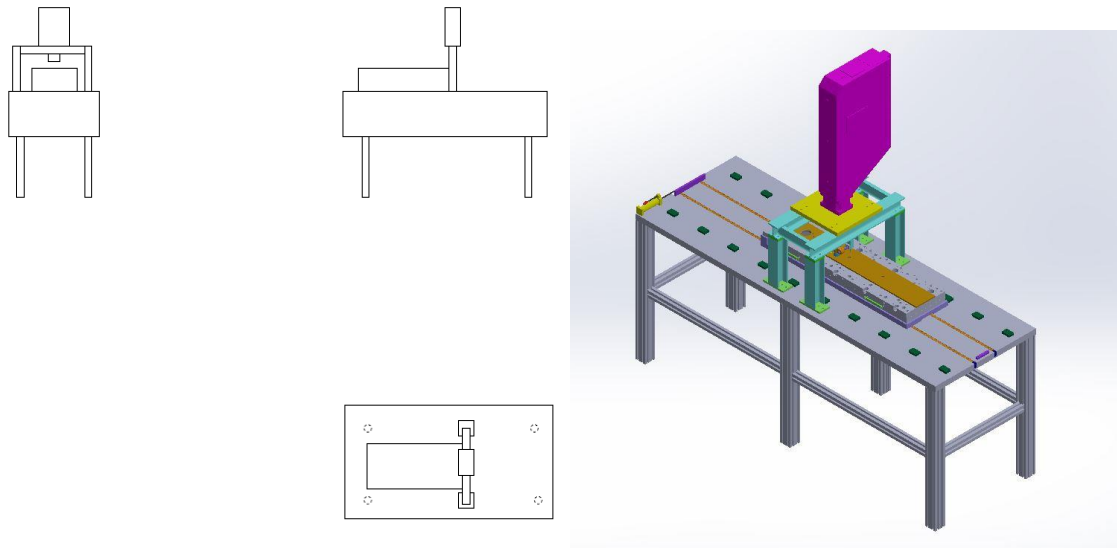


Figure 66 –Concept sketch and computational concept isometric view

3.12 Detailed look at cycle description

The measuring cycle presents different stages. From chapter 3.12.1 to chapter 3.12.6 chapter, each stage will receive a more detailed description.

3.12.1 Moving a tool with spring system that needs to be measured from production to maintenance workshop

This stage (Table 24) represents a work procedure that is already implemented; the major difference is the last step. The tool, instead of being analysed with the current methods, is moved to the measuring machine.

Table 24 – First stage for the measuring cycle

Tools being collected



The tool is collected at presses or at tool collecting points around the factory.

Moving the tool to the measuring machine



Using trolleys, the tool is taken to the maintenance shop.

Tools dies disassembly



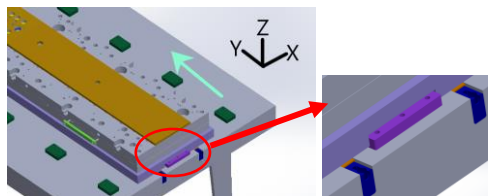
With the trolley lifting capacity, the tool is placed on the maintenance working tables.

Using the hoist, the tools are divided into top and bottom sides.

The top side needs to be turned 180 degrees.

Using again the trolley, the bottom or top side is moved to the measuring device.

Tool is placed on the measuring machine



The tool is pushed in the mint green arrow direction.

The violet component is a barrier to prevent the holding tool component from falling.

A small cut can be made on the tool supporting structure to ensure always the same position for the tool placement and removal.

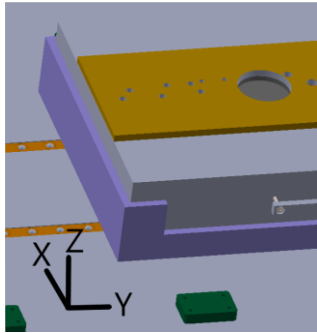
3.12.2 Fixing the tool or create a system to prevent tool movement (future improvement)

This stage only exists for a future stage, where the motion and positioning of the device are performed automatically. In this case, there is an element between the tool and

measuring device (Table 25). The advantage of having this tool is the creation of a reference point that will be the same for all the tools. This makes easier to create automatic functions with the spring systems locations.

Table 25 – Second stage for the measuring cycle [51]

Additional body to automate



A barrier can be created on one of the sides to give a more steady and stable structure.

The reference dimension for this barrier shall be taken based on K83 (Philips codename) dimensions since it is the largest tool analysed.

Adding a fixer



In shorter tools, a hand screw jack can be created to push the tool against the wall and prevent movement.

Inspect if tool fixation was ensured (future improvement)



Check if tool is properly fixed to the system used.

This step is important to prevent tool damage, making the positioning easier for the next steps and preventing tool escape movements.

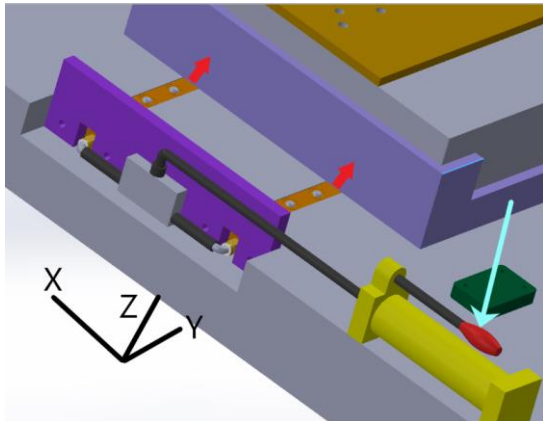
Since this principle of fixation is only used for an automatic positioning system, this inspection shall be performed with sensors, since most devices already have these control elements integrated.

3.12.3 Use a movement system to match the tool with the actuator location

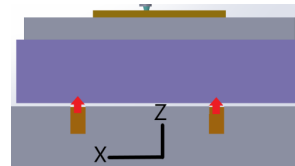
At this stage (Table 26), the spring system to be measured matches the fixed position of the actuator on x and y axis alignment.

Table 26 – Third stage for the measuring cycle

Movement system lifts the tool

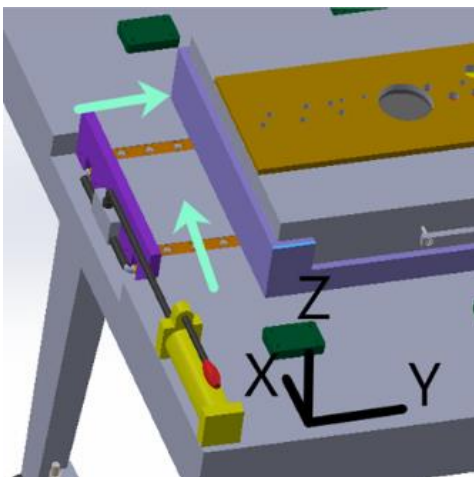


Using a pump (yellow body on the image) the ball rollers are lifted (red arrows), allowing to lift the body connected with the tool.



The violet body represents the principle for a blocker to prevent the tool from escaping or fall on the ground on the automated version.

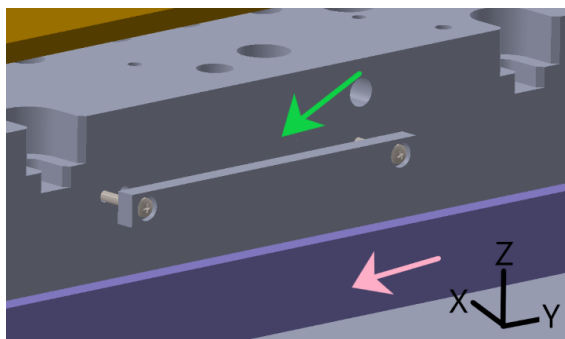
Movement capacity



The arrows represent the tool capacity to move on both x and y axis.

The pump was left on the top of the table to facilitate the machine use. This way the operator only needs to operate in the Y axis shown in the picture.

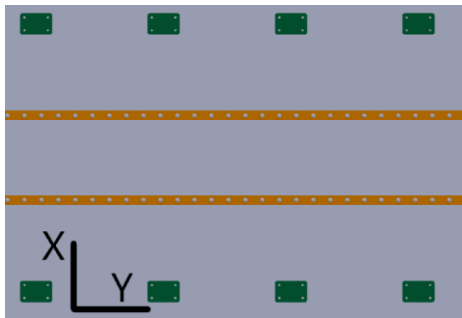
Handlers to assist motion



Using tool handlers (pointed out with the green arrow) the tool is moved or a handler can be created on the tool supporting body (pink arrow).

The pink arrow points out the body for the automated version.

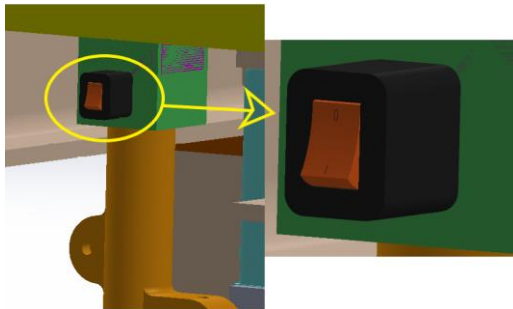
Blockers



The green rectangular boxes aim to prevent tool escape by the lateral side of the table.

It is also possible to have these tool escape blockers as a metal strip identical to the one used on trolleys to prevent tools escape.

Turn on the light pointer to check the position of the actuator relative to a spring system to be tested



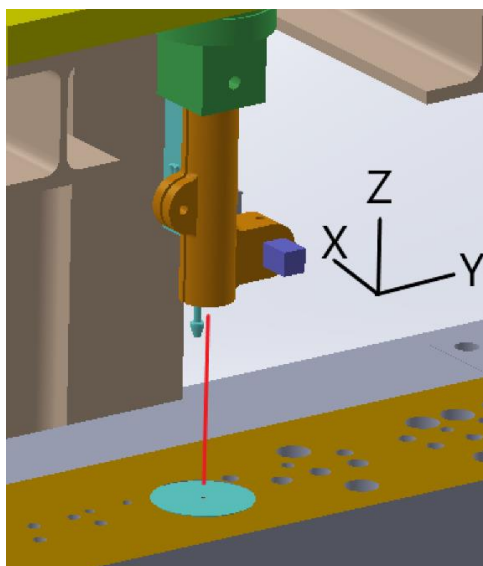
On the actuator shaft, near to the end, a small button is added to turn on the light.

Once the operator pushes the button, the button goes to 1 returning immediately to 0.

The reason for always having the button located in position 0 is to prevent the light from being turned on continuously.

The light system shall have a timer to be kept on for a specific time period.

Laser points to tool surface



In the spring systems a small engraving (small red circle) is performed on the system surface (blue circle).

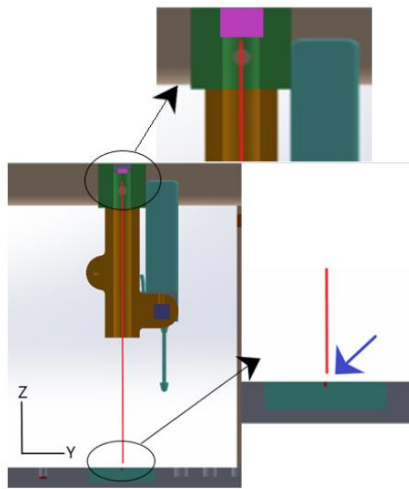
Inside off the actuator a light point is inserted.

The light (red line) shall match the spring system surface (red point).

In the tool, small control points need to be created to ensure a higher matching accuracy, either with a marker or a small laser engraving.

The dot should be coloured red as the colour facilitates the positioning.

Laser principle mechanism

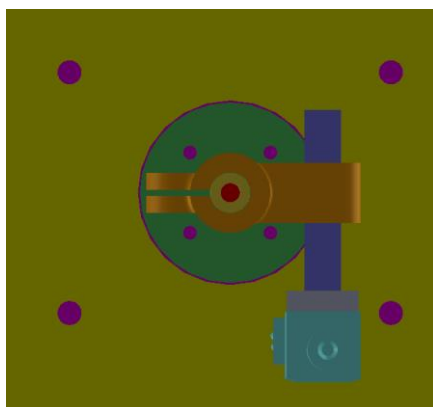


The figure shows the principle inside of the actuator structure. In this picture, the screw connecting the elements was hidden to simplify image analysis.

The pink rectangle represents the laser sensor, the red line represents the light emission and path, the small red rectangle represents the small point (engraved/marked) on the system surface that needs to be matched with the sensor.

The blue arrow points out the matching between the laser beam and the tool engraving point.

View over actuator

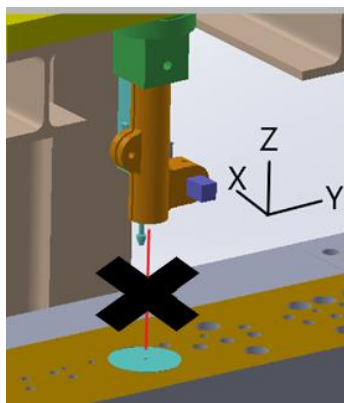


The actuator presents a female thread on the bottom surface. The red circle represents the body that emits light for the alignment between the actuator and the spring system. The yellow circle represents the screw connecting the elements. The orange body is responsible for connecting the external sensor to the actuator.

The screw has a through hole to allow passage of light.

The light shall match the spring system.

Turn off the laser

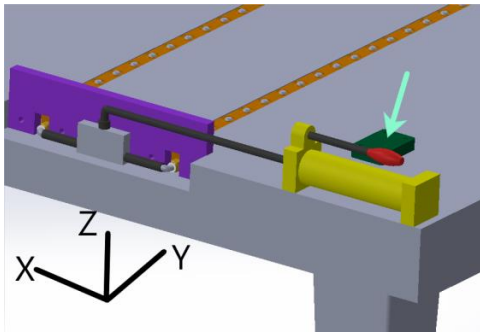


The light is turned off after a preconfigured time (3 minutes for example).

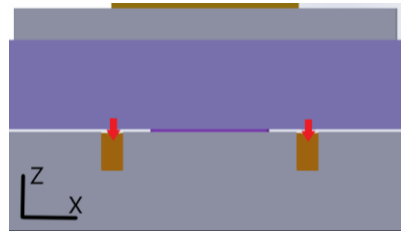
In this way, the laser is prevented from being kept on.

If the alignment has not yet been set, the light switch can be activated again.

Movement system drops the tool

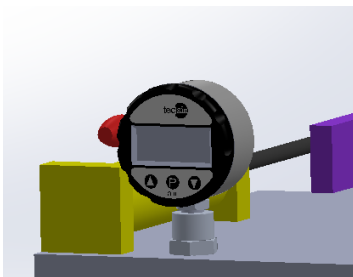


Using the pump (yellow body) the pressure is released.



The red arrows represent the movement of the ball rollers being dropped.

Inspect if the movement was stopped



In the pump, a mechanism must be implemented to check if fluids were released properly.

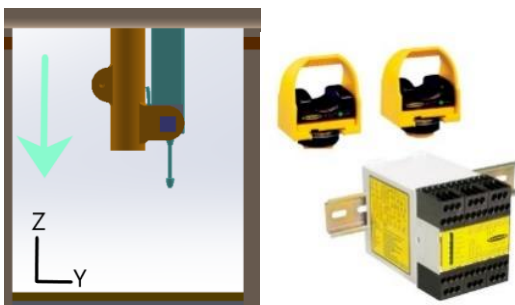
A pressure sensor reader can be added to the line for example. Maintenance is also easier since these system conditions are easily traceable.

3.12.4 Measuring cycle

The steps (Table 27) to perform the alignment on z-axis and perform the dynamic measurement are described here. Most of the steps performed during this stage are preconfigured with a PLC control board.

Table 27 – Fourth stage for the measuring cycle [52]

First actuator movement

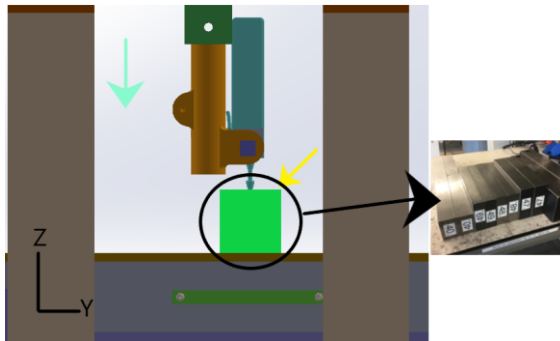


The first movement of the actuator is to lower the actuator in the z axis and make it more easily next steps.

The orange bodies represent connectors for the external displacement sensor (blue body).

A button system must be added to the table to increase safety, making actuator moveable only when operator hands are at the button.

Force and displacement sensor check



The force sensor needs to be checked with the electronic panel, since the sensor is inside the actuator.

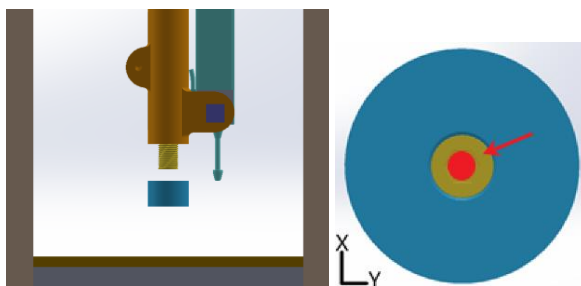
The displacement sensor can be checked with the same blocks used on the Heidenhain table represented on the picture by the green block.

This step needs to be performed by the operator.

This step must validate the sensor capacities to obtain proper data.

Add a section adapter to the actuator cylinder

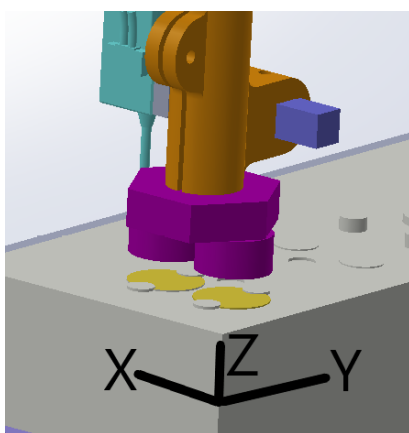
Single spring system example



Since spring systems present different configurations (number of springs, distance between spring systems, etc), an adapted part needs to be added to the actuator to properly activate the full system.

This step is performed by the operator once the movement and sensors check steps are performed properly.

Double spring system example

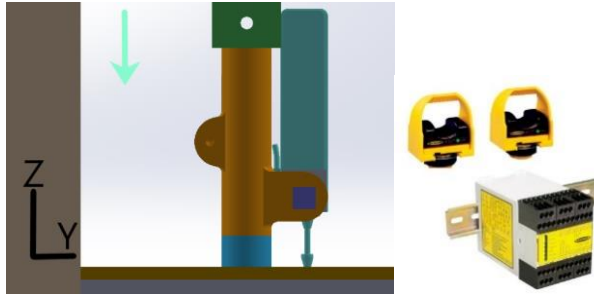


Adding a grub screw (yellow body), the sensor holder (orange body) is connected to the adaptable parts.

The screw presents also a through all hole to allow the light pointer (red circle) recheck if needed.

In this example, the blue body corresponds to a single spring system, and the pink body to a double spring system.

Second actuator movement

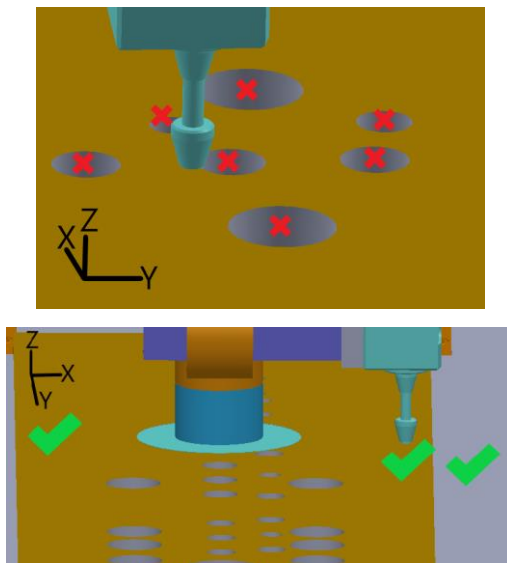


This step is made to aligned z-axis before the measurement. After this step, x, y and z coordinates shall be aligned for the beginning point of the measurement.

The movement can be programmed to stop once the force sensor detects resistance.

A button system must be added to the table to increase safety, making actuator moveable only when operator's hands are at the button.

Displacement sensor pointer positioning



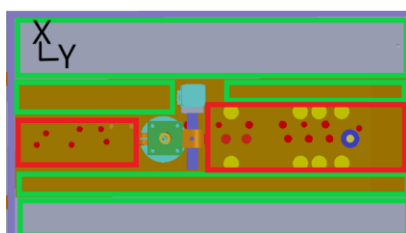
Positioning properly the pointer is important to obtain a correct data acquisition.

The tool surface possesses different systems with different functional characteristics. It is important to prevent the pointer to be used in those systems, since vibrations and movements can occur during force actuation.

The red crosses represent the undesirable places.

The sensor should be used in areas without sub-systems on the hardened plate or at "not working area" on the regular steel plate.

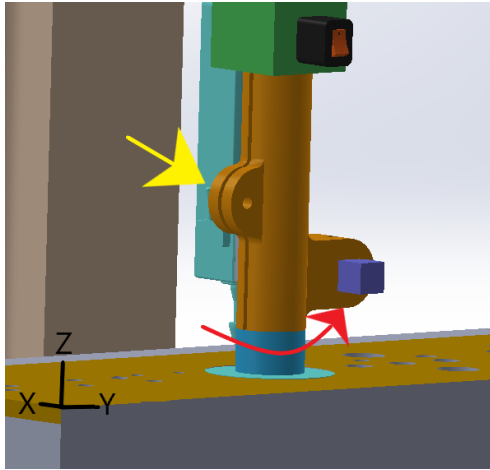
Look at green areas and red areas for sensor pointer



Top view at sections that are good and bad to use as a reference surface for the tool.

The green rectangles represent good areas to place the sensor pointer. Red areas represent less desirable locations.

Displacement sensor pointer positioning mechanism 1



The first movement is about the rotation of the external displacement sensor.

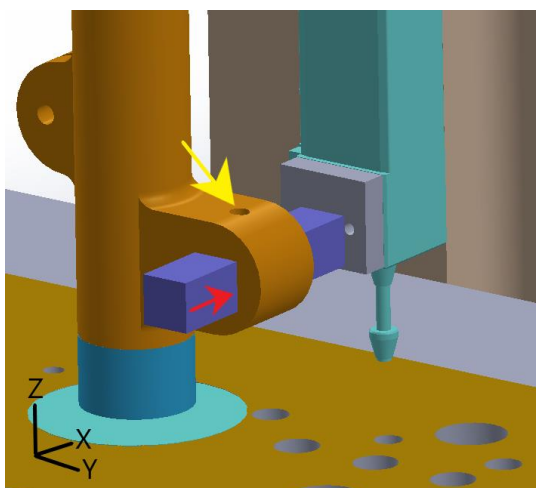
Using a screw on the hole, highlighted by the yellow arrow, mechanical tightening can increase or decrease.

With the decrease of force, the orange body is free to rotate (red arrow) around the actuator shaft.

This rotation is performed for an initial rough alignment.

This stage is performed by the operator.

Displacement sensor pointer positioning mechanism 2



The second movement is about the motion of the external displacement sensor holder.

Using a screw on the hole, highlighted by the yellow arrow, mechanical tightening can increase or decrease.

With the decrease of force, the blue body is free to move (red arrow) around the orange body.

This alignment is more accurate than the previous one. The use of a rectangular / square connector prevents the sensor from rotating.

This stage is performed by the operator.

Displacement sensor reset



At this step, it is important to reset the sensor to zero.

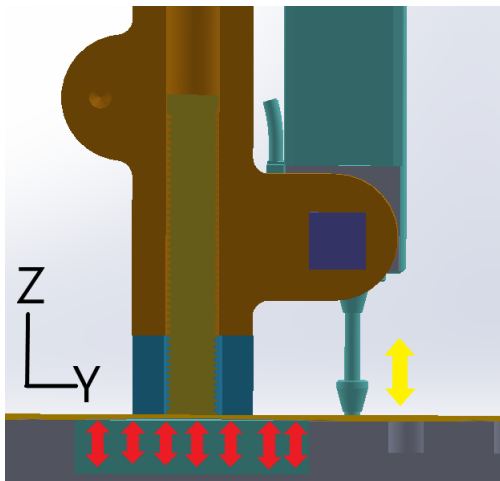
Doing this, the data analysis will be easier, since the starting reference point will be always zero.

An external interface can be mounted with a simple interface similar to the ones already used. This reset is performed by the operator.

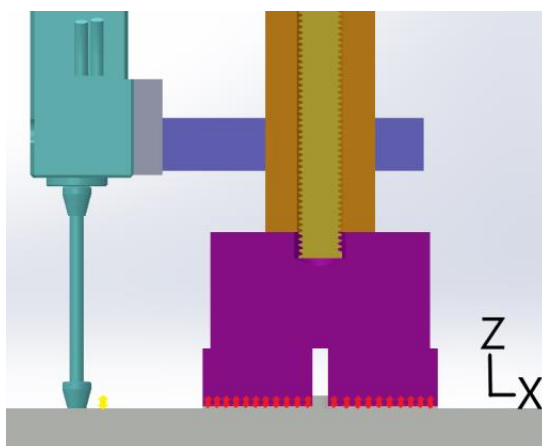
This device needs to collect data automatically so a DAQ (Data acquisition) functionality is required.

Third actuator movement

Single spring system example



Double spring system example



Safety



The electric panel that controls the actuator at this stage needs to request two values.

1. Displacement to be performed by cycle (total spring system displacement), represented by the red arrows length;
2. Number of cycles to be performed (number of arrows on the figure).

The yellow arrow represents the displacement performed by the displacement sensor. This sensor does not need any input if the working principle is based on gravitational forces (free movement of the pointer). It is also important to have the pointer well lubricated to make the movement as easy as possible.

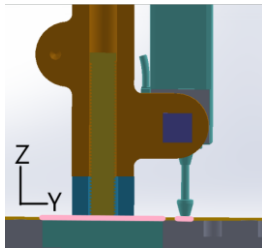
During this step, data is being collected by the sensors and sent to the electronic control panel.

A button system must be added to the table to increase safety, making actuator moveable only when operator hands are at the button.

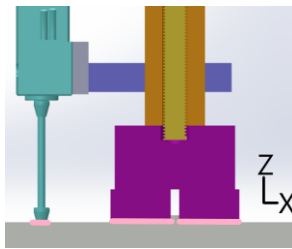
If higher control is demanded. speed can also make part of this interface, even thought to have speed control, more sensors need to be placed on the measuring device.

Actuator goes back to the initial point before the third movement

Single spring system example



Double spring system example



This step presents the end of the measuring cycle and should be triggered automatically after desirable displacement and cycles are performed.

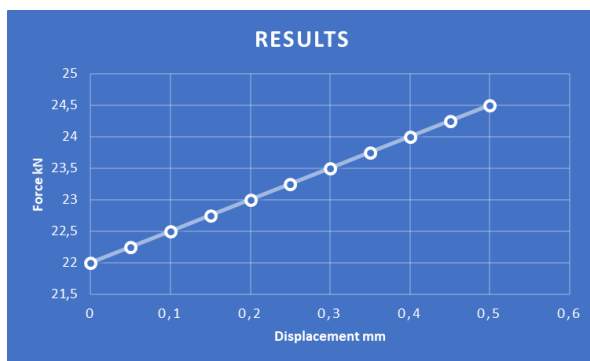
The pink line represents the stop at the starting point.

3.12.5 Data validation and analysis

This stage (Table 28) is fully automated and runs on the PLC board that controls the actuator. The only exception is the second stage of this stage, "Grab tool spring system documentation (testing of new systems)", which is performed by the operator. Although this step is only performed to test new systems and compare them with previous ones.

Table 28 – Fifth stage for the measuring cycle

Check if data was properly obtained



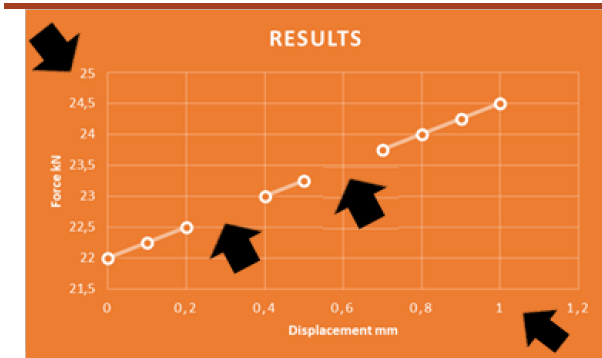
The results shall present a graph with force and displacement. The machine shall inform the operator if the measurement was valid.

The PLC board is programmed for the expected number of samples collected and limits per spring system.

The pictures represent two different outcomes:

-The blue graph represents a correct result with all points obtained and expected values for force and displacement.

-The orange graph presents missing data points, and the displacement is outside of expected values (sensor



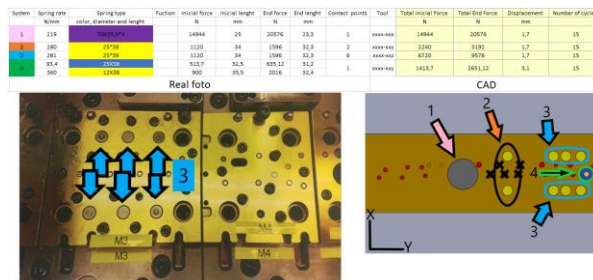
error or displacement inputted in the machine was higher than it should).

The black arrows represent the three topics to be looked at by the decision systems: continuous data, force range and displacement range.

These results shall be presented on the PLC monitor with an Ethernet connection. This connection will allow automatically store collected data to a cloud server.

Grab tool spring system documentation (testing of new systems)

First template



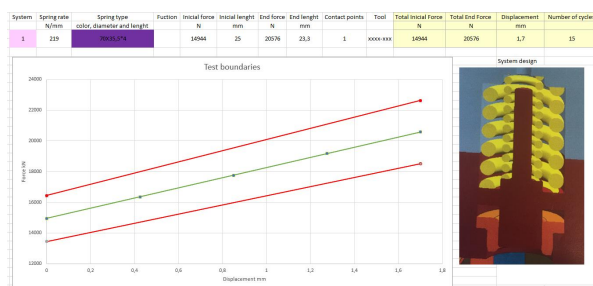
Go to the tool physical archive (Philips factory location) and collect needed documentation.

The template should present two parts.

A first one, more generic, with springs systems locations and inputs table per system.

A second one, more detailed, with historical graphics and working boundaries.

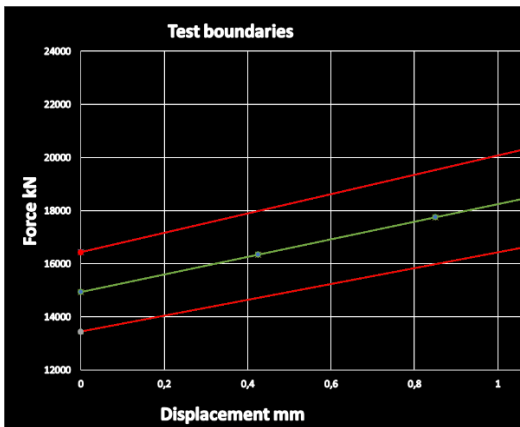
Second template



System design section, besides making clearer the system composition, can also assist in the future to see if there are any similarities between more successful cases (the image is just illustrative and does not match the spring system data and graph).

A deeper look at the templates will be given in the next chapter.

Compare data collected with the historical data



At this stage, conditions presented on the historical data/theoretical calculation are compared with test results.

Cycles can either be analysed individually or combined to produce an overall performance score.

Test boundaries can initial be based on theoretical elastic behaviour, becoming with timeless theoretical and more suitable for process line needs.

The red lines represent the acceptable values of the superior and inferior limits. The green line represents the ideal behaviour for the spring.

Decide spring system condition



If the spring presents acceptable conditions, then the spring system is not replaced.

If the spring presents unacceptable conditions, then the spring system is replaced after being removed from the testing machine.

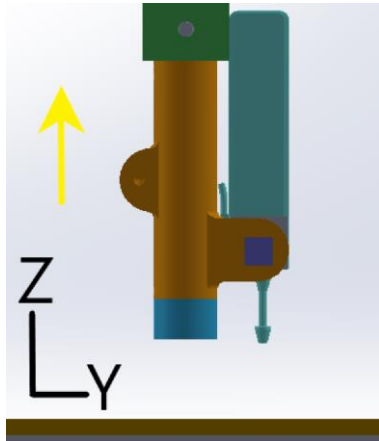
This step is also performed automatically.

3.12.6 Next measurement/Tool being removed

Table 29 details the logic to perform a new measurement or remove the tool of the measuring machine.

Table 29 – Sixth stage for the measuring cycle

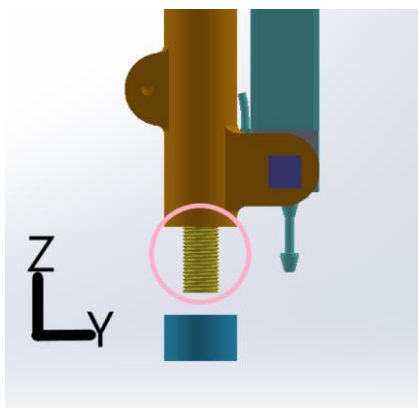
Lift actuator cylinder



The actuator is lifted (yellow arrow).

This step can be performed automatically once the operator/machine validates the test performed to the spring systems.

Remove adaptable parts



After the actuator being lifted, the operator can remove the adaptable part to activate the spring system during the measurement.

The grub screw (highlighted on the pink circle) can be removed as well, or be kept on the actuator.

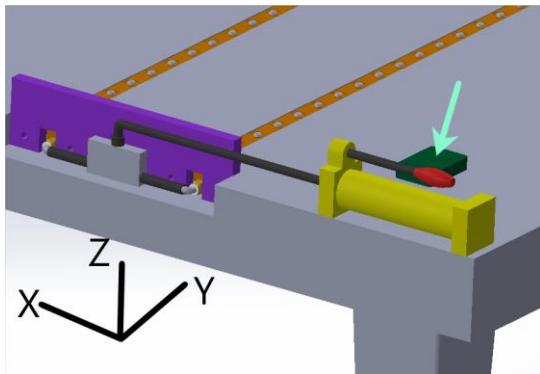
Evaluate other relevant systems



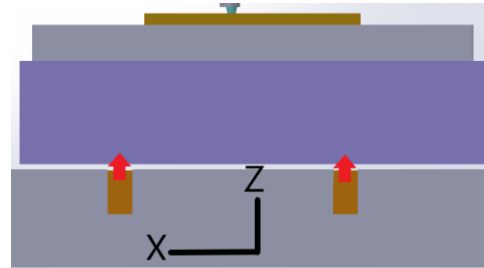
If the tool still has more relevant systems to be analysed, the cycles go back to: “Use a movement system to match the tool with the actuator location” step.

If the tool does not present more systems to be evaluated, then the next step is to “Remove tool”.

Remove tool 1

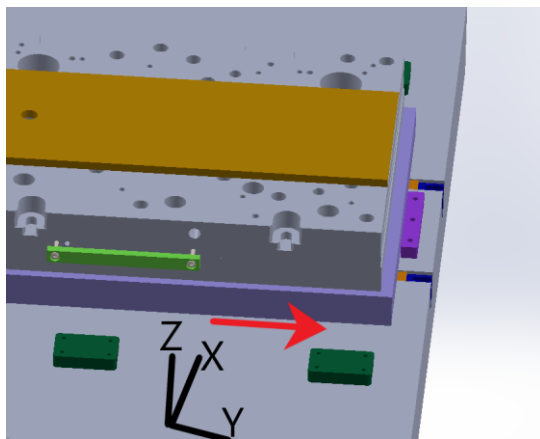


After all the spring systems are tested, the pump is pushed back again lift the ball rollers.



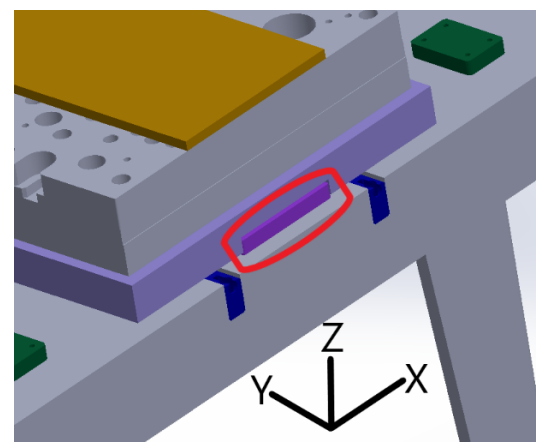
The tool is back again easily moveable by the hydraulic system.

Remove tool 2



Moving the tool until a control point. This stage is initially performed by the operator being possible, on a later stage, to automate this step. The red arrow represents motion.

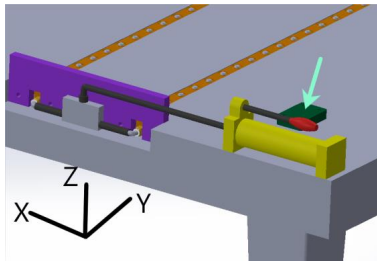
Remove tool 3



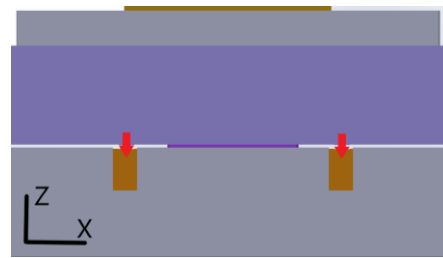
Once the matching between the tool supporting body and the control point (highlighted in red) is done, the pump can release the pressure and allow to have again a stable and unmovable structure.

In the automated version, a small body is added to ensure an ending reference point for the motion cycle.

Remove tool 4

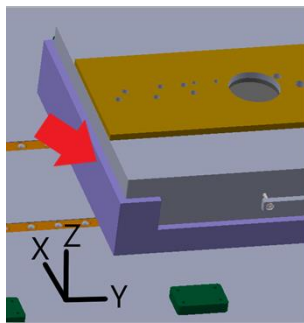


The pump release imposed pressure. The ball rollers are then lowered.



The tool is unmoveable.

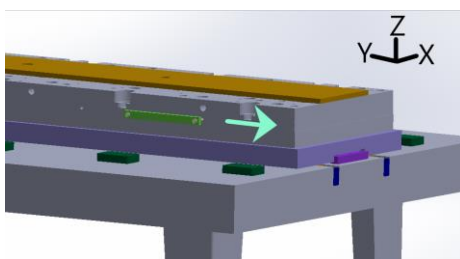
Remove tool 5



After that, the tool can be unfixed (automated version) and taken out of the measuring device.

This stage is only performed for the automated version in a future stage.

Remove tool 6



The last stage performed in the machine: using a trolley, the tool can be removed from the machine.

The hoist tools can assist tool dies assembly.

3.13 Requirements for a database creation

For the database creation, the first step is to create a full spring systems database per tool. Figure 67 illustrates an example for the 7822 142 17000 tool. A higher resolution version can be found in Appendix 13.

	N/mm	Prestress(mm)	Stroke(mm)	K(N/mm)	Pre(N)	Distance (mm)	End(N)	Distance (mm)	Number of springs	Total P (N)	Total E(N)	Force1	Displacement	Force2
25*51	51	8.15	2.88	157	1279.55	42.85	1731.71	39.97	4	5118.2	6926.84	452.16	2.88	1808.64
32*38 + 16*38	38	7	1.7	489	3423	31	4254.3	29.3	1	3423	4254.3	831.3	1.7	831.3
25*38	38	4	1.7	280	1120	34	1596	32.3	6	6720	9576	476	1.7	2856
25*38 + 12*38	38	5.5	1.3	93.4	513.7	32.5	635.12	31.2	1	513.7	635.12	121.42	1.3	1237.42
	38	2.5	3.1	360	900	35.5	2016	32.4	1	900	2016	1116	3.1	
25*38	38	7	1.52	219.7	1537.9	31	1871.844	29.48	1	1537.9	1871.844	333.944	1.52	333.944
12*38	38	3	5.1	36	108	35	291.6	29.9	2	216	583.2	183.6	5.1	367.2
16*38	38	5	1	57.1	285.5	33	342.6	32	2	571	685.2	57.1	1	114.2
20*38	38	2.75	0.85	129	354.75	35.25	464.4	34.4	1	354.75	464.4	109.65	0.85	109.65
32*38	38	4.35	2	488.9	2126.715	33.65	3104.515	31.65	4	8506.86	12418.06	977.8	2	3911.2
10*64	64	6.25	9.15	1.7	10.625	57.75	26.18	48.6	26	276.25	680.68	15.555	9.15	404.43
10*64	64	6.25	5.57	1.7	10.625	57.75	20.094	52.18	26	276.25	522.444	9.469	5.57	246.194
20*51	51	9.05	2	38.9	352.045	41.95	429.845	39.95	1	352.045	429.845	77.8	2	77.8
Fd. Gutekunst 7.3*57.3	57.3	7.55	2.63		0	49.75	0	47.12		0	0	0	2.63	0
25*51	51	8.15	2	157.3	1281.995	42.85	1596.595	40.85	4	5127.98	6386.38	314.6	2	1258.4
40*51	51	7.15	3	559.7	4001.855	43.85	5680.955	40.85	4	16007.42	22723.82	1679.1	3	6716.4
skonda RKNR128 973 (45*	63	7.15	3	1000	7150	55.85	10150	52.85	1	7150	10150	3000	3	3000
25*51	51	6.45	4	157.3	1014.585	44.55	1643.785	40.55	4	4058.34	6575.14	629.2	4	2516.8
25*51	51	5.15	5.5	157.3	810.095	45.85	1675.245	40.35	13	10531.235	21778.185	865.15	5.5	11246.95
40*64+20*64	64	7.7	5.5	520.5	4007.85	56.3	6870.6	50.8	3	12023.55	20611.8	2862.75	5.5	8588.25
16*51	51	3.5	5.5	14.2	49.7	47.5	127.8	42	3	149.1	383.4	78.1	5.5	234.3

Figure 67 – 7822 143 17000-spring systems

After that, it is necessary to decide which spring systems are relevant to analyse and create combined measuring systems, when it is possible to combine them (Figure 68). For this example, the following rules were used:

1. Springs systems only with forces higher than 1 kN where signalized;
2. Another rule was that only similar systems (same arrangement and springs) were combined;
3. Is important that these systems do not surpass 30 kN for the requirements of this assignment. If the actuator force is higher than 30 kN, systems can also surpass that value;
4. If springs systems with different arrangements or/and different springs are combined, it is important to ensure the same stroke;
5. If more than one spring is used per housing, the equivalent spring shall be calculated and used, since the surface only presents one contact point (series configuration) and the measurement can be performed combined as in presses.

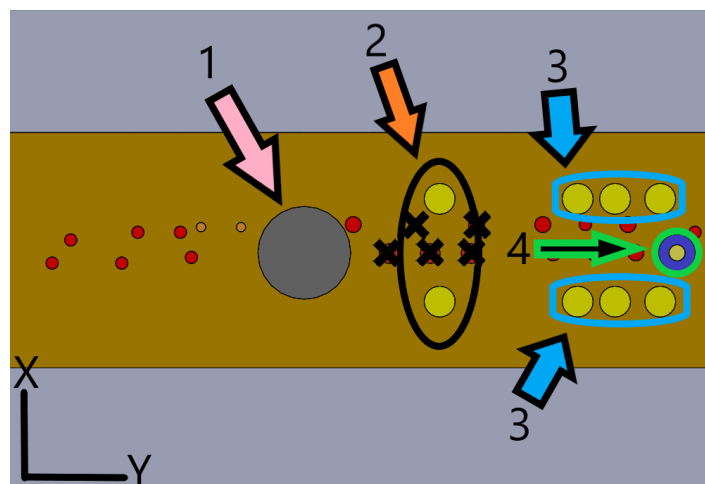


Figure 68 – Spring systems creation and definition on lower K83 tool plate for analysis

After this step, the template in Figure 69 is fulfilled:

System	Spring rate N/mm	Spring type color, diameter and length	Fuction	Inicial force N	Inicial lenght mm	End force N	End lenght mm	Contact points	Tool	Total Inicial Force N	Total End Force N	Displacement mm	Number of cycles
1	219	70X35,5*4		14944	25	20576	23,3	1	xxxx-xxx	14944	20576	1,7	15
2	280	25*38		1120	34	1596	32,3	2	xxxx-xxx	2240	3192	1,7	15
3	281	25*39		1120	34	1596	32,3	6	xxxx-xxx	6720	9576	1,7	15
4	98,4	25X38		513,7	32,5	635,12	31,2	1	xxxx-xxx	1413,7	2651,12	3,1	15
	360	12X38		900	35,5	2016	32,4						

Figure 69 – Fulfilled template example for the bottom part of 7872 143 17000 tool

From this template, the NPI can take:

- Number of points to activate;
- Which tool will be adapted to the actuator;
- Displacement and number of cycles that need to be performed;
- Expected values for the initial force and final force.

A more detailed look at the spring system is given with the second template (Figure 70), which has a more detailed look per system. Data collected from the machine testing can then create results that are more reliable. This template gains special relevance to test and collect data about different spring systems configurations.

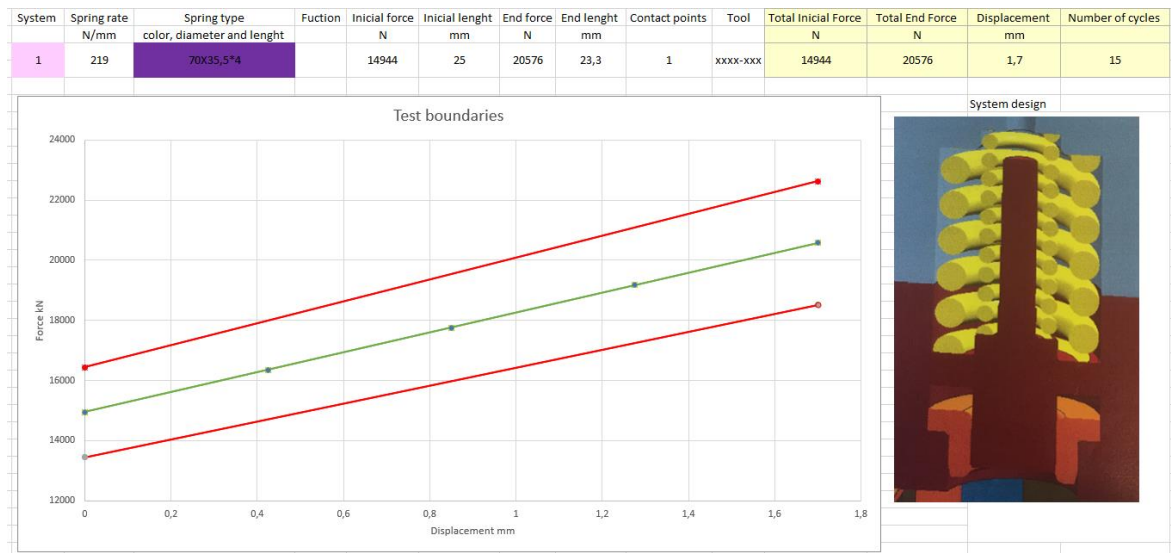


Figure 70 – Template example for a spring system

3.14 Costs analysis

Looking at the project current point, a cost analysis (Figure 71) is performed to have an initial idea about project costs. For the analysis of these costs, a research was done to guarantee the matching of requirements, since the investment must be analysed in a future stage. The machine presents a high cost, although it is a precise machine that performs measurements in the micrometric scale. The analysis to the measuring equipment is always complex, since a measuring equipment does not translate benefits to direct profit.

DESCRIPTION	UNIT €	QTY	TAXED	AMOUNT
Actuator with 35 kN of force capacity (+ internal sensors)	30.000,00	1	X	30.000,00
PLC Board for machine control	7.538,00	1	X	7.538,00
Hydraulic lifting system	1.200,00	1	X	1.200,00
External displacement sensor	6.683,00	1	X	6.683,00
Chassis	1.112,43	1	X	1.112,43
Laser	21,50	1	X	21,50
Develop + Mounting price	13.975,03	1		13.975,03
Operator using the machine (1 hour)	50,00	1		50,00
				-

Subtotal	\$	60.579,96
Taxable value	\$	46.554,93
Tax rate		21,000%
Value paid on taxes	\$	9.776,54
Shipping	\$	2.055,24
TOTAL	\$	72.411,74

Figure 71 – Expected costs

3.14.1 Return of investment (ROI)

To analyse the ROI, it is necessary to understand how much income can be gained using the measuring machine. Since an inspection made 8 times per year, takes 6 hours of operation with an operator costing of 50 euros per hour, it is possible to define the cost for the current operation. At this moment, two operators are used to perform this inspection, although it is expected for the machine to use only one. For this analysis, it is important to consider tools inside scope and outside of research scope. ROI formula can be found it Appendix 14. Table 30 summarizes the impact of using more tools that the ones used on this case of study.

Table 30 – ROI difference between tools inside and outside of the scope

	Inside scope	Outside scope
Number of tools	1	6
Total annual income	2400	14400
Years to pay the machine	30 years	5 years

There are also other factors that do not necessarily reflect financial income but also need to be considered:

- Inspection time decrease of 80 %;
- Inspection near to production speeds;
- Quantitative data;
- Insights on real force and displacement values for tool dies;

- Every tool is expected to be suitable for inspection;
- Knowledge gain about spring system hysteresis;

And most important:


- ✓ Higher product quality.



Since spring systems are the dynamic heart of tool dies, knowing a tool die “heart condition” is vital for a continuous and “healthy” process. Through them (spring systems), all the technical functions of the process pass through t them (process capacity to bend, cut or guide the metal sheet, increase speed, tools longevity, etc.). The combination of all these elements will lead to higher quality and control to final product quality.


3.15 Concept validation

Table 31 summarizes products with technical requirements that validate concept requirements.

Table 31 – Concept validation summary table

Element	Properties	Requirements	
 <p>SCHMIDT® Servo Press Press types 420</p>	Ram stroke: 400 mm	0-10 mm	✓
	Force capacity: 35.01 kN	1 to 30 kN	✓
	Maximum speed: 0.2 m/s (95 SPM)	0.125 m/s (60 SPM)	✓
	Force sensor accuracy: ±0.3901 N	±3 N	✓

Element	Properties	Requirements	
<p>External displacement sensor</p>  <p>HEIDENHAIN-CERTO CT 2502</p>	<p>Measuring range: 25 mm</p>	0 to 10	✓
	<p>System accuracy: ± 0.1 μm</p>	8.33 μm	✓
	<p>Speed capacity until: 0.4 m/s</p>	0.2 m/s	✓
<p>Moving system</p>  <p>Römheld GmbH Ball Bars 8 9215 7X22 L 2900 R G40 H38</p>	<p>Length: 2900 mm</p>	<p>Minimal length for the most critical tool side: 1425 mm × 2 = 2850 mm</p>	✓
	<p>Total load capacity 13 578 kg</p>	<p>Maximum tool weight: 630 kg</p>	✓
<p>Table assisted by the moving system</p> 	<p>Area for tool movement on the measuring table (x and y): 1.6618 m²</p>	<p>Maximum tool die area (x and y): 0.5529 m²</p>	✓

Element	Properties	Requirements	
<p>650nm 5mW Focusable Red Dot Laser Module Laser Generator Diode</p> 	Diameter 12 mm	<p>Maximum diameter (diameter of central actuator bore) 20 mm</p>	
Optimized design		<p>Ready to be fabricated</p>	

CONCLUSIONS

4 CONCLUSIONS AND PROPOSALS OF FUTURE WORKS

4.1 CONCLUSIONS

This report presents a final concept design to test spring systems inside tool dies used in cold forming for Philips. From this case study, the following conclusions were obtained:

- Major achievements obtained: Hooke's law and hysteresis were combined to define a principle for spring systems validation;
- Based on historical data, it was possible to define the technical requirements for the measuring machine;
- A final concept for the machine has been achieved while preserving the interests of stakeholders;
- A detailed cycle description was obtained to set and define different steps and stages to be considered for the machine design;
- The principle to create a database was proposed;
- Possible elements were named to validate the concept and obtain needed requirements;
- At the final date of this report, it is expected that the measuring machine can be used to evaluate every spring system that needs to be validated.

Minor achievements obtained:

- The actuator is particularly suggested for metal forming processes and presents force capacity up to 35 kN making possible to increase force capacity for the spring systems testing;
- The proposed actuator can also achieve speeds near to 95 SPM making the test closer to process speeds, even though higher speeds would be desirable.

4.2 PROPOSALS OF FUTURE WORKS

Spring systems are the heart of the cold deformation process. The conditions found in these systems will affect the overall process. From the speed up to required forces, the wrong work performance of these elements will lead to a product outside the standards required by PHILIPS

With this report, it was possible to define a principle to evaluate spring systems and to obtain a concept capable of using it.

The final description of the cycle is the bridge between the end of this project and the beginning of a future project. The cycle describes the functions required for an appropriate measurement cycle.

At a future stage (Figure 72), the elements and design must be optimized with continuous FMEA analysis to maintain security as a key element. After machine design and FEM analysis, the machine must be constructed, calibrated and tested. Finally, if the previous stages do not present any adversity, the machine will be implemented.

The importance of continuity of this project is essentially related to a greater gain of knowledge about these systems. In an era in which the industry seems to be turning to the automation of mechanisms, it becomes critical to fully understand elements such as these to further implement better production policies as well as a final product to be sold to the consumer with better quality.

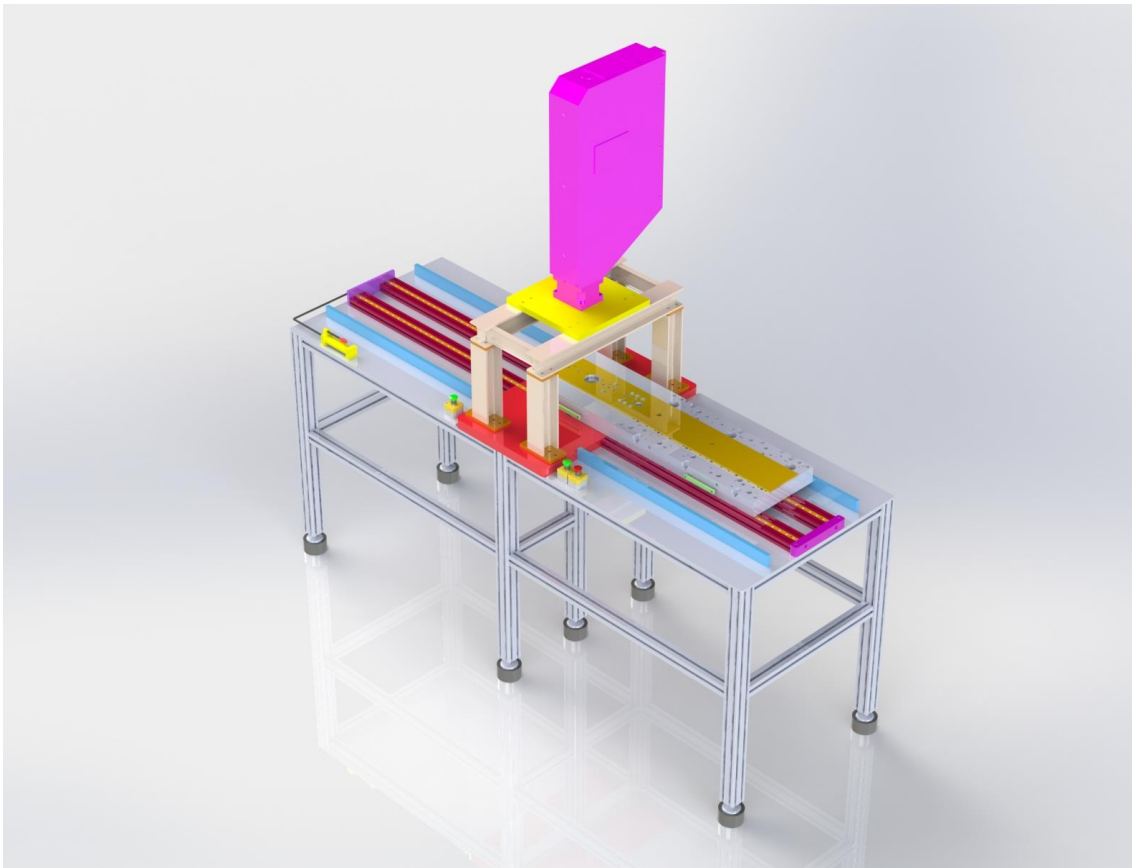


Figure 72 – Continuous improvement for the measuring machine

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SOURCES OF INFORMATION**

5 REFERENCES AND OTHER SOURCES OF INFORMATION

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APPENDIX

6 APPENDIX

6.1 Appendix 1 – Six Sigma and DVOV method

The Six-Sigma was introduced by Bill Smith when he was working for Motorola. Six Sigma is a flexible system that aims to maximize and make the resources and processes of a company sustainable.

Most companies rely on this management philosophy because it allows continuous improvement over the defects of the process, making it predictable (reducing process variations), as well as a methodical analysis to improve financial return.

Sometimes, lean management and six sigma can be confused, even though six sigma is focused on eliminating defects and reducing variability while Lean's focus is on eliminating waste and ensuring efficiency

By quantitative and statistical control, this methodology is implemented. DVOV makes part of the six-sigma planning methodology.

DVOV(M) stands for:

- Define;
- Identify;
- Design;
- Optimize;
- Verify.

Some authors add the letter M standing for Monitor. The words represent the different stages for a project development. Figure 73 presents a more detailed look at each phase scope.

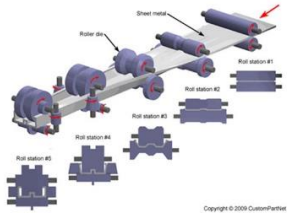
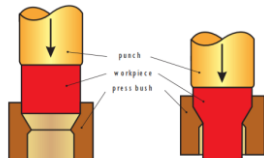
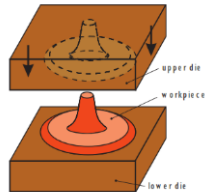
Define	Identify	Design	Optimize	Verify	Monitor
Define a focused project and get approval	Identify customer and user needs	Design new product or process	Optimize product or process design	Verify CTQ performance in pilots	Monitor long-term CTQ performance
<ul style="list-style-type: none"> Identify business need Develop functional breakdown and project funnel Get approval 	<ul style="list-style-type: none"> Identify customer and user needs Translate needs to CTQs Identify quality targets on CTQs 	<ul style="list-style-type: none"> Select best design concept Complete detailed design with transfer functions Predict design capability 	<ul style="list-style-type: none"> Identify gaps between quality targets and predicted capability Optimize design x's to eliminate gaps Develop robust design and mistake proofing 	<ul style="list-style-type: none"> Analyze measurement systems Verify and validate performance in pilots Put control plan in place 	<ul style="list-style-type: none"> Verify CTQ performance on production runs Confirm customer satisfaction Get project approval and celebrate

Figure 73 – Guidelines for each phase [53]

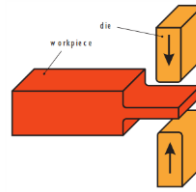
6.2 Appendix 2 – Illustrative tables for metal forming process variation

The following tables (Table 32 to Table 36) present the possible methods to perform the metal forming process.

Table 32 – Compressive forming processes and their representation [5, 54]

Rolling	
Extrusion	
Die forming	

Open-die forming



Indenting

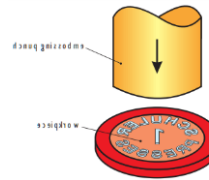
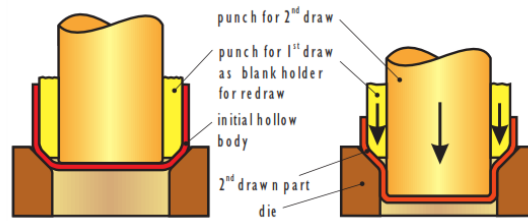
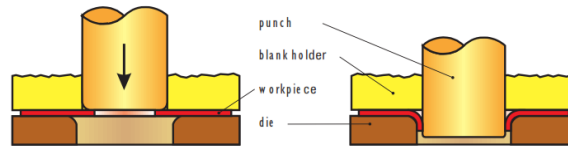


Table 33 – Compressive and tensile forming processes and their representation [5]

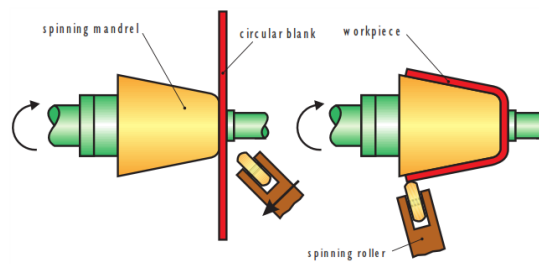
Drawing



Flanging



Spinning



Wrinkle bulging

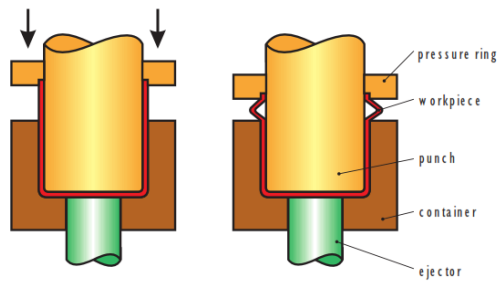
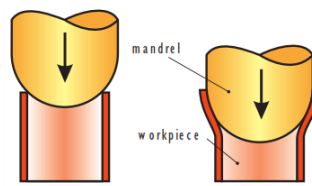
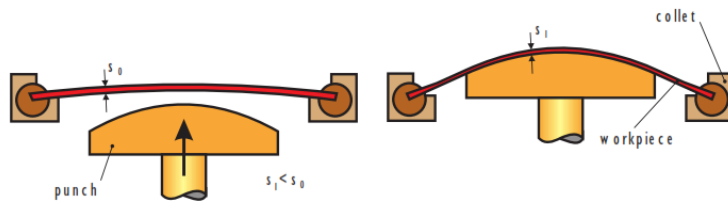


Table 34 –Tensile forming processes and their representation [5]

Extending by stretching



Stretch forming



Embossing

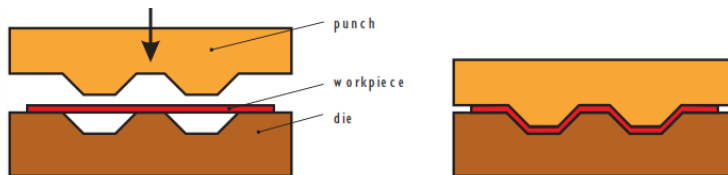
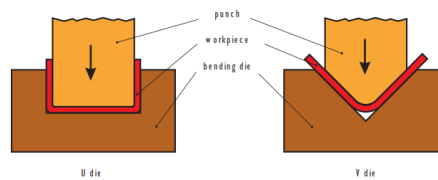
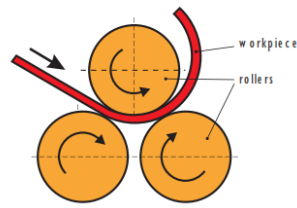


Table 35 –Bending forming processes and their representation [5]

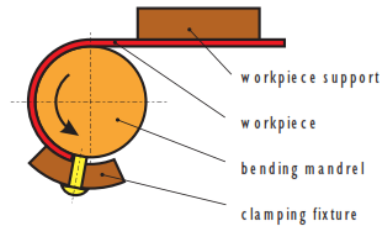
Linear bending



Rotational bending



Circular bending



Swivel bending

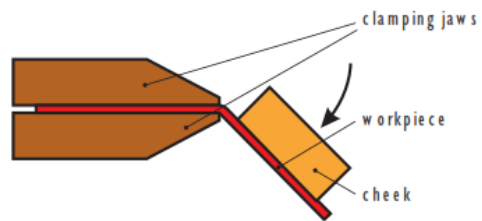
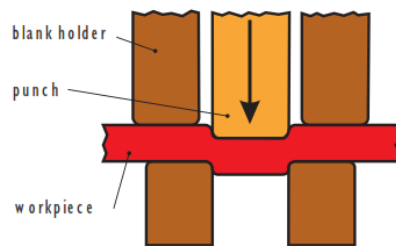
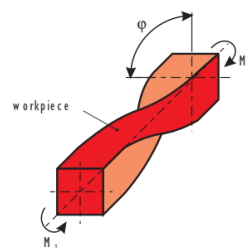


Table 36 –Shearing forming processes and their representation [5]

Displacement



Twisting



6.3 Appendix 3 – Scientific works

Spring systems under cold forming process do not have a scouted scientific documentation. This appendix takes up some relevant reports related to topics relevant to the case study.

Table 37 – Scientific reports

Article	Description
3D Force Sensor Designed Using Pressure Sensitive Electric Conductive Rubber [55]	A force sensor was developed capable of measure pressure under three axis. The sensor was also able to operate under dynamic use. This sensor was directly applied to studies connected with human dynamic analysis as well as ground force reactions
A review of nanometer resolution position sensors: Operation and performance [41]	This paper gives a review on some options on the market to properly measure position. A look on different principles and devices is given. For the tested devices is also given a reference table with measuring ranges and accuracy dynamic behaviour
Advances in the Control of Sheet Metal Forming [33]	Metal forming requires a high control process quality. Small force changes can completely change the process outcome. Lim [33] studied and presented how control is been implemented to sheet metal forming. There is also a review on how quality have evolved and the differences on tool tracking control. This paper gives then focus on blank holder force to improve formability and dimensional accuracy. Leading to, parameters variables such as punch force, draw-in and wrinkling configurations and how to control each one.

Analyses of static and dynamic behavior of coned disk springs: Effects of friction boundaries [56]

Ozaki, Tsuda and Tominaga did different configurations on disk springs under compression to understand friction modifications.

Methods used were initially FEM followed by energies and friction laws were used to predict load-deflection curves when hysteresis is created due to the friction contact on spring edges. Both results were then compared to method validation. It was also created a dynamic scenario to study friction under axial force application. The study proves that frictional dissipation doesn't affect deformation process and loads variations, caused by strain, are almost the same (even under different friction conditions).

Load-deflection curve calculation is proposed under three energies and Coulomb's friction law including hysteresis effect. Later under comparison, FEM proved calculations under mathematical and physical laws made appear to be correct. It was also presented a numerical analysis to a dynamical behaviour on disk springs. Resonance tests were also made on one-dimensional systems with authors suggesting more research on the obtained results.

Analytical and experimental characterization of nonlinear coned disk springs with focus on edge friction contribution to force-deflection hysteresis [57]

This paper presents a new look, on how the edge friction contribution can assist new developments in force –deflection hysteresis. Both analytical and experimental tests were conducted. A new analytical solution is proposed that allows looking independently at spring contacts wear behaviour contrarily to other studies mentioned on the report. It was also validated a new configuration for disc springs via experimental and analytical values obtained on a helical spring. Experimental data also showed that friction significance affect magnitude of hysteresis. Force and displacement characteristics make sense on static cases but, unfortunately, for dynamic scenarios, further analytical and experimental tests should be conducted.

An ultrasonic technique for the measurement of elastic properties of soft surface coatings [58]

Although this paper, was polyethylene as study base which does not represent metal forming typical used materials. A configuration setting is presented to collect reflected waves on the coating surface and determine Poisson's ratio. Limitations for this method are connected with coating surface layer thickness, stiffness generated by bodies (stiffness values conduct to different values and permanent conditions of stiffness is also a big challenge) and coating used materials (hard surface layers also add stiffness to the system). In this study, thought thin layer was possible to determine elastic properties.

Atomic force and lateral force microscopy (AFM and LFM) examinations of cement and cement hydration products [59]

Using AFM and LFM, tests were performed on cement to understand structure changes. During the study, both AFM and LFM are compared base on scales and results obtained. Results for AFM are clearer at a high scan range and for LFM on a low scale range. LFM detected variations on grain surface being missed on AFM analysis although using three dimensional images, it was possible to connect cement paste reduction with time increase. AFM prove to be a possible method to distinguish mortars structure differences

Contact pressure and wear in helical compression springs [60]

Compression leads to wear and failure. This paper tried to have a clearer perception on how contact pressure can affect wear leading to break. Both pressure measurements and FEM were used to understand the tension between the end coil and spring seat or end coil and transition coil. Tribological tests were also used to test the influence of surface roughness specially with shot peeled wires to improve spring's lifetime. Both measurements and FEM proved that tribological effect will depend on the geometrical shape as well as force used because of internal contact arranged between spring pitch coil. The authors suggest that futures works should use FEM to better define spring design rules in respect of contact geometry. Peened tests only proved that special attention should be given to these springs because of residual stress and roughness. Both conditions where verify in lubricated and non-lubricated springs

<p>Crack detection using image processing: A critical review and analysis [61]</p>	<p>Crack detection usually relies on inspector knowledge. Replace inspection for automatic image inspection difficulties and results were studied. Different parameters were set, to understand how predictable would be crack detection on concrete. Conclusions on this paper are too wide and focus on concrete industry, although the approach on factors that allow crack evolution are exactly the same ones expected on disc springs.</p>
<p>Crankshaft Speed Measurements and Analysis for Control and Diagnostics of Diesel Engines [62]</p>	<p>This thesis presents and studies methods to measure the speed at a crankshaft mechanism. Even being the study performed for diesel engines, the mechanical principle is identical to the mechanism found on a press.</p>
<p>Design & Analysis of Frame of 63 Ton Power Press Machine by Using Finite Element Method [63]</p>	<p>Using FEM method assisted with computer calculation, a press was dimensioned. The paper highlights critical points for press failure as well as the methodology proposition to dimension press elements</p>
<p>Design of a slider-crank leg mechanism for mobile hopping robotic platforms [64]</p>	<p>A robotic leg was created under a slider-crank mechanism with a spring on the bottom. This robotic mechanism presents some similarities with a press and a spring system.</p>
<p>Design, Modeling and Structural Analysis of Wave Springs [65]</p>	<p>Pavani, in this study, passes through the stages of a wave spring design. Motivated by the problem that not all systems have space to use a helical spring. Using FEA, different forces and materials were tested with a later comparison with a helical spring samples. Results proved that wave springs could support more stress and present less deformation values on static conditions</p>

Development and use of ASTM standards for wear testing [66]

Report of a comity experiment, to evolve and update some of the tests used by ASTM to test wear on materials. Five different tests where used of different and recommended situation. The report is aimed for companies that may be dealing with wear problems. They also mention that used tests may not be suitable for every equipment but when possible, these tests may assist in problem detection and long-term money savings.

Dimensional synthesis for multi-linkage of high-speed mechanical press [67]

A study focus on optimising relations inside a mechanical press for a better stamping capacity, a smooth displacement, speed and acceleration. Results lead to an increase of speed of 21.5% and a reduction of acceleration around 69.5% on the bottom dead centre reducing press element fatigue

Dynamic analysis and controller design for a slider–crank mechanism with piezoelectric actuators [68]

A slider-crank is connected with sensors to study and evaluate system capacity to collect data under dynamic behaviour changing length of the actuating rod and the slider mass. The application emulates the dynamic behaviour of a press.

Electrical methods for force measurement – A brief survey [42]

In this study, electrical options to measure force were presented and compared. A briefly introduction, principle and advantages and disadvantages where studied and compared. Twelve different options where tested. Numerical data was collected to understand the difference between device's sensitivity. Range of force applications where also investigated being compared with other existent review on it.

Experimental assessment of tribological condition in metal cutting [69]

Cangundo [69] also made studies on how to measure surface variations with his own pin-on-disc configuration. Samples used on the test presented different surface roughness and treatments. Samples used also didn't present any slope between tested surface. Tests proven that values could be collected with one run, allowing decreasing the samples damage. The tests also proved that mechanical properties from the disc and samples affect the surface roughness. When they are near values are easily connected in the same range (especially for stress and hardness). Big differences lead to a more difficult values collection. Filters and properly experimental procedures also need to be highly controlled otherwise frictional conditions will not be correctly obtained.

Failure Analysis of a Helical Compression Spring for a Heavy Vehicle's Suspension System [70]

In this study, springs used on suspension where tested and analysed to predict and detect wear. Identically to springs inside dies, dynamic conditions are verified on this type of system. SEM and chemical analyses where used to detect variations over time. Results show that surface cover was removed, leading to corrosion appear on that points. These points tend to appear on section where the spring contact with remaining system bodies. Cracks also appear and lastly spring break. Wear led to the spring fail and stress was transmitted on a 45-degree axis compared to the spring axis. It was also recommended by the author to prefer non-closed ends to avoid wear propagation otherwise solid film lubrication can also be used to reduce wear effects.

Failure analysis of a set of stainless steel disc springs [71]

Under seawater conditions, disc springs where tested for structural change and spring break. Using visual and microscope elements discs two hypothesis where suggested to analyse. First, one is environmental hydrogen embrittlement and second is hydrogen picking during fabrication. Results showed that hydrogen on this set was the responsible for spring failure supported by morphological samples collected. Samples that receive treatments of 220°C for 12 hours presented properties that are more moldable. In this case, the study, suggested lower care and control for the disc's fabrication.

<p>Fatigue behaviour of helical compression springs at a very high number of cycles— Investigation of various influences [72]</p>	<p>Under different materials and surface conditions, tests were performed to retain and obtain more information about behaviour evolution. Another important topic to understand by the author is how shot peeling will affect springs fatigue evolution. Results showed that inside a range of 10^7 to 10^9 cycles there are decrease of strength properties (around 30% for stainless steel and 10% to SiCr and SiCrV allows). Shot peeling used improved fatigue resistance for SiCr and SiCrV springs although end coil failures could not be avoided from it. Measurements performed with x-ray were not reliable according with the authors.</p>
<p>Fatigue life estimates using Goodman Diagrams [73]</p>	<p>On this study, Stone reviewed some methods used by spring manufacturers Methods used were S-N Curve, Weibull distribution and Goodman Diagram. Stone presents graphical and calculation representation to support any differentiation between fatigue prediction methods. This report does not present a conclusion on which method is better but is noticeable that Goodman diagrams have a more realistic approach to life estimation.</p>
<p>Optical In Situ Micro Tribometer for Analysis of Real Contact Area for Contact Mechanics, Adhesion, and Sliding Experiments [74]</p>	<p>An in-situ equipment was tested on this paper to measure contact between to solid bodies. An interferometric equipment was used to measure contacts, tribofilms and wear. The paper also mentions a zero-interference advantage, allowing the tool a clear perception on height-mapping. Different tests and conditions ca be tested because of a clear force-position synchronization with reproduced images. A rough rubber and polished grass contact were tested on contact and friction level. The equipment was able to do measurements on the order of 50 μN. The reading level goes until 0.4 μm on dimensional position and 14 nm on sliding direction. LED measures 10 μm of separation to capture fringes.</p>
<p>New Challenges in Tribology: Wear Assessment Using 3D Optical Scanners [75]</p>	<p>Biomedical and industrial materials were tested to reduce and failure and material malfunction under digital tribology. It is also stated in the paper that optical scanning field has increased over the last years (the paper was produced in 2017), leading to a natural need to a better understanding and application of this improvements. New instrumentation, accuracy and reproducible</p>

measurements for wear are therefore an option to further investigation. In this article, 3D optical scanners were used to detect and evaluate wear and compare it with actual industry's used techniques. The results show that 3D optical scanners can be accurate depending on the metrical scale of the device. 3D non-contact scanners present different options on the market which leads to an open and inconclusive conclusion although some options were tested, and results presented.

Wear Tests and Pull-Off Force Measurements of Single Asperities by Using Parallel Leaf Springs Installed on an Atomic Force Microscope [76]

Asperities tend to appear on materials over time. This study addressed the influence between asperities and leaf springs. FIB was used to produce asperities and the leaf springs to test. Asperities were created on a single-crystal gold plate to be brushed against the leaf spring under an AFM control. From there, wear and pull-off tests were performed to determine changes between single and parallel leaf systems. Conclusions prove that pull-off force increase with sliding distance and increase rate was similar for two friction loads tested. In parallel case, it was proven that rate increase for higher loaded cases. Flat worn area growth with higher pull-off forces for parallel leaf system, but the same is not verified with a single leaf. The flat worn area was estimated assuming a proportional relation between pull-off force and flat worn area and assuming a hemispherical gold asperity. Wear would monotonically increase with external load but unaffected by adhesion force. Study also observed a hysteresis condition between loading and unloading state.

6.4 Appendix 4 – SMART methodology

This method was introduced by Doran [77] being the word “SMART” an acronym (Table 38).

Table 38 – SMART meaning

S	M	A	R	T
Specific	Measurable	Attainable	Relevant	Time-bound

Doran proposed these five words as key elements for a proper project scope. The guidelines for each word can be found in Table 39.

Table 39 – Guidelines for each word

Specific	Measurable	Attainable	Relevant	Time-bound
What	Quantity	Reasonable	Why this?	When
Where	Quality	Controllable	Why not?	Scheduling
Who	Cost	Resources available	Alignment	Timelines
Which				

6.5 Appendix 5 – Historical data supportive documents

Table 40 presents the meaning of the columns used to collect historical data.

Table 40 – Columns meaning, properties and assisting comments

Column	Property	Comments
1	Type of spring. Diameter per free length	Shows the type of spring related with colour Represents the diameter and free length for the spring
2	Pretension force of the spring	Represents the force when the spring is mounted on the tool die
3	Pretension spring length	Represents the length of the spring after being mounted on the tool
4	Maximum force of the spring	Represents the force when the spring is activated by a full stroke
5	Full compressed spring length	Represents the length of the spring for a full stroke actuation

Column	Property	Comments
6	Total pretension force for a spring system	Represents the total force for springs with identical pretension forces and functions Diameter and length are the same per spring system
7	Total maximum force for a spring system	Represents the total force for springs with identical full stroke forces and functions Diameter and length are the same per spring system
8	Force range per spring	Represents the force variation during one cycle for one spring
9	Displacement range	Represents the displacement variation during one cycle This value is the same per spring or spring system since forces are distributed equally for identical spring systems
10	Force range per spring system	Represents the force variation during one cycle for the spring system

Figure 74 presents the data collected to choose the range of force and displacement for the measuring machine.

Sample	Pre (N)	Distance (m)	End (N)	Distance (m)	Total P (N)	Total E(N)	Force Range Spring	Displacement Range	Force Range Sytems
9,5*76	15	72,4	55,7	60,9	150	557	40,7	11,5	407
9,5*51	15	44,4	38	32,9	60	152	23	11,5	92
vema D117	9,5	8,5	16,7	7	19	33	7,2	1,5	14
12,5*51	95	41,6	149,5	36,2	1330	2093	54,5	5,4	763
12,5*51	170	40,1	273	33,4	104	167	103	6,7	63
31*64	1489,5	47	1932	41,9	1967	3018	442,5	5,1	1051
20*64	325	52,3	507,4	47,3	2030	2211	182,4	5	181
24*76	1320	62,8	1920	58,8	2640	3841	600	4	1201
63*76	9600	64,6	14652	58,6	19200	29304	5052	6	10104
19,5*76	750	63,4	1227,6	55,4	750	1228	477,6	8	478
24*51	1034	36	1171,8	34	2064	2344	137,8	2	280
20*44	2000	39,6	2361,6	38,8	4000	4723	361,6	0,8	723
vema D124	76	14,5	85,6	14	75	86	9,6	0,5	11
70*40,5*5	26700	27,4	28200	27,2	26700	28200	1500	0,2	1500
70*40,5*5	25200	27,6	28900	27,1	25200	28900	3700	0,5	3700
16*32	93,5	28,3	203,9	23,9	187	408	110,4	4,4	221
20*76	160,5	66	257,1	60	321	514	96,6	6	193
vema D116	6	11	7,2	10,8	36	65	1,2	0,2	29
9,5*51	29	45,9	29	45,9	116	116	0	0	0
25*32	1239	28,5	2301	25,5	1239	2301	1062	3	1062
12*89	62	85,5	120	76,5	248	479	58	9	231
vema D124	80	14,5	88	14	80	88	8	0,5	8
9,5*38	31	34	58	30,5	94	148	27	3,5	54
20*64	742	56,8	1089	53,3	1484	2178	347	3,5	694
12*89	28,5	84	60	78,5	114	240	31,5	5,5	126
vema D124	80	14,5	88	14	160	176	8	0,5	16
10*32	847	28,5	1573	25,5	847	1573	726	3	726
16*76	14,5	73	115	52	48	460	100,5	21	412
vema D11595		14		9				5	
8*51	37	47,5	95	42	74	190	58	5,5	116
9,5*38	22,4	30	33,6	26	90	134	11,2	4	44
32*51	4715	46,9	6612	45,25	9430	13224	1897	1,65	3794
9,5*64	42,8	54,5	60	50,65	257	360	17,2	3,85	103
9,5*44		87,2		81,2				6	
9,5*51	63,84	87,2	112,95	81,2	385	677	49,11	6	292
12*44	30	85	85	79,5	240	683	55	5,5	443
48,5*76	4225	63,5	5577	59,5	8450	11154	1352	4	2704
25,4*50*3	8500	45,89	10500	44,24	17000	21000	2000	1,65	4000
24*38	514	32,5	654	31	514	654	140	1,5	140
12*38	90	35,5	205	32,3	90	205	115	3,2	115
48,5*76	5509	59,7	6861	55,7	11018	13723	1352	4	2705
40,5*70*5	23090	61,57	28653	59,92	23090	28653	5563	1,65	5563
vema D116	14	9,8	14	9,8	56	56	0	0	0
7,2*14*0,8	433	2	519	1,9	866	1038	86	0,1	172
vema D124	76	14,5	86	14	229	258	10	0,5	29
vema D111	10	13	10	13	50	50	0	0	0
vema D119	23	9	23	9	46	46	0	0	0

Figure 74 – Database used

6.6 Appendix 6 – Gage Repeatability and Reproducibility (GR&R)

GR&R makes part of the tools to use under six sigma management. GR&R allows to set limits being possible to use it on an initial stage to define requirements or on a final stage to check process repeatability and reproducibility.

To control process repeatability and reproducibility, the trust level (GR&R) presents three different stages (Table 41). The graphs are then constructed based on the needs, being possible to use plots or pareto graphs as well as R X and box charts. Figure 75 and Figure 76 present data used to define needed accuracy for the measuring device.

Table 41 – Stages of GR&R control

Percentage	Comment
GR&R < 10%	Suitable
GR&R = 10-30%	Depending on the process method and variables can be acceptable
GR&R > 30%	Requires improvements

Initial force (N)	Final force (N)	Force difference (N)	Sigma (N)
50	44	6	0.1
116	116	0	0
56	56	0	0
46	46	0	0
80	88	8	0.1333333333
75	86	11	0.1833333333
19	33	14	0.2333333333
160	176	16	0.2666666666
36	65	29	0.4833333333
229	258	29	0.4833333333
90	134	44	0.7333333333
94	148	54	0.9
104	167	63	1.05
60	152	92	1.5333333333
257	360	103	1.7166666666
90	205	115	1.9166666666
74	190	116	1.9333333333
114	240	126	2.1
514	654	140	2.3333333333
866	1038	172	2.8666666666
2030	2211	181	3.0166666666
321	514	193	3.2166666666
187	408	221	3.6833333333
248	479	231	3.85
2064	2344	280	4.6666666666
385	677	292	4.8666666666
385	677	292	4.8666666666
150	557	407	6.7833333333
48	460	412	6.8666666666
240	683	443	7.3833333333
750	1228	478	7.9666666666
1484	2178	694	11.5666666666
4000	4723	723	12.05
847	1573	726	12.1
1330	2093	763	12.7166666666
1967	3018	1051	17.5166666666
1239	2301	1062	17.7
2640	3841	1201	20.0166666666
26700	28200	1500	25
8450	11154	2704	45.0666666666
11018	13723	2705	45.0833333333
25200	28900	3700	61.6666666666
9430	13224	3794	63.2333333333
17000	21000	4000	66.6666666666
23090	28653	5563	92.7166666666
19200	29304	10104	168.4
No data	No data	No data	No data

Figure 75 – GR&R data for force

Initial point (mm)	Final Point (mm)	Displacement (mm)	Sigma (mm)	Sigma (μm)
45.9	45.9	0	0	
9.8	9.8	0	0	
9	9	0	0	
2	1.9	0.1	0.001666666	1.666666666666
27.4	27.2	0.1999999999999999	0.003333333	3.333333333333
11	10.8	0.1999999999999999	0.003333333	3.333333333333
14.5	14	0.5	0.008333333	8.333333333333
27.6	27.1	0.5	0.008333333	8.333333333333
14.5	14	0.5	0.008333333	8.333333333333
14.5	14	0.5	0.008333333	8.333333333333
14.5	14	0.5	0.008333333	8.333333333333
13	13.5	0.5	0.008333333	8.333333333333
39.6	38.8	0.8000000000000004	0.013333333	13.33333333333
8.5	7	1.5	0.025	25
32.5	31	1.5	0.025	25
46.9	45.25	1.65	0.0275	27.5
45.89	44.24	1.65	0.0275	27.5
61.57	59.92	1.65	0.0275	27.5
36	34	2	0.033333333	33.33333333333
28.5	25.5	3	0.05	50
28.5	25.5	3	0.05	50
35.5	32.3	3.2	0.053333333	53.33333333333
34	30.5	3.5	0.058333333	58.33333333333
56.8	53.3	3.5	0.058333333	58.33333333333
54.5	50.65	3.85	0.064166666	64.16666666666
62.8	58.8	4	0.066666666	66.66666666666
30	26	4	0.066666666	66.66666666666
63.5	59.5	4	0.066666666	66.66666666666
59.7	55.7	4	0.066666666	66.66666666666
28.3	23.9	4.4	0.073333333	73.33333333333
52.3	47.3	5	0.083333333	83.33333333333
14	9	5	0.083333333	83.33333333333
47	41.9	5.1	0.085	85
41.6	36.2	5.4	0.09	90
84	78.5	5.5	0.091666666	91.66666666666
47.5	42	5.5	0.091666666	91.66666666666
85	79.5	5.5	0.091666666	91.66666666666
64.6	58.6	5.999999999999999	0.099999999	99.99999999999
66	60	6	0.1	100
87.2	81.2	6	0.1	100
87.2	81.2	6	0.1	100
40.1	33.4	6.7	0.111666666	111.66666666666
63.4	55.4	8	0.133333333	133.33333333333
85.5	76.5	9	0.15	150
44.4	32.9	11.5	0.191666666	191.66666666666
72.4	60.9	11.5	0.191666666	191.66666666666
73	52	21	0.35	350

Figure 76 – GR&R data for displacement

6.7 Appendix 7 – Morphological overview

The morphological overview is a key element for every mechanical engineer. The idea behind an M.O (Figure 77) is to define critical functions necessary for a concept and add all possible options to satisfy that purpose.























ID	Function	Concepts				
A	Apply Force	Hand Push 	Winch 	Tow Cable 	Handle Pull 	Engines/Fans 
B	Grip	Clamp Plates 	Tension Cables 	Magnets 	Suction 	Frame 
C	Lift	Block & Tackle 	Hydraulic/Pneumatic 	Mechanical Gears 	Actuator/ Ball Screw 	Crane/Hoist 
D	Rotate	Wheel & Axle 	Tilting Piston 	Motor & Axle 	Tension Cables 	
E	Provide Motion	Wheels 	Hover Fans/Skirt 	Treads/Belts 		

Figure 77 – Morphological overview example [78]

Years of experience and the ability to understand systems play an important role for an engineer to use this method. Figure 78 exemplifies a quite simple M.O. to be interpreted by any person outside the engineering branches. The simpler this analysis, the better the result obtained from the process.
























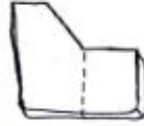












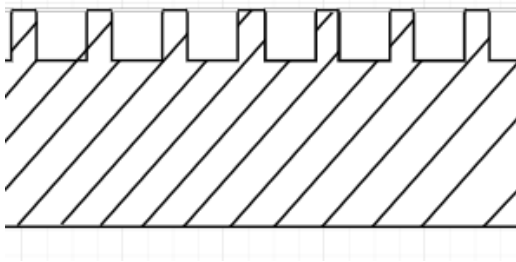
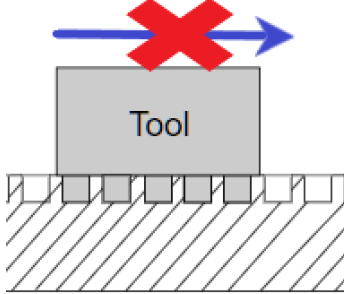
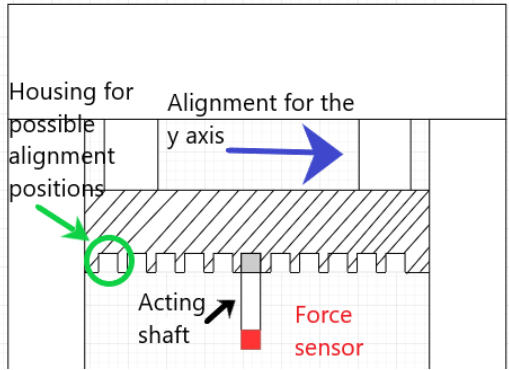
OPTION TOPIC	1	2	3	4
Material/s Selection	 STEEL	 WOOD	 PLASTIC	 ALUMINIUM
Seat	SQUARE 	ROUND 	IRREGULAR 	TRIANGLE 
Drinking Bottle Holder	STEEL NET 			HANGING BOX 
Leg				
Body	NORMAL 			
Small Table				
Lifting Mechanism				
Basket/ space for Books etc.				SPACE UNDER TABLE 
Adjustable Height Mechanism	HAND WHEEL 	STICK 	HAND BRAKE 	SPRING 

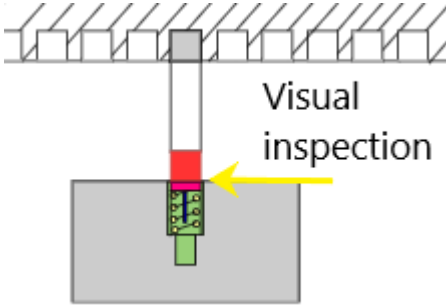
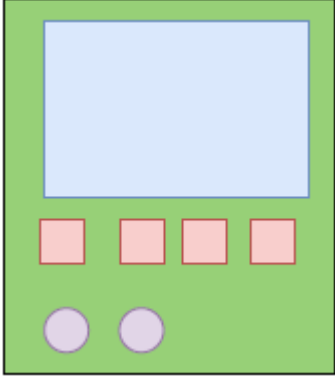
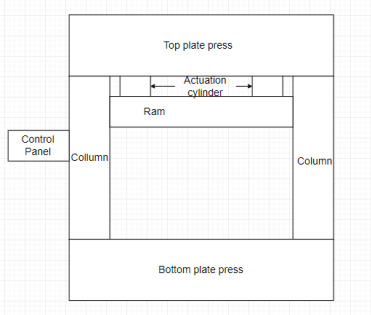
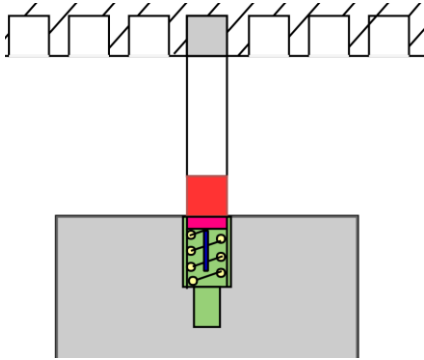
Figure 78 – Morphological overview example 2 [79]

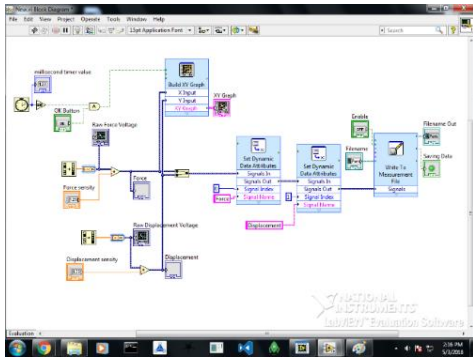
6.8 Appendix 8 – Different concept tables

The following tables (Table 42 to Table 46) present the main ideas behind each concept presented in Chapter 3.6.

Table 42 – Kistler concept answers for chapter 3.4 questions

Question/Answer	Picture
<p>How should the tool be placed on the machine?</p> <p>Tool is placed manually and fixed on a hydraulic press bottom table</p>	 <p>(cross view representation of a bottom press surface when tool is fixated)</p>
<p>Should the tool die be moveable or fix relative to the measuring machine?</p> <p>The tool is not moveable</p>	
<p>Should the measuring machine be moveable or fix relative to the tool?</p> <p>An acting shaft is added to the press ram. This shaft is manually configured by the operator being aligned in x and y axis</p>	 <p>Alignment for the x axis is equal to this view</p>

Question/Answer	Picture
<p>How can the alignment between the tool and the measuring machine be ensured?</p> <p>Visual inspection</p>	
<p>Should the testing speed allow velocity variation or should velocity always be the same?</p> <p>The testing speed is variable and configurable by the press control panel</p>	
<p>Which mechanism will produce speed, force and displacement during the test?</p> <p>An hydraulic press</p>	
<p>Which type of sensors should be used for measuring force and displacement?</p> <p>Only sensor used is a piezoelectric force sensor. Displacement is obtained from force values</p>	

Question/Answer	Picture
<p>Are sensors accuracy according to the accuracy needed for a proper testing?</p> <p>Displacement accuracy is ensured but does not reflect integrally spring systems displacement since it is based on force values</p>	 <p>(initial software development)</p>

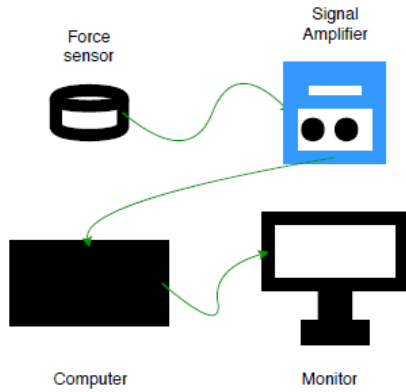
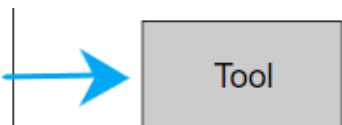
<p>How data is collected?</p> <p>Data is obtained with a signal amplifier device connected with a computer and monitor</p>	
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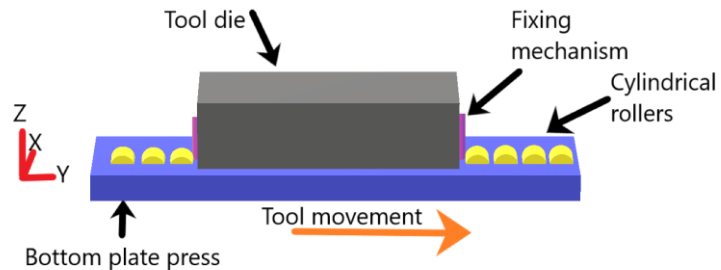
Table 43 – Press concept answers for chapter 3.4 questions

Question/Answer	Picture
<p>How should the tool be placed on the machine?</p> <p>The tool is placed manually</p>	 <p>Manually placement of the tool Bottom plate press</p>

Question/Answer	Picture
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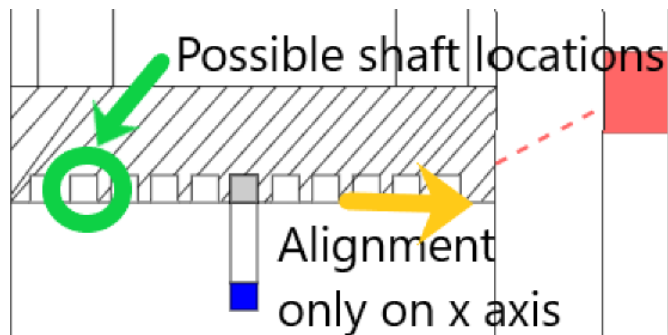
Should the tool die be moveable or fix relative to the measuring machine?

The tool is moveable on y axis assisted by rolling cylinders being then fixed on predetermined positions



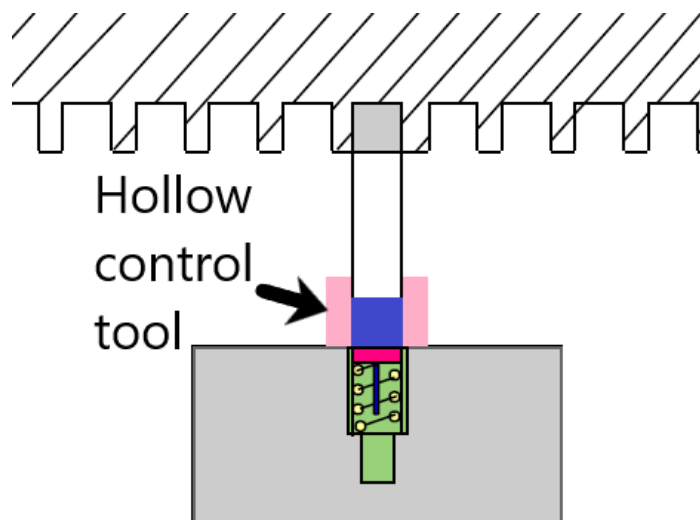
Should the measuring machine be moveable or fix relative to the tool?

An acting shaft is added to the press ram. This shaft is configured by the operator being aligned only on x axis



How can the alignment between the tool and the measuring machine be ensured?

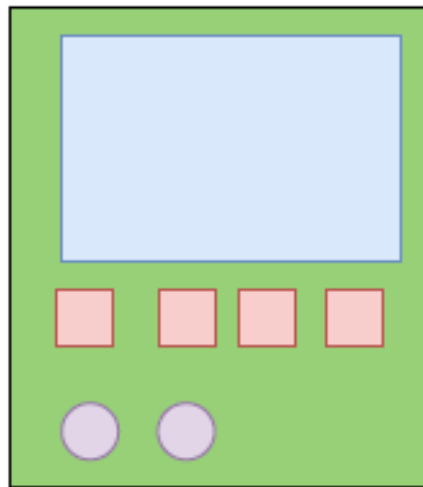
A hollow control tool can be added to ensure a proper concentricity between the acting shaft and the spring system



Question/Answer	Picture
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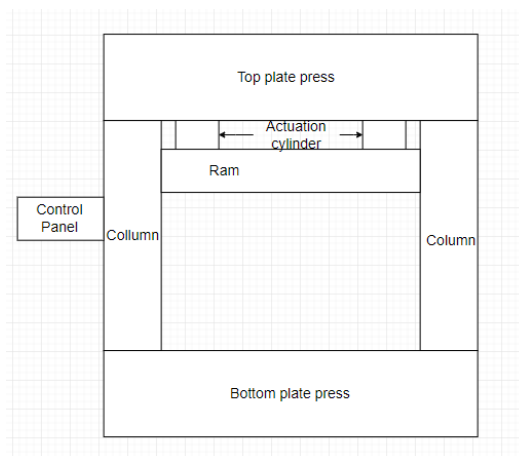
Should the testing speed allow velocity variation or should velocity always be the same?

The testing speed is variable and configurable by the press control panel



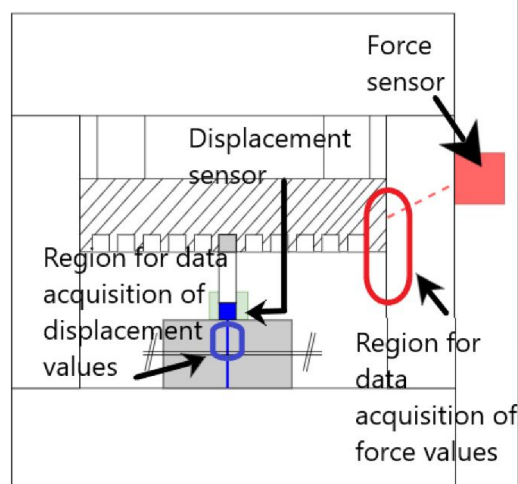
Which mechanism will produce speed, force and displacement during the test?

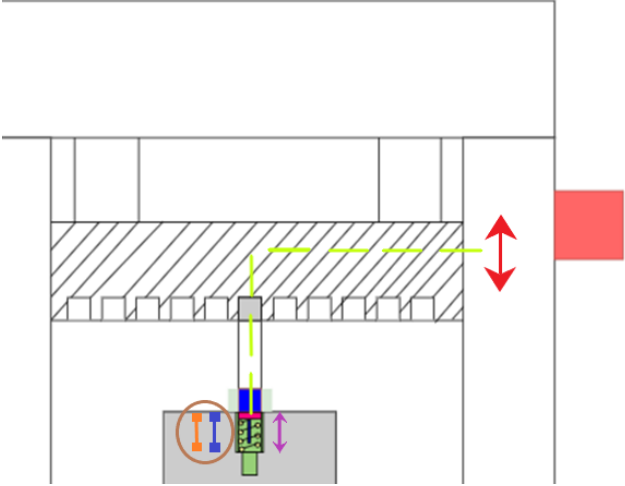
The figure shows a servo electric press



Which type of sensors should be used for measuring force and displacement?

Force is measured in the press ram and displacement is directly obtained from the shaft movement



Question/Answer	Picture
<p>Are sensors accuracy according to the accuracy needed for a proper testing?</p> <p>The use of a piezoelectric sensor in direct contact with spring system for measuring displacement should be reliable enough. Collecting force from the press ram may present force values different then the values on spring systems</p>	 <ul style="list-style-type: none"> • Brown circle represents the theoretical displacement (orange line) vs the displacement collected by the sensor (blue line) • Dash green line represent the distance and the path between theoretical force (pink arrow) and the force collected by the sensor (red arrow).

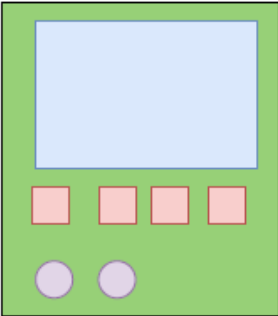
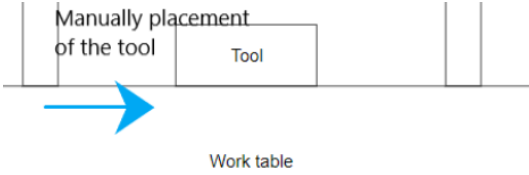
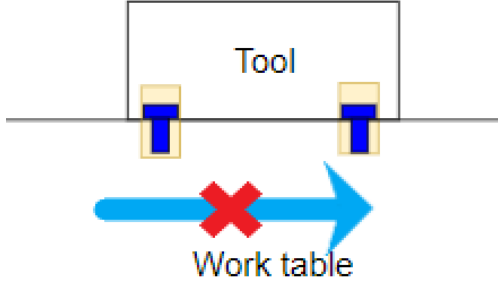
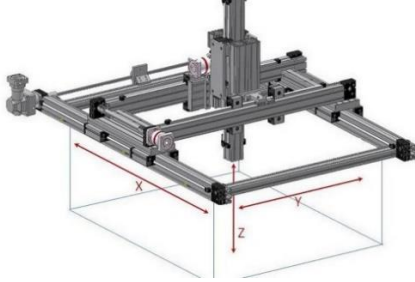
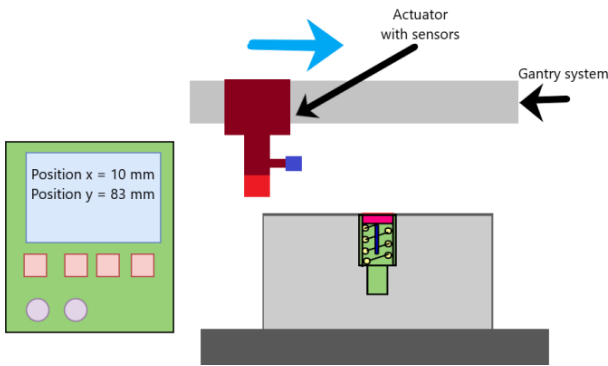
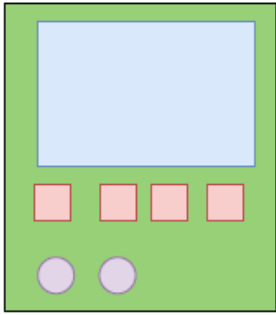
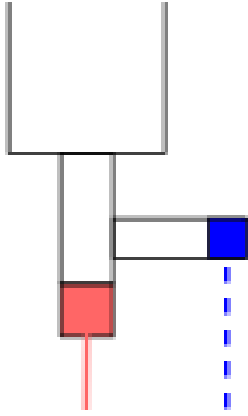
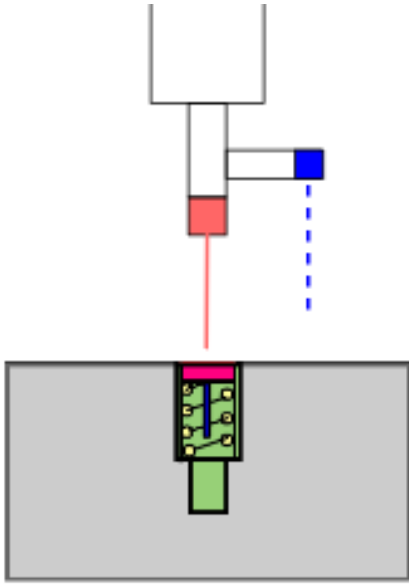
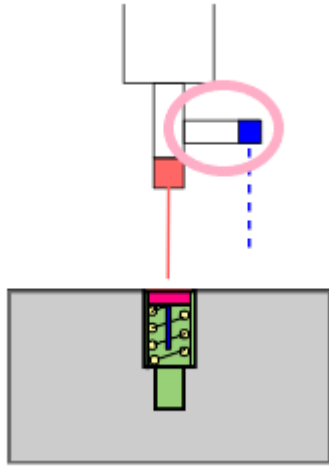
<p>How data is collected?</p> <p>Data is obtained directly from the press control panel</p>	
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Table 44 – Actuator concept answers for chapter 3.4 questions [80]

Question/Answer	Picture
<p>How should the tool be placed on the machine?</p> <p>Tool is placed manually</p>	

Question/Answer	Picture
<p>Should the tool die be moveable or fix relative to the measuring machine?</p> <p>The tool is not moveable on this concept</p>	 <p>Screws can be used to prevent movement (blue arrow) on both axis</p>
<p>Should the measuring machine be moveable or fix relative to the tool?</p> <p>An acting shaft is added to the press ram. This shaft is configured by the operator being aligned only on x axis</p>	 <p>Gantry Systems moveable on three axis</p>
<p>How can the alignment between the tool and the measuring machine be ensured?</p> <p>Since the system is automated, the accuracy is ensured by the control panel controlling motion on x and y axis</p>	 <ul style="list-style-type: none"> • The blue arrow represents motion for the actuator • The mechanism can have different functions based on tool to be analysed • Motion is identical for x or y axis

Question/Answer	Picture
<p>Should the testing speed allow velocity variation or should velocity always be the same?</p> <p>The testing speed is variable and configurable by the actuator control panel</p>	
<p>Which mechanism will produce speed, force and displacement during the test?</p> <p>A servo electric actuator is used</p>	
<p>Which type of sensors should be used for measuring force and displacement?</p> <p>Force is measured on the contact point between the spring system and the actuator shaft.</p> <p>Displacement is obtained from the relative movement between the actuator shaft and the tool surface</p>	

Question/Answer	Picture
<p>Are sensors accuracy according to the accuracy needed for a proper testing?</p> <p>Force sensor should present properly values since force is collected with direct contact. For displacement, only need is to ensure that vibration do not affect sensor measurement quality (pink circle)</p>	

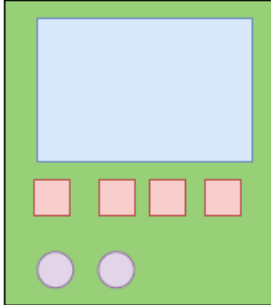
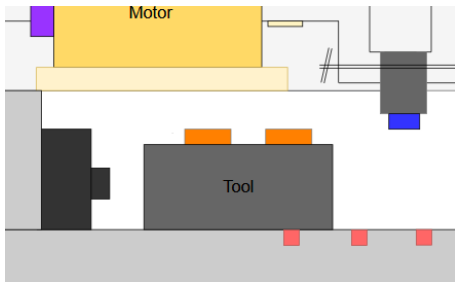
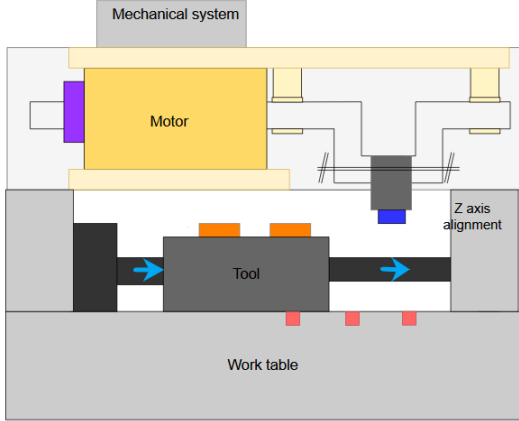
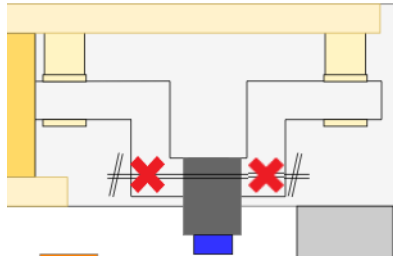
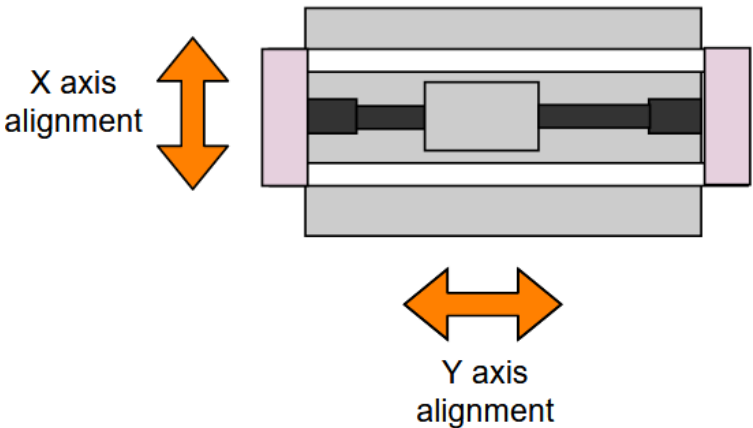
<p>How data is collected?</p> <p>Data is obtained directly from the control panel connected with the actuator</p>	
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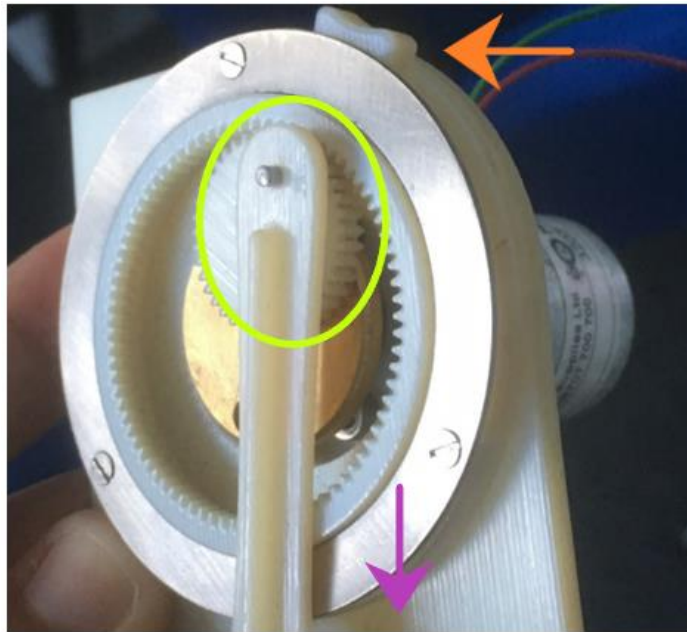
Table 45 – Piston concept answers for chapter 3.4 questions

Question/Answer	Picture
<p>How should the tool be placed on the machine?</p> <p>Tool is placed manually</p>	

Question/Answer	Picture
<p>Should the tool die be moveable or fix relative to the measuring machine?</p> <p>The tool is moveable (blue arrows) on this concept using actuators to properly place the tool under the acting shaft</p>	
<p>Should the measuring machine be moveable or fix relative to the tool?</p> <p>The acting shaft is fixed on a reference point</p>	
<p>How can the alignment between the tool and the measuring machine be ensured?</p> <p>Alignment is ensured by the control board for the actuator for the y-axis. X axis is moved on a limited range for a guided mechanism (purple boxes)</p>	

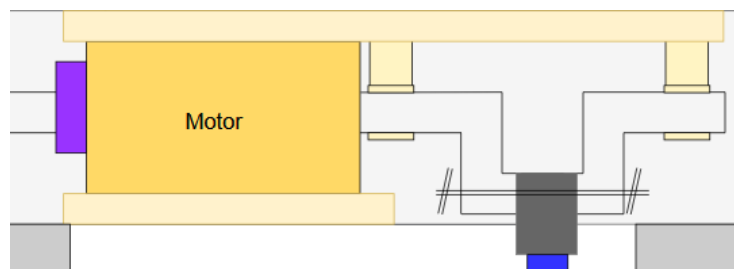
Should the testing speed allow velocity variation or should velocity always be the same?

Since the displacement is short, the idea is to have an adjustable switch (orange arrow) to vary motor diameter relation (green circle) and consequently vary acting shaft travel length (pink arrow).



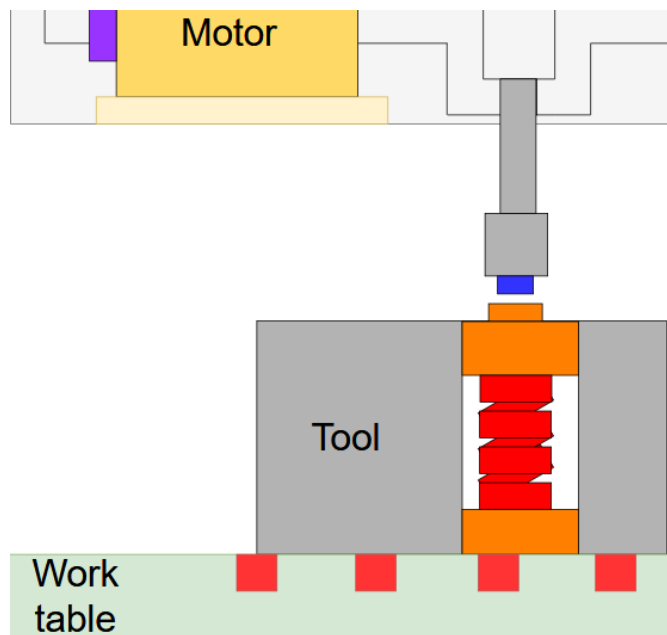
Which mechanism will produce speed, force and displacement during the test?

An electric motor with a acting shaft



Which type of sensors should be used for measuring force and displacement?

Force load cells (red squares) are placed under the working table to measure force acting on the tool. Displacement (blue rectangle) is obtained from the direct contact between the acting shaft and the spring system



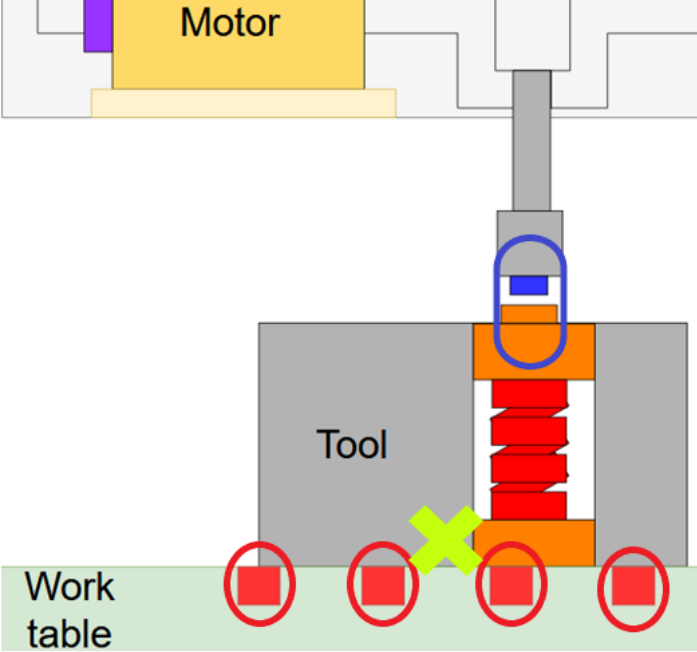
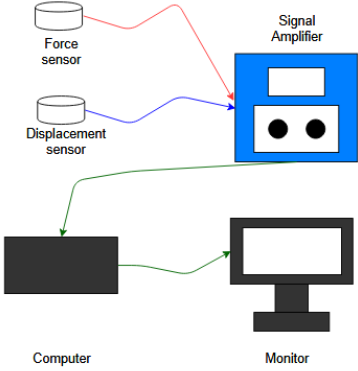
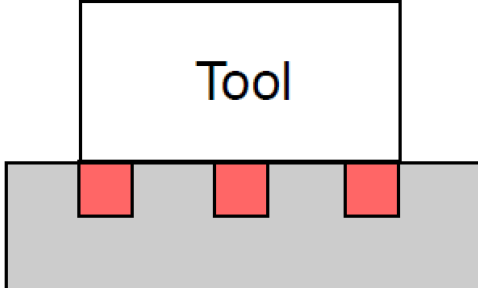
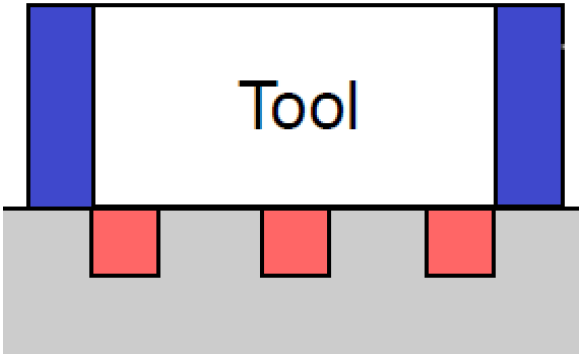

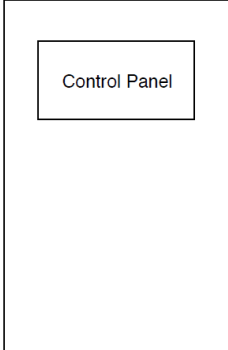
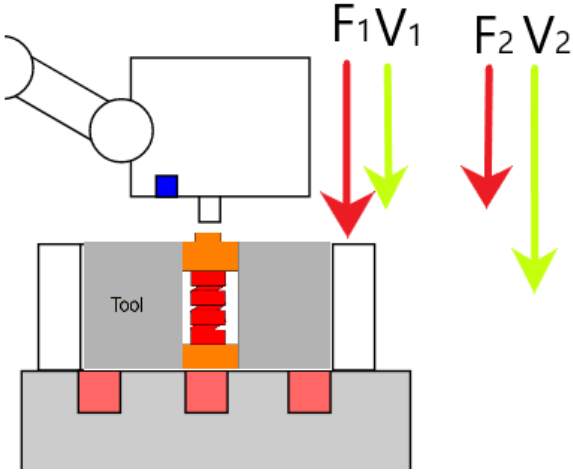

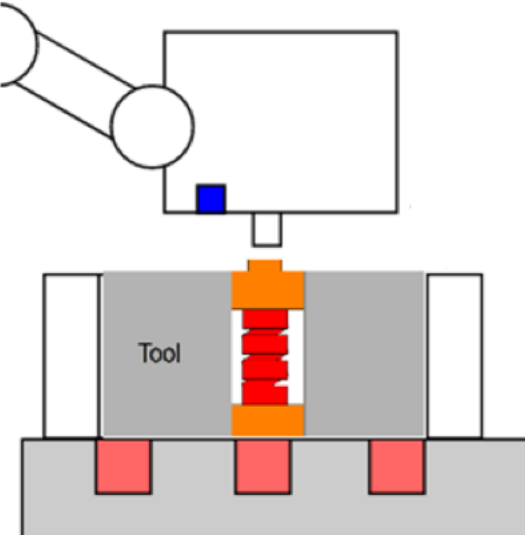
Question/Answer	Picture
<p>Are sensors accuracy according to the accuracy needed for a proper testing?</p> <p>Force is collected in different points (red circles) being then combined to an overall value (green cross) This filter should present a high trustable result even due sometimes the value is not aligned on the z-axis with the spring system.</p> <p>Displacement since is collected directly from the spring system also presents a reliable accuracy (blue circle)</p>	
<p>How data is collected?</p> <p>Data is collected directly from the sensors passing through a signal amplifier and presenting a result on a monitor after being processed by the computer.</p>	

Table 46 – Robot arm concept answers for chapter 3.4 questions [81]

Question/Answer	Picture
<p>How should the tool be placed on the machine?</p> <p>Tool is placed manually on a work table</p>	
<p>Should the tool die be moveable or fix relative to the measuring machine?</p> <p>The tool is not moveable on this concept. Blocks (blue boxes) are added to prevent tool movement</p>	
<p>Should the measuring machine be moveable or fix relative to the tool?</p> <p>The measuring machine is moveable on the three axis.</p>	
<p>How can the alignment between the tool and the measuring machine be ensured?</p> <p>The control panel ensure a properly positioning</p>	

Question/Answer	Picture
<p>Should the testing speed allow velocity variation or should velocity always be the same?</p> <p>Speed will be dependent on force necessary to move the spring system</p>	
<p>Which mechanism will produce speed, force and displacement during the test?</p> <p>A robotic arm is used</p>	
<p>Which type of sensors should be used for measuring force and displacement?</p> <p>Force load cells (red squares) are placed under the working table to measure force acting on the tool.</p> <p>Displacement (blue square) is collected by measuring relative robot movement to the tool surface</p>	

Question/Answer	Picture
<p>Are sensors accuracy according to the accuracy needed for a proper testing?</p> <p>Force is collected from more than one sensor allowing having a high filter for force values.</p> <p>Displacement can be more concerning since high forces, high speed and system leak of robustness can lead to errors (lines on drawing)</p>	<p>Purple misalignment measurement Green not continuous data acquisition (blank points) Blue surpassing the measuring area</p>
<p>How data is collected?</p> <p>Sensors are connected to the robot control panel presenting after the measurement the results</p>	

6.9 Appendix 9 – Pugh Matrix

Pugh matrix is used to evaluate available options for different parameters. S. Pugh [82] was responsible for introduction this method in his book around 1991. The use of Pugh matrix (Figure 79) is used for the following objectives:

The Pugh Matrix	
The Pugh matrix <u>is</u> for	The Pugh matrix is <u>NOT</u> for
<ul style="list-style-type: none"> • Structuring and representing an evaluation procedure <ul style="list-style-type: none"> –Serves as common visual –Provides a discipline –Helps break down self-sealing behavior • Convergence <ul style="list-style-type: none"> –Eliminates weaker ideas –Retains a set of strong concepts • Divergence <ul style="list-style-type: none"> –Helps to identify opportunities for combination 	<ul style="list-style-type: none"> Automatic decision making <ul style="list-style-type: none"> –"the scores or number ... are for guidance only and must not be summed algebraically." –"it avoids the rigidity and false confidence of rating/weighting matrices" • Completely controlling the process • Stimulates creative unconstrained thinking • Due to its lack of rigorous structure"

Figure 79 – Pugh matrix objectives [82]

For the elaboration of the matrix, a reference is fixed as standard and the following are compared with the first. The weight tab is also added to classify and prioritize the evaluation parameters. Figure 80 presents an example.



		Weight	Baseline	Fennestron	NOTAR
Quality	Safety	4	0	2	3
	Weight	3	0	-3	2
	Noise	2	0	2	3
	Flight Dynamics	5	0	3	2
	Subtotal		0	18	34
Cost	Manufacturing Cost	5	0	-2	-1
	Service Cost	3	0	-1	1
	Subtotal		0	-13	-2
Schedule	Design Time	3	0	-1	1
	Parts Availability	1	0	-1	-1
	Subtotal		0	-4	2
Total	Sum		0	1	34
	# of positive values		0	3	6
	# of negative values		0	5	2

Figure 80 – Pugh matrix example [83]

One of the major advantages of this method for engineering is that it allows individual and independent evaluations to make the decision safer and more accountable from a business point of view.

Figure 81 presents the template given to each stakeholder to be fulfilled.

Pugh Matrix							
Solution Alternatives							
Key Criteria	Importance Rating	Piston	"Kistler"	Press	Actuator	Robot arm	Guillotine
	Measurement Accuracy		S				
Safety		S					
Cost		S					
Time		S					
Project Feasibility / Availability		S					
Maintenance/Fatigue		S					
Universal		S					
Robustness		S					
Friendly interface/Easy to use		S					
	Sum of Positives	0	0	0	0	0	0
	Sum of Negatives	0	0	0	0	0	0
	Sum of Sames	9	0	0	0	0	0
	Weighted Sum of Positives	0	0	0	0	0	0
	Weighted Sum of Negatives	0	0	0	0	0	0
TOTALS		0	0	0	0	0	0

Figure 81 – First stage Pugh matrix template

6.10 Appendix 10 – Concept dimensions

Figure 82 presents the dimension for “measuring tank” concept

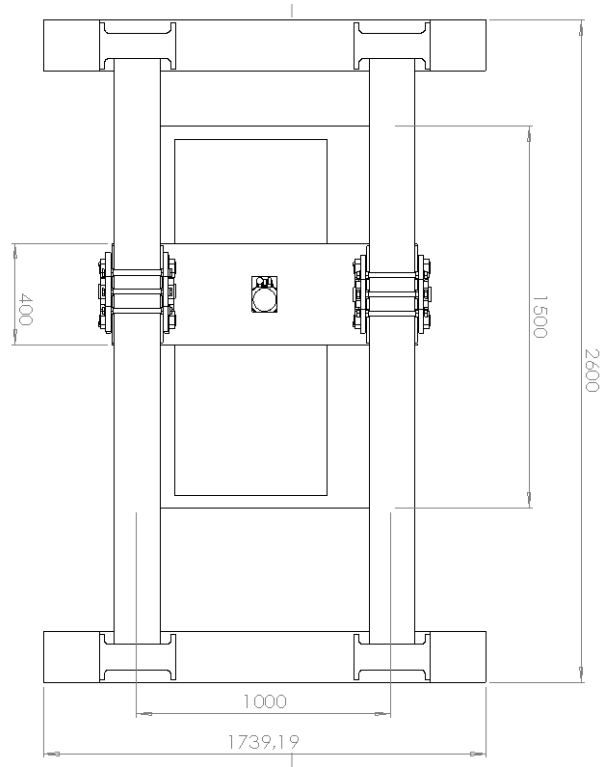


Figure 82 – “Measuring tank” dimensions

Figure 83 presents the dimension for “neo” concept

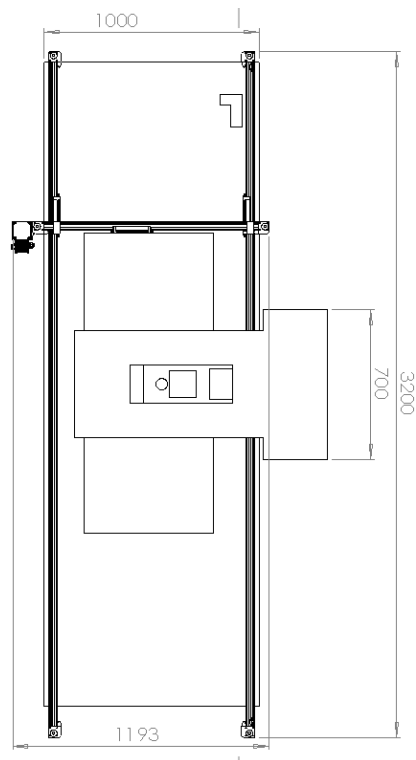


Figure 83 – “Neo” dimensions

Figure 84 presents the dimension for “Drive thru” concept

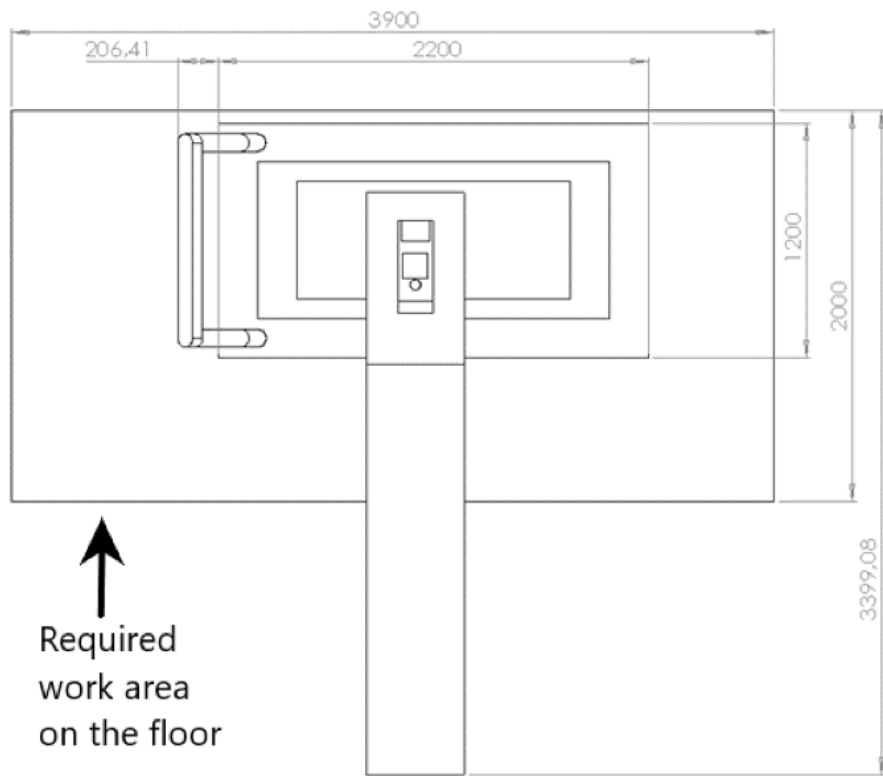


Figure 84 – “Drive thru” dimensions

Figure 85 presents the dimension for “Bowie” concept

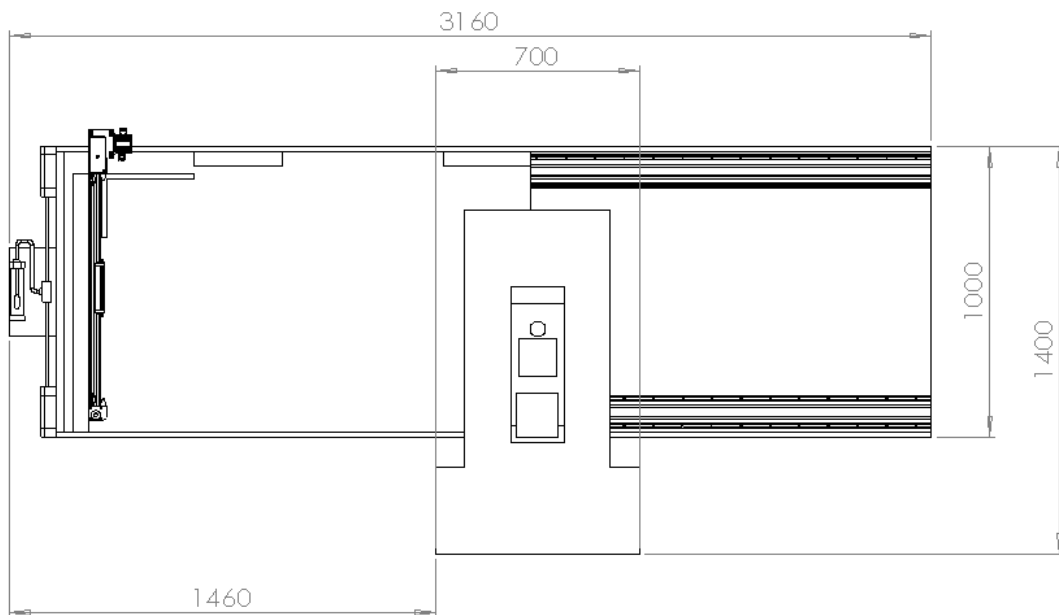


Figure 85 – “Bowie” dimensions

Figure 86 presents the dimension for “Mermaid” concept

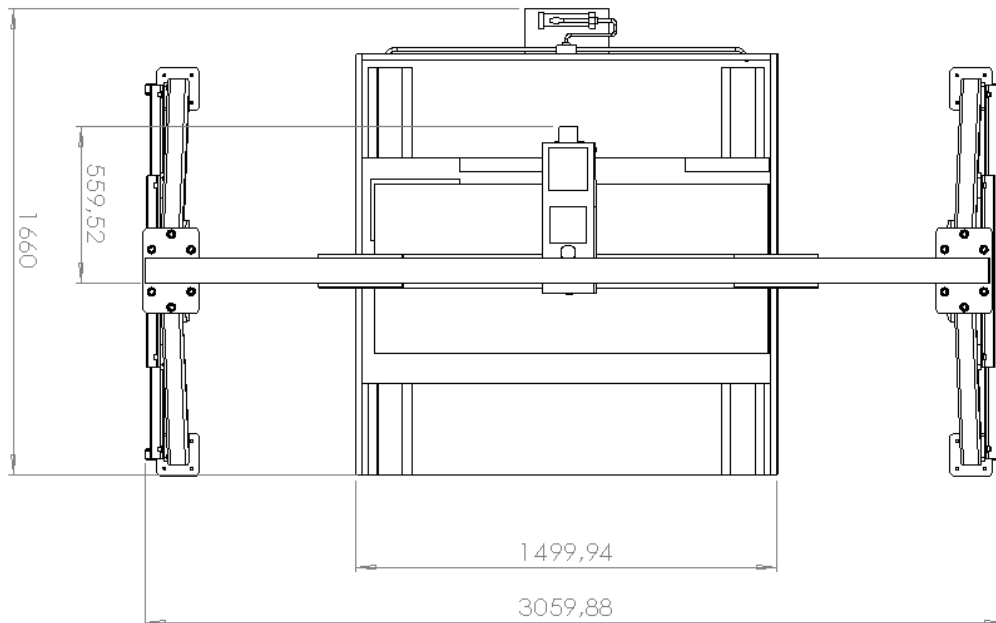


Figure 86 – “Mermaid” dimensions

Figure 87 presents the dimension for “Vegas” concept

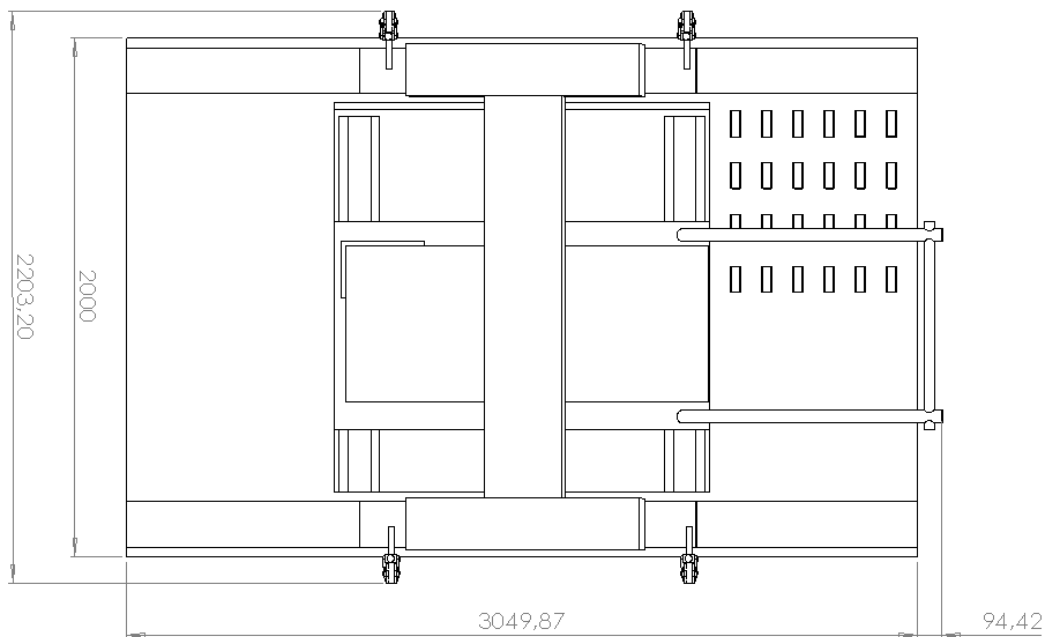


Figure 87 – “Vegas” dimensions

6.11 Appendix 11 – Pugh Matrix (Optimized concept selection)

Figure 88 presents the final score for the Pugh matrix. Table 47 presents motivations behind the given ratings.





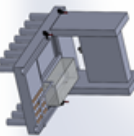

		Pugh Matrix						
		Solution Alternatives						
		Mermaid	Tank	Drive thru	Bowie	Vegas	Neo (automated tool positioning)	
								
Key Criteria	Importance Rating							
Positioning accuracy	5	S	-	-	+	+	++	
Vertical system stiffness	4	S	-	+	+	++	+	
Surrounding independency (wall/floor)	5	S	S	S	++	++	++	
Size	3	S	+	+	++	+	++	
Safety	5	S	S	++	+	+	++	
Investment	1	S	S	+	+	S	--	
Positioning time	2	S	S	-	+	+	++	
User friendliness	4	S	S	++	+	+	++	
Sum of Positives		0	1	7	10	9	13	
Sum of Negatives		0	2	2	0	0	2	
Sum of Sames		8	5	1	0	1	0	
Weighted Sum of Positives		0	3	26	37	37	52	
Weighted Sum of Negatives		0	9	7	7	7	0	
TOTALS		0	-6	19	30	30	52	

Figure 88 – Second stage Pugh matrix results

Table 47 – Key criteria

Key Criteria	Value	Motivation
Positioning accuracy	5	Important to ensure a proper measurement
Vertical system stiffness	4	Important due to the high forces and testing speeds used Reinforcer for testing accuracy
Surrounding independency (wall/floor)	5	The system should be independent of external elements since the device may need to be moved from location.
Size	3	Size should not compromise testing needs although a smaller device is appreciated
Safety	5	The most important factor, the machine needs to be safer to use
Investment	1	The initial investment is the lowest factor to be taken into consideration for a measuring device
Positioning time	2	Positioning time is not a concern if accuracy is ensured
User friendliness	4	The device should be easy to use by anyone on the factory.

6.12 Appendix 12 – FMEA

Safety is not always easy to quantify since there is no formula to prevent it. FMEA is a technique that helps eliminate potential errors for a process.

FMEAs were introduced around 1960 for the aerospace industry. The search for space and the unknown forced the special control to guarantee high security having this tool being critical for the success of the future of this area.

To carry out an FMEA, several hypotheses are considered by a team of specialists. The assumptions are then labelled by risk priority number (RPN). RPN is obtained by:

$$RPN = S \times O \times D \quad (9)$$

RPN can have a value between 1 to 1000. To understand every factor affecting RPN, Table 48 was added.

Table 48 – Meaning of RPN parameters [84]

Symbol	Meaning	Value
D	Detection – Probability to detect a failure before the impact, from it, is realized	Each potential failure is rated from 1(lowest) to 10(highest)
O	Occurrence – Frequency of failure occurrence	
S	Severity – Consequence of the failure	

Failure Mode and Effects Analysis Worksheet																			
Process or Product: EMEA Team: Team Leader:		EMEA Date: (Original) (Revised)		EMEA Number: Page: 1 of 1															
Line	Component and Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	FMEA Process			Action Results											
					Potential Cause(s) of Failure	Current Controls, Prevention	Current Controls, Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Severity	Occurrence	Detection	RPN				
1																			
2																			
3																			
4																			
5																			
6																			
7																			
8																			
9																			
10																			

Figure 89 – FMEA worksheet template example [84]

6.13 Appendix 13 – Database creation documents

Figure 90 presents data used to exemplify a database creation document. Figure 91 and Figure 92 present a template suggestion and an example for each model.

	N/mm	Prestress(mm)	Stroke(mm)	K(N/mm)	Pre (N)	Distance (mm)	End(N)	Distance (mm)	Number of springs	Total F (N)	Total E(N)	Force 1	Displacement	Force 2
25*51	51	8.15	2.88	157	1279.55	42.85	1731.71	39.97	4	5118.2	6926.84	452.16	2.88	1808.64
32*38 + 16*38	38	7	1.7	489	3423	31	4254.3	29.3	1	3423	4254.3	831.3	1.7	831.3
25*38	38	4	1.7	280	1120	34	1596	32.3	6	6720	9576	476	1.7	2856
25*38 + 12*38	38	5.5	1.3	93.4	513.7	32.5	635.12	31.2	1	513.7	635.12	121.42	1.3	1237.42
25*38	38	2.5	3.1	360	900	35.5	2016	32.4	1	900	2016	1116	3.1	333.944
25*38	38	7	1.52	219.7	1537.9	31	1871.844	29.48	1	1537.9	1871.844	333.944	1.52	333.944
12*38	38	3	5.1	36	108	35	291.6	29.9	2	216	583.2	183.6	5.1	367.2
20*38	38	5	1	57.1	285.5	33	342.6	32	2	571	685.2	57.1	1	114.2
20*38	38	2.75	0.85	129	354.75	35.25	464.4	34.4	1	354.75	464.4	109.65	0.8500000000	109.65
32*38	38	4.35	2	488.9	2126.715	33.65	3104.515	31.65	4	8506.86	12418.06	977.8	2	3911.2
10*64	64	6.25	9.15	1.7	10.625	57.75	26.18	48.6	26	276.25	522.444	9.469	5.57	246.194
10*64	64	6.25	5.57	1.7	10.625	57.75	20.094	52.18	26	276.25	522.444	9.469	5.57	246.194
20*51	51	9.05	2	38.9	352.045	41.95	429.845	39.95	1	352.045	429.845	77.8	2	77.8
Fd Güreklüster 7.3*57.3	57.3	7.55	2.63		0	49.75	0	47.12	4	0	0	0	2.63	0
25*51	51	8.15	2	157.3	1281.995	42.85	1596.595	40.85	4	5127.98	6386.38	314.6	2	1258.4
40*51	51	7.15	3	559.7	4001.855	43.85	5680.955	40.85	4	16007.42	22723.82	1679.1	3	6716.4
Skonda FM(R)28 973 (45*4	63	7.15	3	1000	7150	55.85	10150	52.85	1	7150	10150	3000	3	3000
25*51	51	6.45	4	157.3	1014.585	44.55	1643.785	40.55	4	4058.34	6575.14	629.2	4	2516.8
25*51	51	5.15	5.5	157.3	810.095	45.85	1675.245	40.35	13	10531.235	21778.185	865.15	5.5	11246.95
40*64+20*64	64	7.7	5.5	520.5	4007.85	56.3	6870.6	50.8	3	12023.55	20611.8	2862.75	5.5	8588.25
16*51	51	3.5	5.5	14.2	49.7	47.5	127.8	42	3	149.1	383.4	78.1	5.5	234.3

Figure 90 – Tool database example

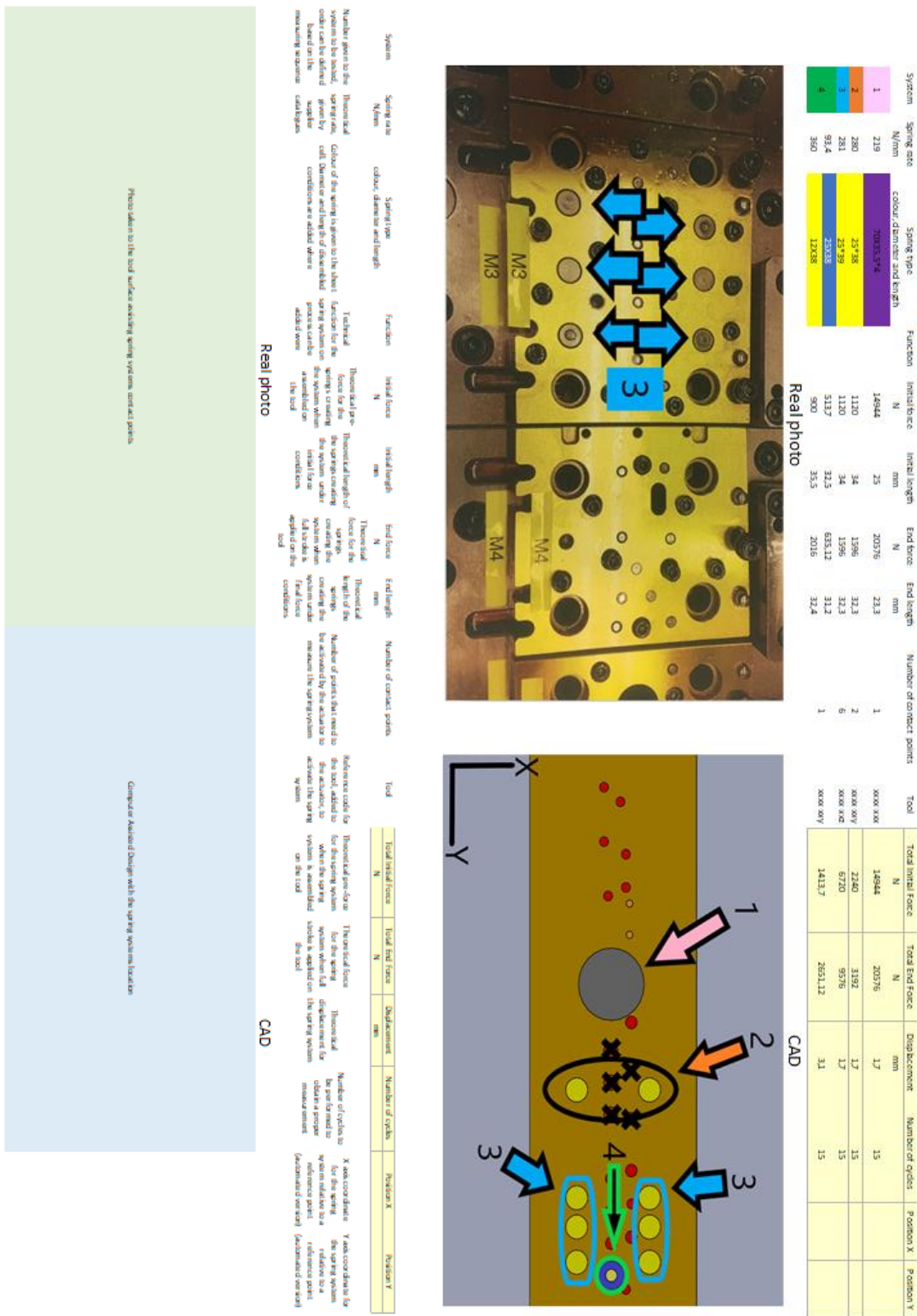


Figure 91 – First template guidance (left) and 1700 tool example document (right)

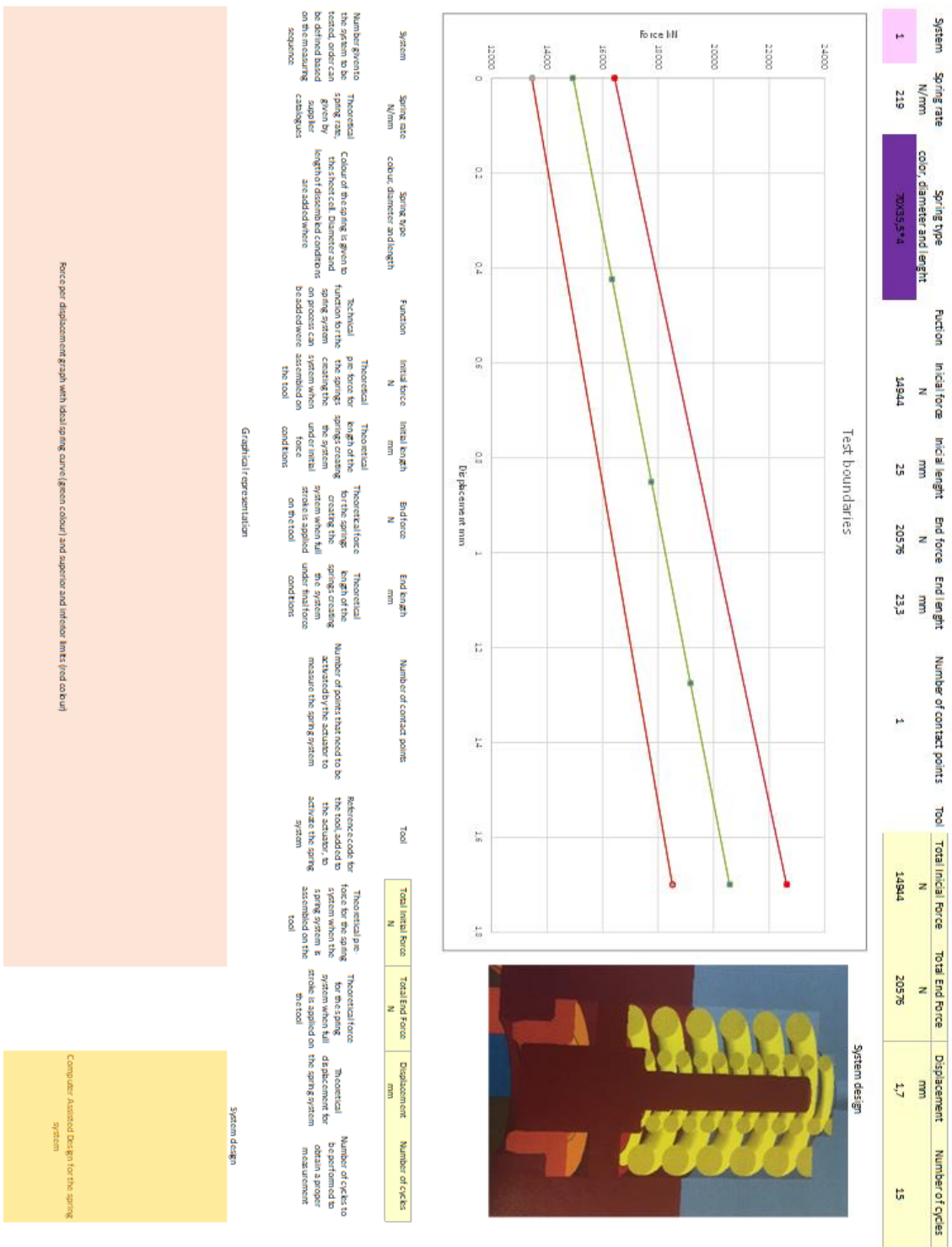


Figure 92 – Second template guidance (left) and 1700 tool example document (right)

6.14 Appendix 14 – ROI

Return of investment (ROI) is a formula used to evaluate and measure the ratio between profit and initial investment needed. ROI formula is calculated by:

$$ROI = \frac{\textit{Gains from investment} - \textit{Costs of investment}}{\textit{Costs of investment}} \quad (10)$$