CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Electrical Engineering

Adhesive Joints Formed of Electrically Conductive Adhesives

Adhezní spoje vytvořené elektricky vodivými lepidly

Master's thesis

Study program: Electrical Engineering, Power Engineering and Management
Study field: Electrical Power Engineering

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Supervisor of the Master's thesis: doc. Ing. Pavel Mach, CSc.

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ZADÁNÍ DIPLOMOVÉ PRÁCE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Adhezní spoje vytvořené elektricky vodivými lepidly

Název diplomové práce anglicky:

Adhesive Joints Formed of Electrically Conductive Adhesives

Pokyny pro vypracování:

1. Seznamte se s principy elektricky vodivých lepidel a s technologiemi jejich aplikace.
2. Vytvořte skupiny adhezních spojů.
3. Proveďte stárnutí spojů dle zadání vedoucího práce.
4. Vytvořte model stárnutí spojů pomocí úplných faktorových experimentů.
5. Proveďte výpočet vlivu jednotlivých klimatických faktorů na sledovaný elektrický parametr spoje technikou Taguchi-ho ortogonálních oblastí.
6. Porovnejte výsledky získané technikou úplných faktorových experimentů a Taguchi-ho přístupem.

Seznam doporučené literatury:

[1] Morris, J. E.: Electrically Conductive Adhesives, (ECAs), available on https://pdfs.semanticscholar.org/d4aa/b6bcd54c10676edcfdd609eb47d16ede4add.pdf
[2] Li, Y., Wu, D., Wong, C. P.: Electrical Conductive Adhesives with Nanotechnologies, Springer Science + Bussines Media, N.Y. 2010, pp. 166 ? 176
[3] Yim, M. J., Paik, K. W.: Review of Electrically Conductive Adhesive Technologies for Electronic Packaging, Electronic Material Letters, Vol. 2, No. 3, 2006, pp. 183 ? 194

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání

Podpis studenta

Declaration

I hereby declare that this master's thesis is completely my own work and that I used only the cited sources in accordance with the Methodical instruction about observance of ethical principles of preparation of university final projects.

In Prague ………………… Signature ……..……………
Bc. Ferdinand Závora

Prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze dne ……………… Podpis ……..……………….
Bc. Ferdinand Závora

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Master’s thesis title

Adhesive Joints Formed of Electrically Conductive Adhesives

Abstract

This work focuses on the application of quality control methods in the field of Electrotechnology. It examines joints created using electrically conductive adhesives. Specifically it looks at the influence of climatic factors on the aging of these joints. Individual factors are compared using full factorial experiments (where linear mathematical model of the climatic aging process is also created and then tested using real measured data) and Taguchi orthogonal arrays. The final and main output of this thesis is the comparison of these two methods in respect to their usability in the field of Electrotechnology and more specifically with joints made of electrically conductive adhesives.

Key words

Taguchi, orthogonal arrays, full factorial experiments, FFE, TOA, Electrically conductive adhesives, ECA, quality

Název diplomové práce

Adhezní spoje vytvořené elektricky vodivými lepidly

Abstrakt

Tato práce se zabývá aplikací metod řízení jakosti v odvětví elektrotechniky. Zkoumá spoje vytvořené elektricky vodivými lepidly. Konkrétně vliv klimatických faktorů při stárnutí těchto spojů. Jednotlivé vlivy jsou porovnávány pomocí metody úplných faktorových experimentů (kde je zároveň vytvořen lineární matematický modelu stárnutí, který je následně ověřen na naměřených datech) a metodou Taguchiho ortogonálních oblastí. Finálním a hlavním výstupem této práce je porovnání těchto dvou metod řízení jakosti a ohodnocení jejich budoucí použitelnosti v oblasti elektrotechniky a konkrétně u lepených spojů.

Klíčová slova

Taguchi, ortogonální oblasti, úplné faktorové experimenty, FFE, TOA, elektricky vodivá lepidla, ECA, jakost, kvalita

Table of Contents

1. List of abbreviations

ACA – Anisotropic conductive adhesives

ACF – Anisotropic conductive film

ACP – Anisotropic conductive paste

ANOVA – Analysis of variance

ASQ – American Society for Quality

AXMC – Amepox Microelectronics Ltd.

CF – Correction factor

COG – Chip on glass

COF – Chip on foil

CTU – Czech Technical University in Prague

DMAIC – Define, Measure, Analyze, Improve and Control

DOE – Design of experiment

DOF – Degrees of freedom

ECA – Electrically conductive adhesive

EFQM – the European Foundation for Quality Management

FFE – Full factorial experiment

hrs - Hours

ICA – Isotropic conductive adhesive

ISO - International Organization for Standardization

L – Level

P – Parameter

PCB – Printed circuit board

PDCA – Plan-Do-Check-Act

ppm - Parts per million

RH – Relative humidity

RohS – Restriction of the use of certain hazardous substances in electrical and electronic equipment

RSS – Residual sum of squares

SOCR – Statistics Online Computational Resource

TOA – Taguchi orthogonal arrays

TQM – Total Quality Management

2. List of Figures

3. List of Tables

4. Introduction

Taguchi orthogonal arrays and full factorial experiments are two different yet very similar approaches to designing an experiment with multiple factors (and evaluating how big the influence of each factor or factors interactions (contrasts) on said experiment are). In this work, the goal will be to describe these two methods and show their strengths, benefits and uses. To do that properly, we will design and perform an actual experiment, which will then be evaluated throughout these two approaches.

For this experiment, we have chosen electrically conductive adhesives, which have been so to speak put to the forefront of Electrotechnology in Europe since the 2009 regulation on the use of lead in soldering. Because they are relatively new, their properties and inner functions are still quite unknown. With the right experiment, we hope to help achieve the future goal of a wider commercial use of electrically conductive adhesives. Conductive adhesives will have to, in some cases, replace soldering in the future.

For the experiment itself multiple sets of joints that were created using adhesive assembly of 0R0 resistors on test boards and were aged in straining climatic conditions which represented our factors. The first main climatic stress test was the application of thermal shocks onto our joints, which is an area that has been relatively unexplored so far. It represents quite a common real-world scenario (good example would be starting a car in winter where the temperatures go from low to high quite quick and can strain the car's electronic devices). The second test was the aging of the joints in a chamber with high relative humidity and high temperature.

In the beginning of this work, basics regarding electrically conductive adhesives are given. Why are they used, what are some of their benefits and how do they work. Then, the term quality and quality engineering in general which will lead us to our desired Taguchi orthogonal arrays and full factorial experiments (both are often connected to quality engineering). At the end of the theoretical part, a detailed description of each of these two methods and their usage to evaluate the experiments performed are presented.

The second part of the work is the whole practical experiment and its description, where the discussed theory is applied to a set of joints. Taguchi orthogonal arrays and full factorial experiments are evaluated when used in the area of adhesive assembly.

5. Electrically conductive adhesives

Today in the world of electrotechnics, there are three main ways to create conductive joints. Mechanical joints where the parts we wish to connect are being pushed together via a force, which provides the necessary contact resistance throughout the lifespan of the device (the force is caused by the elastic deformation of the parts). Next we have the metallurgical joints where the parts are connected using a melted material. These can be divided into solder joints where we add a material that is then melted and welded joints where the material of the parts themselves is melted. The last and newest types of joints are adhesive conductive joints, which will be the focus of the following work.

5.1. The composition and basic principle of ECAs – Percolation threshold

The electrically conductive adhesive (ECA) consists of two components called the **binder** (or matrix) and the **filler**. The basic principle of ECAs is simple – the binder acts as a “glue” mechanically connecting the two parts of the joint. The binder part needs to be hardened first, usually by heat. The filler in the form of small metal particles acts as a conductor – allowing electrons to cross the connection.

5.1.1. Binder/Matrix

The binder is usually an organic adhesive material – organic matrix. It determines the mechanical properties of the adhesive. As for the types of matrices, we can distinguish between two basic types of materials – thermoplastic materials and thermoset materials.

Thermoset materials are usually polymer resins, non-polymerized monomers or polymerized oligomers. It can be epoxide resins (up to 200 °C; polyamide or silicon) or acrylic resins (up to 100 °C). These resins have the advantage of having quite high hardness but the disadvantage of being brittle. Other thermoset materials used as binders can be polyimides or alkyds. All of these materials are liquids or low temperature-melting solid substances. The material, together with a catalyst and a hardener, will retain its form when heated above a certain temperature creating the desired join. Adding more heat could technically result in a softening of the polymer, but the material should not be able to move too much. This means that these materials cannot be reworked again (disadvantage). Most thermoset polymers are either one-component or two-component. [1] [2]

Thermoplastic polymer (resin) materials are newer and overall less used – a lot of experimenting is still being done. The material consists of longer strings that are intertwined together. Heating to temperatures above a certain threshold allows the strings to move independently – liquefying the material. Cooling below certain temperature hardens the substance. These polymers can be heated up and reworked just like solder, which is their main advantage. Unfortunately, there are other drawbacks preventing them from being more widely used. [1] [2]

5.1.2. Filler

The conductive component, called the filler, is usually an inorganic material in the form of small mostly metallic particles. These allow the electric current to travel through the adhesive. The particles can have the form of flakes, balls, fibers, powder and others of micrometric and/or even nanometric proportions. The concentration of these particles in the binder is usually quite high 70% to 80% of the weight of the whole adhesive (but depending on the special type of ECA it can be lower – overall between 10% and 80%). Debatably, the best materials used as fillers are silver and gold – silver can be seen in most ECAs since gold is far more expensive. Silver is very easily shaped into the desired form (flakes, powder, etc.) and is one of the best conductors available. Oxidation does not affect the conductivity too much. Other less expensive materials include nickel and copper. These can be problematic due to the formation of oxides that do not conduct. One way around this problem is covering non-precious materials in a precious platting – silver-platted copper for example – quality and not so expensive filler is achieved. Other materials beside silver, gold, copper and nickel are also used but only rarely. The concentration of the conductive filler particles must be sufficient to make the whole adhesive conductive, but should not be too high – that might influence the mechanical properties in a bad way. There is a certain threshold of critical volume where the material suddenly becomes conductive. Once this volume is reached the resistance drops significantly. This is where percolation threshold comes in. [1] [2]

5.1.3. Percolation threshold

Percolation threshold is a term related to the percolation theory – theory used in mathematics and statistics to describe the creation of a connecting path within a random system. This is the case in ECAs. The binder (polymer) itself is a dielectric and upon adding the filler particles, the resistance starts dropping only slightly until the concentration reaches the percolation threshold – that describes the critical volume of filler metallic particles. This establishes the first continuous metal path through the material and at that moment there is a big drop in resistance. The resistance from there on again continues to drop but slowly again. The following Figure *1* shows this in a simplified way. [3] [4]

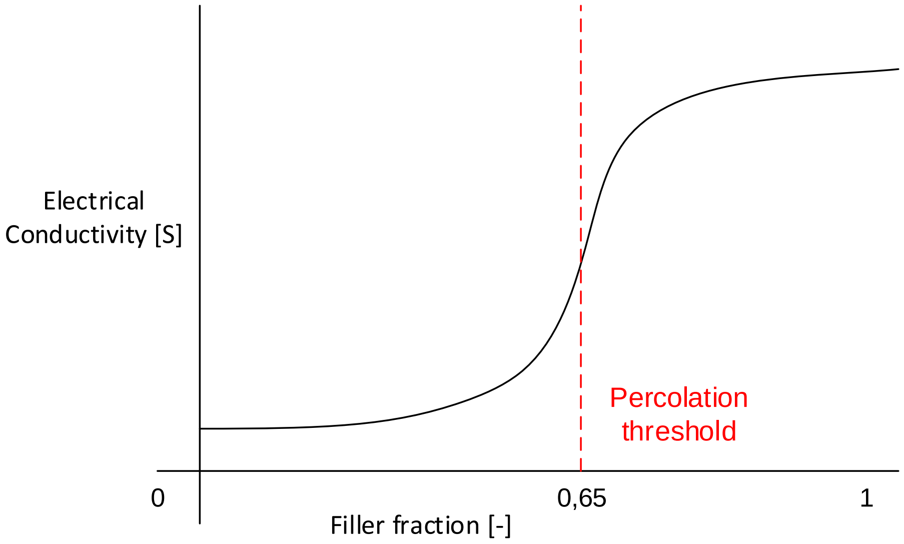

Figure 1. Electrical conductivity of an adhesive as a function of the filler fraction of weight of the whole adhesive ***[3]***

We can clearly see that as we increase the filler fraction from 0 to 0,65 the conductivity rises slowly. Upon reaching the threshold (here at 0,65 or 65% - common number for most metallic fillers) the conductivity rises significantly faster before slowing down its rise again.

5.2. Types and application of electrically conductive adhesives

Electrically conductive adhesives are used to craft products that contain printed circuit boards (PCB). They create a permanent mechanical connection between the PCB and a specific component, which also conducts current well.

Individual adhesives must meet many required parameters based on the application. The range of all the possible applications of conductive adhesives is large, therefore the variety in the types of adhesives is also wide.

Electrically conductive adhesives can be split into two main groups – isotropic conductive adhesives (ICA) and anisotropic conductive adhesives (ACA). ACAs are available as a paste (ACP) or as a film (ACF). [4]

The difference between ICA and ACA is that anisotropic adhesives conduct differently in different directions (within the material that is) – a feature that can be useful in variety of applications. Isotropic adhesives on the other hand, have the same conductivity for all directions within the material.

5.3. The theory of conductivity of ICAs

The conductivity in ECA joints is achieved via the tunneling effect.

For ACAs, the anisotropic properties are achieved by deformation of the metal conductive particles (the ones used as a filler – around 11 % concentration which is much lower than what we have in the ICAs). By deforming the particles, we alter the individual resistances of the given particles. [1]

5.3.1. Improving the conductivity of ECAs

There are many techniques to increase the conductivity of ECAs the main probably being picking the proper quality particles. Another technique worth mentioning that is used more and more of late is adding nanoparticles in between the filler particles. Nanoparticles in general have gained a lot of attention in the recent years with uses in many fields and applications, their potential within electrotechnics is immeasurable. The main idea here is that the added nanoparticles will act as “bridges“ that will help connect the filler particles which should lead to an increase in the conductivity (the density of conducting particles increases – resistance goes down). [1]

Another technique is to intensively mix the adhesive before application which creates shear forces – those free up the ions of the dissolvent that are around the conductive particles. That increases the probability of agglomeration of the particles. Mixing is usually achieved via a rotation or it can also be done using ultrasound. [1]

5.4. Using adhesives versus soldering

ECAs seem like the ideal substitute for lead solders, which were banned by the EU on the 1st of July 2006 via the RoHS directive. But ECAs are a lot different from lead solders. While joints created via soldering can be subjected to, for example environment with high relative humidity without the joint losing its functionality, ECA joints are much more sensitive. [1]

We can find many differences in quality when it comes to ECA joints and soldered joints. We can almost always say that the soldered joints will be better in all aspects. The price is still one of the main problems for the ECA joints – they are considerably more expensive. Despite all that there are many applications where the use of ECA is preferable compared to their solder counterparts – for example: technologies using COG (Chip on Glass) or COF (Chip on Foil). Both are used in attaching chips to special surfaces. [1]

6. Quality

The term quality can be quite ambiguous. Many firms in the modern world feel the need to somehow control quality (and improve it) but a lot of them do not exactly understand what quality is or means. In this chapter, We will be looking at the basic definitions of quality.

6.1. Defining quality and why is it important

There are many definitions of quality. Before we delve into them, let us first look at some of the parameters that may describe – or can be summarized by the term – quality. [5] [6] [7]

The following parameters can be considered when talking about quality.

- The overall service, marketing, engineering, and maintenance level through which the product/service meets the expectations of the customer
- Reliability
- Degree of excellence
- The resistance against improper use
- The appearance (aesthetics) of the product
- Moral point of view
- Conformance to requirements
- Ecological point of view

We could go on and list many more, but this provide us a general idea of what quality can mean. The easiest definition of quality that summarizes most of the above terms quite well is oriented towards the customer.

Quality is the measure of how well the products fulfils the requirements of the customer. [6]

Among other definitions are “Quality is achieved when the customer returns and not the product“ or “Quality is the measurement of appropriateness for use“. [6]

6.1.1. Why should companies control quality

Today the customers’ requirements on quality of products are quite high. This is even more amplified in our highly competitive environment. We can safely assume a lower limit of quality where the customer will refuse to buy a certain product. In Figure 2 we can see the probability density function (normal distribution) of a high quality process and a low quality process – both resulting in a product. The final product will have a certain quality quantified as x – we want x to ideally be equal to target – not above or below this target. Yellow areas show us the areas where the x is unacceptable (by the customer). We can clearly see that in the case of low quality process we get more products that will not be tolerable resulting in bigger financial loss for the company.

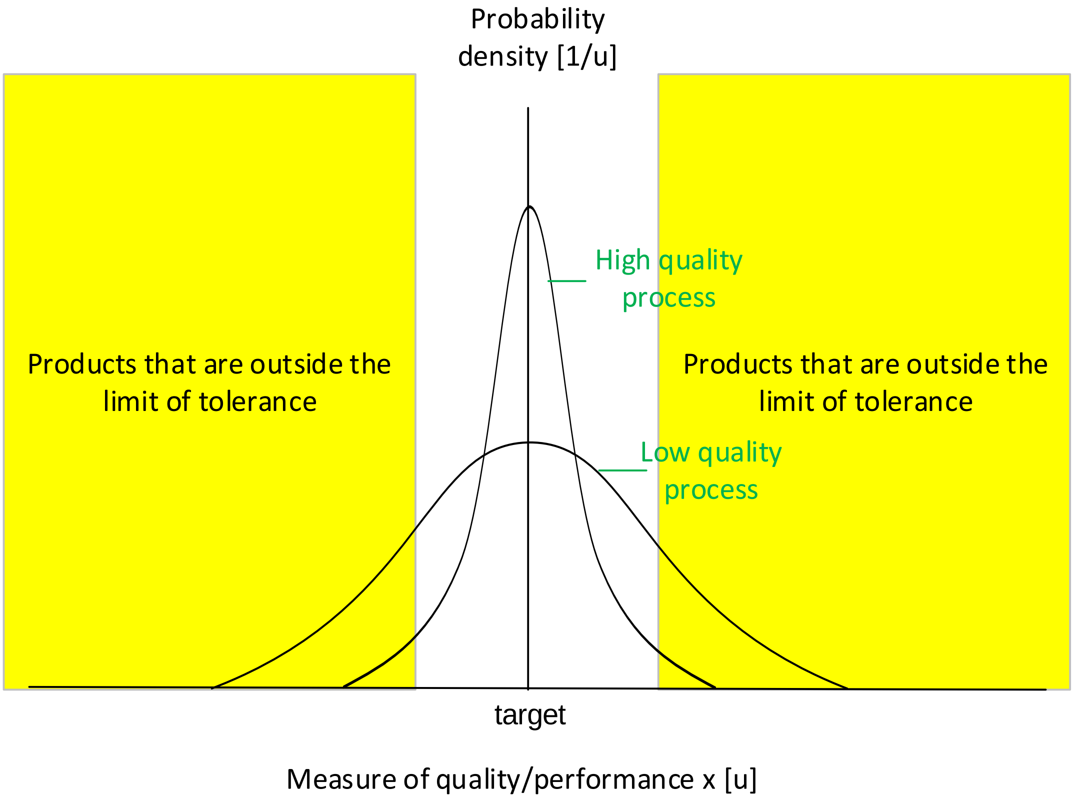

Figure 2.** Probability density distribution of two processes (low and high quality) with areas showing tolerance limits **[6]

How much should a company be focused on improving the quality of its manufacturing process can vary form one field to another. To demonstrate this, consider the manufacturing of pixels for a television – one modern television contains around 5 to 10 million pixels. Most people that buy television would notice even one dead pixel on their device, therefore the process of manufacturing these pixels must be of an extraordinary quality in order to create acceptable TVs[1].

6.2. Tools and methods to manage quality

Various tools for quality control and management have been invented. In most of these, we do not control the quality of products themselves but the quality of the processes that are used to manufacture the said products. Quality is difficult to implement into the product after it has been made, it needs to be implemented at all the stages of the production. All systems/tools for quality control have one thing in common – they are all general enough so that they can be used in various processes.

We can summarize the above paragraph by saying that all quality control systems should be generic (applicable to all processes) and process oriented (we control the process and not the product). [6]

To show where quality can be implemented, see Figure 3 below. It shows the whole life cycle of a product (often referred to as quality loop – used in obtaining the ISO 9000 certification).

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[1] I would like to thank my supervisor doc. Ing. Pavel Mach, CSc. for this example – he used it in one of his lectures

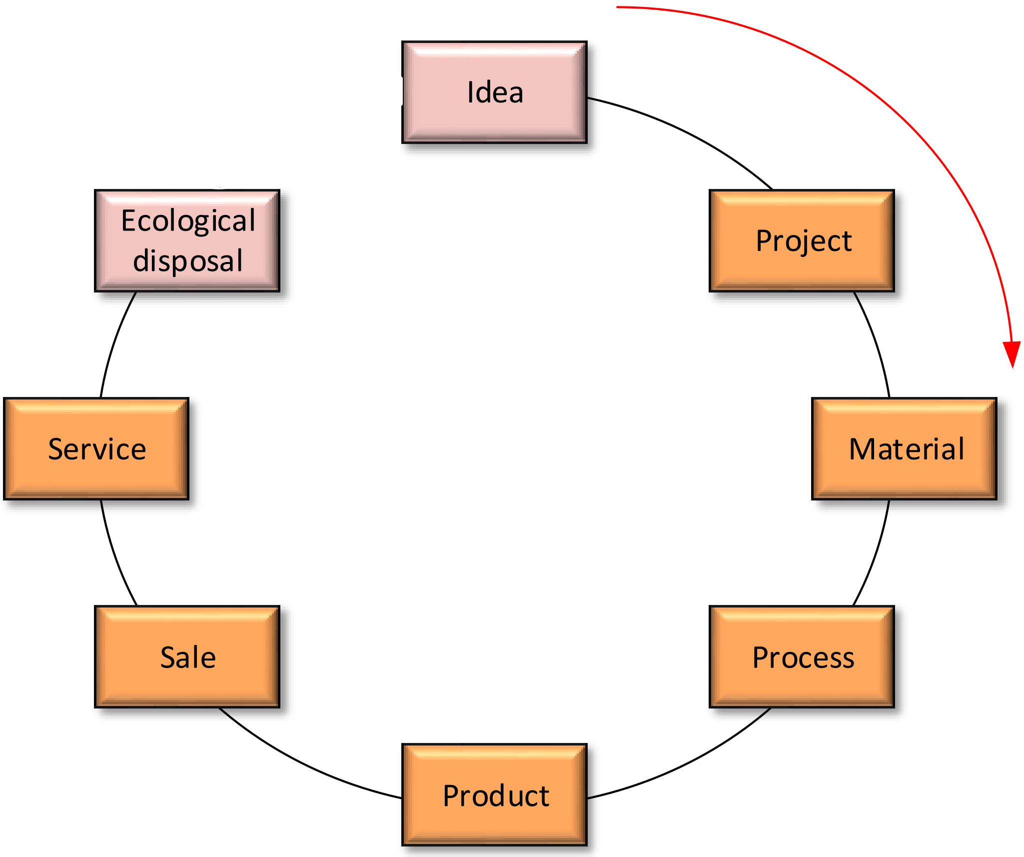

Figure 3. *Quality loop (or a life cycle) of a product* ***[6]***

Some of the used quality control methods that are used today include the standard ISO 9000, Total Quality Management (TQM) and Kaizen. In Czech Republic, most companies use the ISO 9000.

6.2.1. Standard ISO 9001:2015

The original ISO 9000 standard has introduced by the International Organization for Standardization (ISO) in the eighties. It has been reworked a few times since then. The latest is the 2015 version ISO 9001:2015 – available for purchase from the official ISO web site. [8]

In the Czech Republic, the standard has been accepted and integrated in February of 2016 – hence the confusing name CSN EN ISO 9000:2016 (same as 9001:2015 but in Czech). [9]

The basic characteristics of the ISO 9000 standards [6] are

- Organization oriented towards the customers (as stated in the definition of quality)
- The leadership of the company needs to take an active part in quality control
- The workers of the company need to have the necessary knowledge about quality control
- Focus on processes
- Systemic approach towards management
- Always try to improve everything
- Decisions based on facts
- Mutually beneficial relationship between the consumer and producer

Let us emphasize the importance of the fourth characteristic – focus on processes. What is meant here is the application of system of processes in organization together with the identification of these processes. In all of them, we can apply the methodology plan-do-check-act (PDCA) which is also known as the Deming Cycle. [10]

6.2.1.1 PDCA

This methodology can be described in the following way [10]:

P – Plan: In the planning phase we look at the goals and processes that we will use to achieve them

D – Do: The implementation of the plan and measuring of its performance

C – Check: Asses the measurements done in the previous step

A – Act: If necessary, decide the changes that are needed to improve the process

6.2.1.2 Applications of the standard

All the applications of the standard are purposely phrased in such a way that they can be used in a wide range of fields and companies regardless of the type, scale or characteristics of the products that are manufactured there. [6]

6.2.1.3 Required documents

In regards to the systemic approach towards management, the ISO technical standard puts an emphasis on keeping a thorough documentation of your quality management.

The documentation of quality management system should include the following [11]:

- The policies of quality management and its goals
- Quality manual (required when asking for the ISO 9000 certification – includes the quality loop shown in Figure 3)
- Documented steps that were taken in accordance to the ISO 9000 standard
- All general files that the company/organization needs to effectively plan and function (for their processes to work)

6.2.1.4 Application for the ISO 9000 certificate

Before the certification itself, it is sometimes ideal to conduct a so-called "pre-certification check". It will show the applicants the basic errors and faults in their quality management systems. It also gives an estimate on how much it would cost to reach the necessary criteria required for the ISO 9000 certification. This check should be done by a subject that is in no way connected to the organization that will do the official ISO 9000 certification. [6]

In the case of the official certification, it is ideal if the certifying subject is from the same country where the organization plans to export.

The main documents for the certification are the quality manual (example shown in reference [12]), directives and regulations. After the issuance of the certificate, the certifying subject has the right for regular or irregular inspections (the irregular inspections happen in case of notifications of poor quality of some products). [6]

6.2.2. Total Quality Management

Total Quality Management (TQM) is used mostly in the US. We could say that it supersedes the ISO 9000 standard, which is used in Europe. The reasons why it is currently not used in Europe come from different technological levels of European countries (TQM could be applied, but not to full extent in all countries).

TQM describes the overall approach to a long-term success of an organization through the satisfaction of the customers. The framework focuses on the effort of the entire organization to introduce and maintain an environment in which the quality of the products, services and the work culture of the organization will constantly be improved. [13]

TQM can be summarized via the following eight points [13]:

1 Focus on customer (as stated in the definition of quality)
2 Every employee contributes to the quality management
3 Centered around processes
4 Integrated system (everyone in the organization knows the common goal)
5 Strategic and systematic approach
6 Constant improvement
7 Decisions based on facts
8 Communication

TQM builds on the principles set forth in the ISO 9000 standard, the Lean manufacturing or the Six Sigma strategy.

6.2.3. Lean Manufacturing

The methodology of lean manufacturing (also lean production or just lean) has been invented in the fifties by Toyota. The basic principle is to reduce all the activities in a manufacturing process that add no value (from the perspective of a customer) to the final product. [14]

The whole method reduces costs as much as possible using various lean tools. One of the main tools is the 5S (from the Japanese words Seiri – Sort, Seiton – Set in order, Seiso – Shine, Seiketsu – Standardize, Shitsuke – Sustain). Different organizations use different lean tools. [6]

6.2.4. Six Sigma

Six Sigma is often described using the abbreviation 6σ or σ^4 (meaning the Smart Six Sigma Solution). It is a quality control system invented by Motorola. To explain it let us look at an example of a general process that is used to manufacture a product. Its probability distribution function is shown in Figure 4 below.

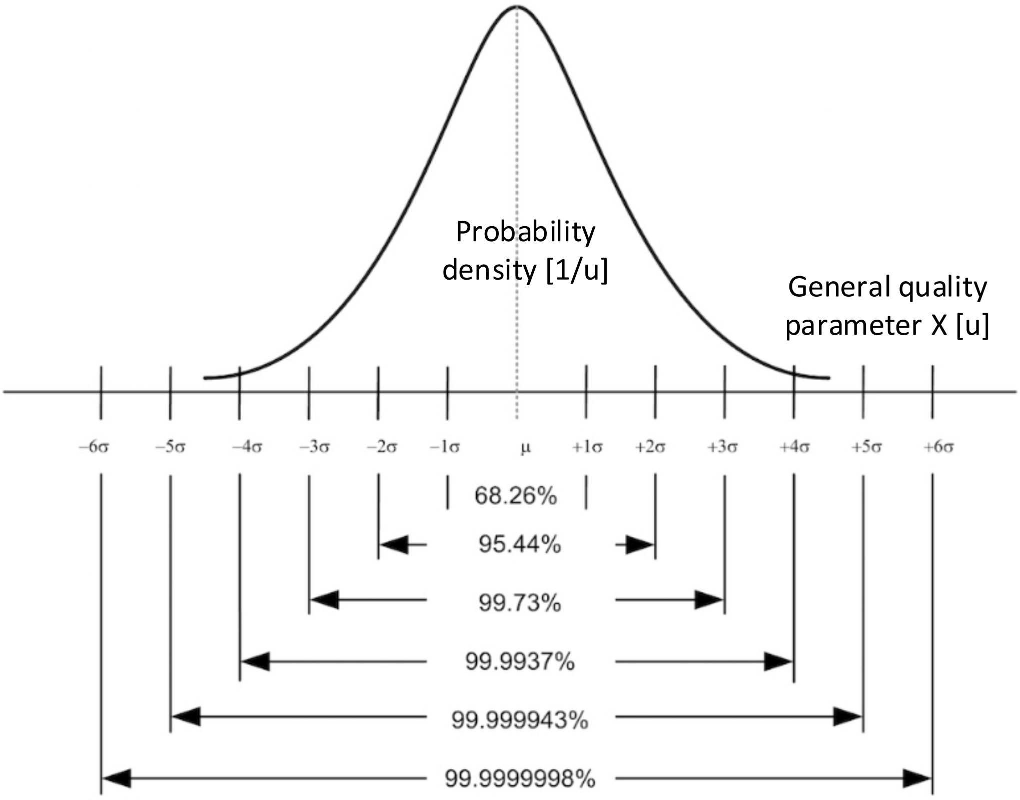

Figure 4. *Probability density function of a general process showing what percentage of the population is contained within mean +- multiples of the standard deviation σ* ***[15]***

The idea here is that in any process with Six Sigma quality the limits to acceptable products will be at least six sigma away from the mean. Considering the case in Figure 4 above, 99,9999998 % of all products manufactured will be accepted (assuming normal distribution). That gives us about 0,002 faulty products in ppm (parts per million).

The average factory produces with levels of 3,5 to 4,5 sigma. Airlines function on levels 6 to 7 sigma (under 0,002 ppm crashes). It seems appropriate to again mention our example with pixels in a television that we talked about in 6.1.1 – six sigma might not be enough in this case since that would give us one faulty/dead pixel in every TV. [6]

6.2.5. Kaizen

Kaizen is a quality management system that comes from Japan. It is based on the japanese mentality and puts an emphasis on sustainable development. It focuses on constant improvement involving all members of the organization. The word Kaizen means “change for the better“. [16]

The five basic principles of Kaizen are [6]:

- Teamwork
- Discipline of employees
- High moral
- Quality circles
- Suggestions for improvement

7. Calculating contrasts using full factorial experiments (FFE)

The two tools that we will be using in this work to study the quality of ECAs will be the full factorial experiments (FFEs) and the Taguchi orthogonal arrays. First, we will be looking at FFEs, which are relatively speaking, simpler.

Let us first talk about the term factorial experiments in general. Factorial experiments are related to design of experiment (DOE) which was coined by R. A. Fisher in 1920s. Factorial experiments are used when we want to investigate the effects of two or more factors (inputs) on an output parameter. Since this whole work and factorial experiments in general are closely tied to quality control, we can say that this output parameter will be a measurement of quality. In most applications of factorial experiments, we will be trying to investigate the effect of certain factors on the quality of the product.

Each of these factors will have two or more levels (options). The purpose of the factorial experiment is then to test various combinations of factors and their levels. When we test all possible combinations of all levels of all factors, we then call it the full factorial experiment. Simple illustration of a basic FFE is given Figure 5.

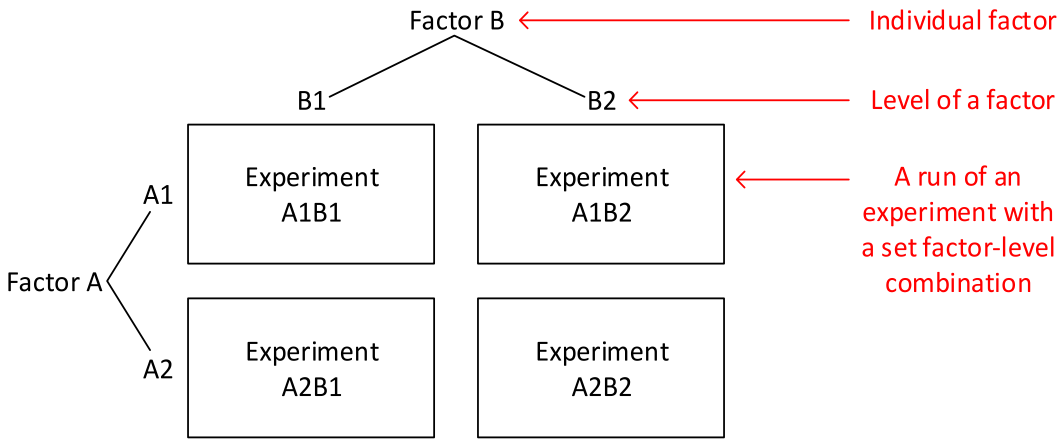

Figure 5. *An illustration of a basic FFE with two factors that each has two levels - total of four combinations (runs)*

In the case of an FFE, we can write a simple formula to determine the number of combinations (runs required to perform the FFE) we will get based on the number of factors and their levels (the number of levels needs to be the same for every factor!)

$$Q^F = c\,, \tag{1}$$

Quantity *Q* represents the number of levels and *F* is the number of factors. The quantity *c* is then the number of combinations/runs required to perform an FFE. The levels of a factor may be quantitative (we are able to measure them and they can be written as a number) or qualitative (cannot be expressed as a number – e.g. short/tall).

FFEs can be used not only to measure and calculate the effect of individual factors but also the effect of interaction between certain factors – this will be discussed in more details in chapter 7.2. Another thing FFEs can be used for is to construct a mathematical model of the process that was tested – this model can then be used to optimize the conditions and inputs of the process.

7.1. Basic types of FFEs - n^n

In order to conduct an FFE we need to choose the factors and their levels that will be considered. We have already established how to calculate the minimum amount of runs/combinations required to perform an FFE. The word minimum is important here – in most real world applications, we will be testing each factor-level combination more than once. This leads us to an expanded version of equation (1) in the following form

$$N = r * Q^F . \tag{2}$$

Like in the previous instance, *Q* represents the number of levels and *F* the number of factors; *r* is the number of repetitions that we will be doing for every factor-level combination to get more credible results. *N* is then the final number of experiments that needs to be performed in the FFE. [6]

It is quite clear that the number of experiments we will need to perform can get very high very quickly, which can lead to a resource and time demanding experiment. If we for example take five factors each with three levels and two repetitions for each run (which is still quite conservative, the number of repetitions is usually at least five) we would get $2*3^5 = 486$ – number of experiments required. To avoid this, the number of factors and levels needs to be reduced to viable values. The most common FFEs are with 2 to 5 factors each with 2 (rarely 3) levels.

When designing an FFE we first create a plan of the FFE. This comes in the form of a table, which clarifies how the experiment will look and allows for a simple recording of the results that we can then use and work with. Below are examples of some basic plans.

7.1.1. Type 2^2

Table 1. *Plan of an FFE with two factors each with two levels – 2^2* ***[6]***

A_1		**A_2**	
B_1	**B_2**	**B_1**	**B_2**
(1)	b	a	ab
$y_{1,1}$	$y_{2,1}$	$y_{3,1}$	$y_{4,1}$
$y_{1,2}$	$y_{2,2}$	$y_{3,2}$	$y_{4,2}$
.	.	.	.
.	.	.	.
$y_{1,r}$	$y_{2,r}$	$y_{3,r}$	$y_{4,r}$
T_1	T_2	T_3	T_4

In Table 1, we can see a general example of a 2^2 type plan FFE. In the orange section, each row represents one factor with alternating levels – from this, we can see that every column of the table is representing one of all the factor-level combinations that we need to perform.

The yellow row is a simplification of the orange rows – we write a small letter of the factor if it is on level two and we do not write anything if it is on level one. In case all the factors are on level one then we write (1). This gives us a simple and transparent way to describe each column. We will adopt this notation of combinations from now on. [6]

The main part of the table are the results for each individual run, marked $y_{c,r}$ (*c* denotes the column and *r* the row), which is the output parameter we are interested (quality parameter) and that we are trying to optimize (max/min usually). There is *r* rows representing the number of repetitions we are doing for each combination.

In the last green rows we have the total sums of the results for a given factor-level combination

$$T_1 = y_{1,1} + y_{1,2} + y_{1,3} + y_{1,4} + ... + y_{1,r} \ . \tag{3}$$

We will be using these values later in our analysis of the results.

Below are some more examples of commonly used plans/tables of FFEs.

7.1.2. Type 2^3, 2^4

Table 2. *Plan of an FFE with three factors each with two levels – 2^3* ***[6]***

A_1				**A_2**			
B_1		**B_2**		**B_1**		**B_2**	
C_1	**C_2**	**C_1**	**C_2**	**C_1**	**C_2**	**C_1**	**C_2**
(1)	c	b	bc	a	ac	ab	abc
$y_{1,1}$	$y_{2,1}$	$y_{3,1}$	$y_{4,1}$	$y_{5,1}$	$y_{6,1}$	$y_{7,1}$	$y_{8,1}$
$y_{1,2}$	$y_{2,2}$	$y_{3,2}$	$y_{4,2}$	$y_{5,2}$	$y_{6,2}$	$y_{7,2}$	$y_{8,2}$
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
$y_{1,r}$	$y_{2,r}$	$y_{3,r}$	$y_{4,r}$	$y_{5,r}$	$y_{6,r}$	$y_{7,r}$	$y_{8,r}$
T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8

Table 3. *Plan of an FFE with four factors each with two levels – 2^4* ***[6]***

A_1								A_2							
B_1				B_2				B_1				B_2			
C_1		C_2		C_1		C_2		C_1		C_2		C_1		C_2	
D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
(1)	d	c	cd	b	bd	bc	bcd	a	ad	ac	acd	ab	abd	abc	abcd
$y_{1,1}$	$y_{2,1}$	$y_{3,1}$	$y_{4,1}$	.	.	.	.	.	.	.	.	.	.	.	$y_{16,1}$
$y_{1,2}$	$y_{2,2}$	$y_{3,2}$	$y_{4,2}$	.	.	.	.	.	.	.	.	.	.	.	$y_{16,2}$
.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
$y_{1,r}$	$y_{2,r}$	$y_{3,r}$	$y_{4,r}$	.	.	.	.	.	.	.	.	.	.	.	$y_{16,r}$
T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}

7.2. Calculating the influence of factors on a quality parameter using FFEs

We have so far not talked too much about the benefits or goals of FFEs – what can we get when using them. What are the benefits? When using the statistical approach of FFEs we can eventually get a mathematical model of the process (the process being the one that transformed our input parameters, i.e. the factors, into the output quality parameter). The method for obtaining the mathematical model is described in many textbooks and publications. Before we take a look at it, let us first examine whether we can somehow quantify the influence of individual factors on the process. This information could be quite useful in real world applications – ability to determine which factors influence the quality of a product and which don´t would lead to a significant quality improvement. The other reason is that the purpose of this work is to compare FFEs and Taguchi orthogonal arrays (those will be described in the next chapter – Calculating contrasts using Taguchi orthogonal arrays) in their application on ECAs and in case of Taguchi, his approach does not lead to a mathematical model of the process.

We will evaluate not only the influence of individual factors (**from now referred to as contrasts**) but also the influence of interactions between factors. We might get a scenario in which the effect of one variable changes the impact of different levels of a different variable (factor). To simplify it, we can look at a basic example – process of salting a cup of water. If we consider two factors – amount of salt added and the amount of stirring done, there will be a clear interaction between these two because the water will not be salted unless we get a combination of both of them.

Another reason for considering interactions between factors is shown on the next example in Figure 6.

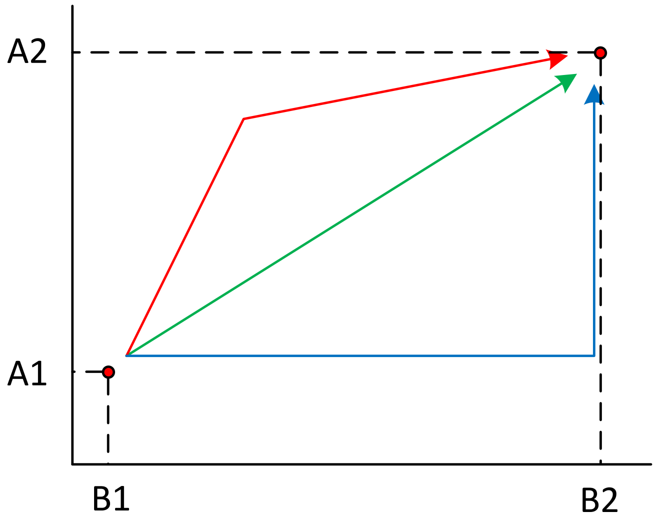

Figure 6. *Illustration of different ways to move from A1B1 to A2B2 in a process* ***[6]***

In a basic process when moving from state *(1)* to state *ab* (meaning from the setting where factors A and B are both on level one to the setting with A and B both on level two) there are multiple ways to do it. In Figure 6 there are three ways illustrated – green, red and blue. This can influence the final quality parameter *y* because its history will be different and therefore its properties might be different as well. [6]

7.2.1. Contrasts of factors and interactions

In order to calculate the contrasts of individual factors and interactions in percentages, we need to go through a few steps of statistical mathematics. Let us start by calculating an estimate of influence for each factor and interaction (in a number of sources also called contrasts but here only called estimates [17]). There are multiple ways to do it; we are going to look at one of them. Let us assume a general process with two factors A and B each with two levels 1 and 2 just like in Table 1. For the estimations of influence, we can write the following

$$Z_A = T_a + T_{ab} - T_{(1)} - T_b = T_3 + T_4 - T_1 - T_2\,, \tag{4}$$

$$Z_B = T_{ab} + T_b - T_{(1)} - T_a = T_4 + T_2 - T_1 - T_3\,, \tag{5}$$

$$Z_{AB} = T_{ab} + T_{(1)} - T_a - T_b = T_4 + T_1 - T_3 - T_2\,. \tag{6}$$

In equations (4), (5) and (6), the Z represents the estimate of an influence of a factor/interaction. The T represents the sum of all the results from a given column as defined in chapter 7.1.1. Equations (4) and (5) are quite intuitive – if we look at Table 1, then for Z_A we take the sum of column where A is in its higher level limit (in this case level two = A2) with a plus sign. We add these together with the sum of columns where A is in its lower level limit (in this case level one = A1) which we will take with a minus sign. Similarly for factor B. [6]

For the estimation of the interaction $Z_{AB,}$ we again add the sums of the columns together. To determine the sign of each column we have add up the signs from the same column when calculating the estimation of individual A = Z_A and of individual B = Z_B. Column *b* was taken with a plus sign for Z_B and with a minus sign Z_A – together they give a minus sign so we will be adding column *b* with a minus sign to calculate Z_{AB}. We do the same thing for other columns and we arrive to equation (6). [17]

The next important value that we need to consider is the sum of squares of deviations from the mean – it is the individual components that it is made of that interest us (we will be using sum of squares more in chapter 8). We first need to calculate the mean

$$\overline{M} = \frac{\sum_{i=1}^{c}\sum_{j=1}^{r} y_{i,j}}{c * r}. \tag{7}$$

Letters *c* and *r* represent columns and repetitions (rows) of the FFE plan (examples of FFE plans in Table 1, Table 2, Table 3) as previously defined in equations (1) and (2). [6]

Sum of squares of deviations is then given by (still assuming the test case of two factors each with two levels) [6] [17]

$$S = \sum_{i=1}^{c}\sum_{j=1}^{r} (y_{i,j} - \overline{M})^2, \tag{8}$$

$$S = S_A + S_B + S_{AB} + RSS. \tag{9}$$

The values $y_{i,j}$ are measured outputs and a common method to analyzing them is the so called ANOVA (analysis of variance) approach. Without going into too much detail, the key idea is to make a mathematical model of the dependence of $y_{i,j}$ on the input (most often this is done using the linear regression model, i.e., proposing a linear model) and then interpret the sum of squares of deviations (often denoted TSS) as a sum of squares of the deviations of $y_{i,j}$ from the model and the error of the linear model. The sum of squares of deviations of $y_{i,j}$ from the model is often called the ESS (explainable sum of squares), here denoted as $S_A + S_B + S_{AB}$. The rest is, in this notation, the error of the model and is often called the RSS (residual sum of squares). For further references, see [17], [18], [19], [20].

RSS can be calculated using the following equation [6]

$$RSS = \sum_{i=1}^{c}\sum_{j=1}^{r} (y_{i,j} - \frac{\sum_{j=1}^{r} y_{i,j}}{r})^2. \tag{10}$$

Residual sum of squares tells us how tightly the data for a set factor/level combination fits around its mean and it describes the repeatability of the process – as in how well are we able to repeat the experiment and obtain the same data again. We can clearly see this upon closely inspecting equation (10). Indeed, we are computing the deviation of each result in a given column to the mean of said column – these numbers are then all summed together. If the data in each column were all the same then RSS according to equation (10) would be equal to zero, which would mean a perfect repeatability of the process (we can theoretically repeat it ad infinitum and always get the same results).

For the individual sums of squares of each factor and interaction, we can write the following equations that use the previously defined estimates in equations (4), (5), (6) and the number of repetitions and columns [6]

$$S_A = \frac{Z_A^{\ 2}}{c * r}, \tag{11}$$

$$S_B = \frac{Z_B^{\ 2}}{c * r}, \tag{12}$$

$$S_{AB} = \frac{Z_{AB}^{\ 2}}{c * r}. \tag{13}$$

Recalling the original purpose of computing the percentages, the ANOVA framework usually uses the so-called F-statistics. F-statistic is the ratio of variation between the means of each column and the variation among results in each column. [21]

For the purpose of our calculation, we can write the following

$$F_A = \frac{S_A}{(\frac{RSS}{DOF})}, \tag{14}$$

$$F_B = \frac{S_B}{(\frac{RSS}{DOF})}, \tag{15}$$

$$F_{AB} = \frac{S_{AB}}{(\frac{RSS}{DOF})}. \tag{16}$$

The quantity DOF (degrees of freedom) is a common statistical term used to describe the number of variables in a system that can vary. In other words, it is the number of observations minus the number of defined unchangeable relations between these observations (restrictions). [22]

We will come back to DOF in chapter 8. For now in our case, we can say that DOF is dependent on the number of repetitions and columns in our FFE plan [6]

$$DOF = c * (r - 1). \tag{17}$$

From the F-statistics, we can now get the contrasts of factors and interactions by comparing the individual F-statistics to the sum of them, i.e.

$$P_{\inf A} = \frac{F_A}{F_A + F_B + F_{AB}}, \tag{18}$$

$$P_{\inf B} = \frac{F_B}{F_A + F_B + F_{AB}}, \tag{19}$$

$$P_{\inf AB} = \frac{F_{AB}}{F_A + F_B + F_{AB}}. \tag{20}$$

From equations (18), (19) and (20) upon multiplying the results by a 100, we get the final contrasts of each factor and interaction in percent for our test case. These can then be plotted, compared, and addressed accordingly to improve the overall quality of a product (process).

7.3. Using the FFEs to construct a mathematical model of a process

From the previously calculated contrasts we can now determine which factor (interaction) is "important enough"(from now on called statistically important) to be considered in our mathematical model. For this purpose, we take the F-statistic of each factor (interaction) and compare it to the critical value of the following F-distribution.

$$F_{\alpha}\,(1\,,\ DOF). \tag{21}$$

Formula (21) represents an F-distribution with the numerator degrees of freedom equal to one and the denominator degrees of freedom equal to *DOF* (which we already defined for our case in equation (17). Greek letter α represents the significance level or in other words the probability of making a type 1 error (that is the error that occurs if we a reject a correct hypothesis) – commonly used term in most statistical literature. [6] [23]

Therefore, the significance level α has to be determined by the person conducting the FFEs and is usually between 0,01 to 0,1 – the critical value of our distribution can then be taken from any available statistical table. [6] [23]

The critical value is then compared to the calculated F-statistic for each factor/interaction (calculated in equations (14), (15) and (16)). If the F-statistic is larger than the critical value of F then that factor/interaction must be considered in our model.

To show the construction of the model, we will be considering our case of two factors and two levels that we used in chapter 7.2.

First, we need to transform each factor into a dimensionless unit as follows (example shown for a general factor A with two levels) [6]

$$X_1 = \frac{2}{A_2 - A_1} * \left(A - \frac{A_1 + A_2}{2} \right). \tag{22}$$

This way we get the factor A transformed into X_1. A_1 and A_2 represent the lowest and highest level of factor A respectively. Factor *B* will be transformed into X_2.

The final model of the process will be linear and can be written in the following general form

$$Y = k_0 + k_1 * X_1 + k_2 * X_2. \tag{23}$$

Quantity *Y* represents the output of the process that interests us (quality parameter) and k_0, k_1 and k_2 are the unknown coefficients of our model. To calculate these, we can use the method of linear regression. We start by writing the formula for the total sum of squares of deviations for our model [6]

$$S = \sum_{i=1}^{c} \left(\overline{y_i} - k_0 - k_1 * x_{1,i} - k_2 * x_{2,i} \right)^2 . \tag{24}$$

Again, *c* is the number of columns in our FFE (in our case 4) and *i* then represents the number of individual column. Variable $x_{1,i}$ is the value of the transformed factor A in i-th column. The y_i with an overbar represents the arithmetic average in i-th column of the FFE, which is just the sum of all the values in column *i* divided by the number of repetitions (or rows) *r*. [6]

Considering the total sum of squares of deviations form equation (24) and differentiating it with respect to each coefficient k_0, k_1, k_2, we can formulate conditions to obtain the stationary points (i.e. coefficients.) In particular, writing

$$0 = \frac{\partial S}{\partial k_0} , \tag{25}$$

$$0 = \frac{\partial S}{\partial k_1} , \tag{26}$$

$$0 = \frac{\partial S}{\partial k_2} , \tag{27}$$

we will get 3 (one more than we have factors – in our case 2 factors + 1) equations. Computing the partial derivatives, these can be reformulated as [6]

$$\sum_{i=1}^{c} \overline{y_i} = k_0 * c + k_1 * \sum_{i=1}^{c} x_{1,i} + k_2 * \sum_{i=1}^{c} x_{2,i} , \tag{28}$$

$$\sum_{i=1}^{c} (x_{1,i} * \overline{y_i}) = k_0 * \sum_{i=1}^{c} x_{1,i} + k_1 * \sum_{i=1}^{c} (x_{1,i})^2 + k_2 * \sum_{i=1}^{c} (x_{1,i} * x_{2,i}) , \tag{29}$$

$$\sum_{i=1}^{c} (x_{2,i} * \overline{y_i}) = k_0 * \sum_{i=1}^{c} x_{2,i} + k_1 * \sum_{i=1}^{c} (x_{2,i} * x_{1,i}) + k_2 * \sum_{i=1}^{c} (x_{2,i})^2 . \tag{30}$$

Upon solving these equations, we can get the final values of coefficients k_0, k_1, and k_2 as [6]

$$k_0 = \frac{1}{c} \sum_{i=1}^{c} \overline{y_i} , \tag{31}$$

$$k_1 = \frac{1}{c} \sum_{i=1}^{c} (x_{1,i} * \overline{y_i}) , \tag{32}$$

$$k_2 = \frac{1}{c}\sum_{i=1}^{c}(x_{2,i} * \overline{y_i}). \tag{33}$$

For k_1 and k_2 we can also use the estimations of the influences of factor A and B that we calculated in section 7.2.1 [6]

$$k_1 = \frac{Z_A}{c * r}, \tag{34}$$

$$k_2 = \frac{Z_B}{c * r}. \tag{35}$$

Now we have the finalized linear mathematical model of our process that we wanted. To test the model we can use a similar approach as in the beginning of this chapter with the critical value of the F-distribution. Easier way, which we are going to use in our practical part, is to actually perform the process (in our case the experiment), get the output data, and compare those to the data obtained from the model. More in our practical part.

8. Calculating contrasts using Taguchi orthogonal arrays

The second approach of obtaining the influences of factors on the quality parameter will be the Taguchi approach. Let us start by talking about Taguchi himself.

8.1. Taguchi’s take on quality

When talking about Dr. Genechi Taguchi, we first need to look at the term Design of Experiments (DOE). Sir R. A. Fisher first introduced DOE in the 20s; it is a statistical technique that enables the user to lay out all of the possible combinations of factors included in an experimental study. This is achieved by creating a matrix, which allows each factor an equal number of test conditions. This, if given too many factors, can lead to having too many experiments to perform. Some ways to reduce the number of experiments and only perform a fraction of them were devised. Fisher was the one who created the first method to analyze the effect of multiple factors at the same time. First use of these techniques was demonstrated on an agricultural experiment. After, these methods remained in the academic environment, use in industries was rare – this problem got even bigger since these methods got even more complicated and convoluted. [24]

Dr. Genechi Taguchi was a Japanese scientist who spent most of his life figuring out ways to improve quality of generally manufactured products. Taguchi was one of the first to show that DOE and its methodology was not just for science applications, but also that it is applicable in the general population in manufacturing of goods as well. He standardized and created a number of special orthogonal arrays, each of which can be used in many experimental applications. [24]

Taguchi was a strong advocate for implementation of quality into the products before they are manufactured. Many companies in the past and even today only inspect quality of products after they have been manufactured – it is often too late to correct anything at that point. Quality philosophy of Dr. Genechi Taguchi was to do it up-front – quality needs to be considered in every phase of the engineering activities. From the planning to the manufacturing. It is important to note that we should not abandon checking produced goods after they are manufactured; it just means that we will check and control quality in activities leading to the production of said goods as well. [24]

Below in Figure 7 are some examples of the quality control tools that are available for each step of the engineering process.

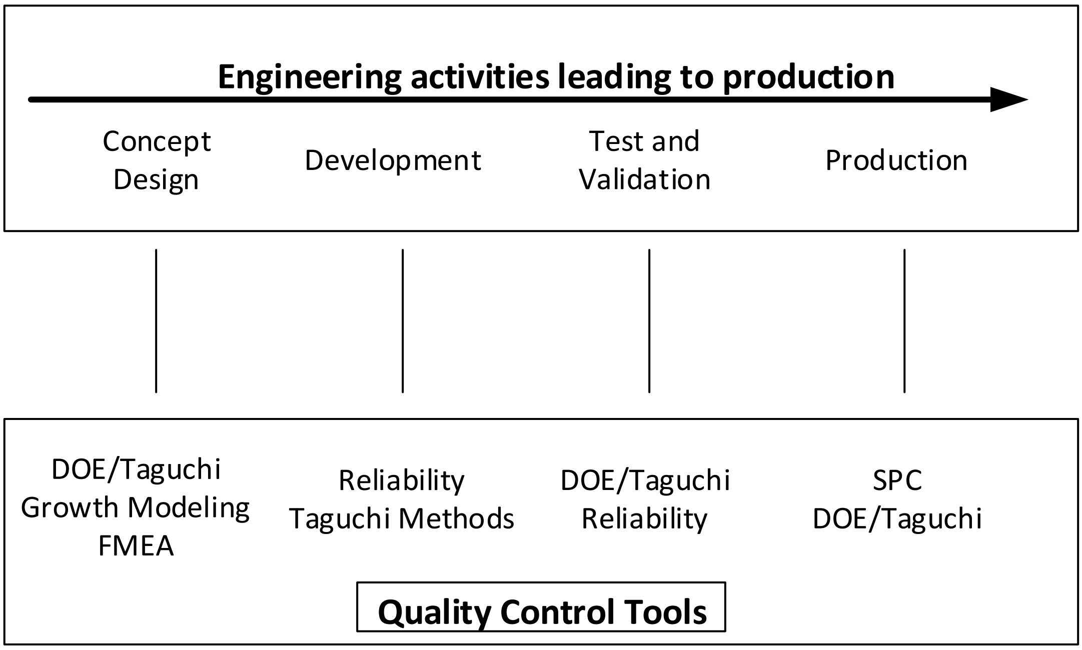

Figure 7. *Quality tools that can be applied to the engineering steps that lead to production **[24]***

It has been proven that it is much easier to implement quality into products when the quality improving is done before the production of the said product. Now, what exactly is quality – we already brushed upon that subject in chapter 0 – in technical terms, it can be many things: performance, longevity, durability, size/shape, etc. [24]

According to Taguchi, the best way to measure quality is to ask how consistent the performance is (performance is probably the most important part of the overall quality of a product). Improving quality means reducing the variation around our desired target by perfecting our consistency of performance. How to achieve this consistency? In a general performance, the mean might be far away from the target and the overall distribution is quite shallow – we want to avoid that. We want to reduce the distance of the mean to the target and we want to reduce the standard deviation to a minimum (make the distribution more narrow so to speak). Visually shown in Figure 8 below. [24]

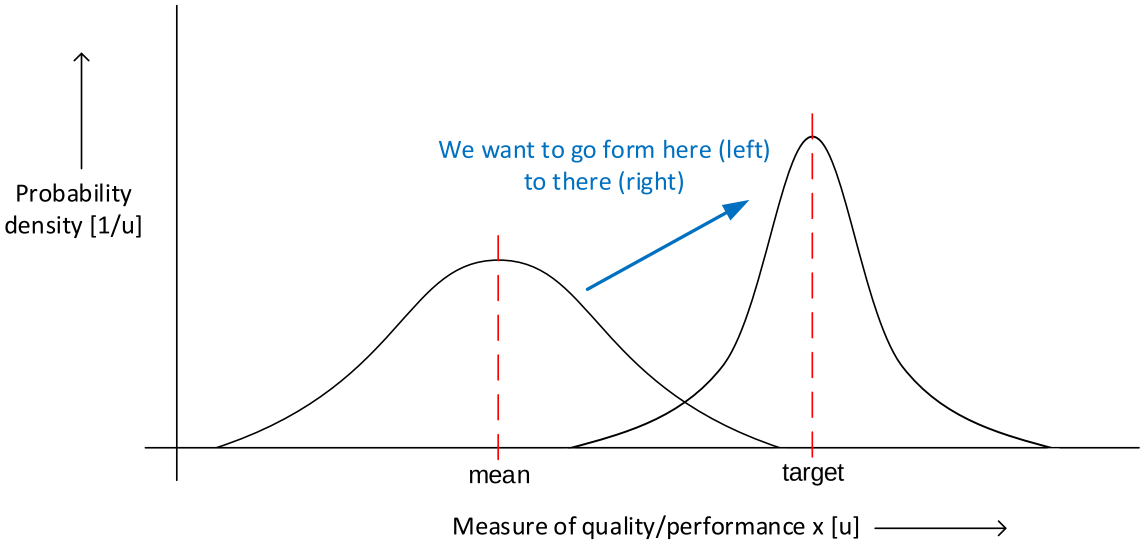

Figure 8. *How to improve quality by reducing variation around the target and by reducing the distance of the mean to the target **[24]***

DOEs can help us achieve exactly these goals – to reduce the standard deviation and to bring the mean closer to the target.

Quality is closely tied to costs. It is true that if we improve quality it usually adds expenses to the overall process (material/time/manpower needed to improve quality) but rather than calculating that, Taguchi suggests to calculate the financial loss suffered when quality is not as good as it can be. To do that we would take the number of rejected items and multiply it by the cost of production of one. However, as Taguchi rightly pointed out, this does not take into account the problems when low-quality products leave the production. These can cause multiple problems (and costs) throughout their lifespan in the hands of the customer – service costs, waste work force, discouragement of future customers, and other things. For this Taguchi suggested a mathematical formula called the loss function, which estimates the financial loss due to poor quality (this function is out of the scope of this work – for more details about it, see referred literature). [24]

8.2. Taguchi arrays

Taguchi quality approach greatly utilizes DOEs – via the so-called Taguchi arrays. Therefore, the second method that we will be using on top of the full factorial experiments are Taguchi Orthogonal Arrays (TOA). To be able to explain and work with TOAs, we first need to talk about Taguchi Arrays in regards to factorial experiments and about Taguchi himself and his ideas behind these arrays.

8.2.1. Taguchi's designed experiments – full and fractional factorial experiments

One of the "simplest" solutions when designing an experiment is the full factorial experiment (FFE) which was discussed in Chapter 7. The word simplest here is in quotes since it means "most easily understood" but definitely doesn't mean "the most simple experiment to perform". In a full factorial experiment, we perform every possible combination of the factors and their levels at least once. For example with 4 parameters (P) and 3 levels (L) for each parameter, we would have to perform $3^4 = 81$ runs for a full factorial experiment. [25]

The experiment can be simplified into a fractional factorial experiment where we in a smart way "skip" some of the runs. If there is a reason to assume that some of the interactions are not that decisive when it comes to the output parameter then we can leave some interactions out and run only a fraction of the FFE. If we take an example in the form of 5 parameters with 2 levels each (P = 5; L = 2) then we can describe the fractional factorial experiment as follows

$$2^5 = 32, \tag{36}$$

which is the number of runs required for an FFE.

$$2^{(h-n)}, \tag{37}$$

is the number of runs for a fractional factorial experiment where *h* represents the number of factors and for *n* we have the following term

$$\frac{1}{2^n}. \tag{38}$$

The term (38) represents the fraction of the full factorial where n is a natural number.

Let us now say we want 1/4 of our specified FFE. We are going to get

$$\frac{1}{4} = \frac{1}{2^2} = \frac{1}{2^p}\,. \tag{39}$$

From here, we can see that

$$p = 2\,. \tag{40}$$

Number of parameters remains unchanged from the beginning

$$h = 5\,. \tag{41}$$

From here, we can count the final number of experiments in our case where we want 1/4 of the FFE

$$2^{(5-2)} = 8\,. \tag{42}$$

The final number of runs will be reduced from 32 to only 8. Of course it is up to the experimenter to decide which runs (combinations of levels/parameters) to skip. [25]

8.2.2. Taguchi design arrays

To aid experimental design Taguchi has developed tables, which are called design arrays. These are used for full and fraction factorial experiments. These designs are very similar to classic fractional factorial designs, but Taguchi has made some improvements.

We will define an optimal Taguchi design array for a fractional factorial experiment as one that follows these two rules [26]:

I. **Every level for every parameter must be represented the same number of times.**
II. **Runs where two or more parameters stay on the same level are minimized.**

The first rule is quite self-explanatory. In order to better explain the second rule let us take an example of 4 parameters *A, B, C, D* each with 4 levels 1, 2, 3, 4. Now let us say we have a run with parameter *a* on level 1 and parameter *b* on level 2 – by following the second rule we try to minimize other runs that also have *a* on 1 and *b* on 2. In our example, if we were to perform a full factorial experiment we would need to do 256 runs. With Taguchi array, we can significantly reduce the number of runs required. If we design the experiment well we can only require 16 runs instead of 256. Let us say we want to test each level of each parameter four times – therefore 4*4 = 16 runs.

Table 4. *Design of experiment arrays for 4 parameters each with 4 levels, where each level is tested 4 times* ***[26]***

Run	**Parameters = 4, Levels = 4**			
	A	**B**	**C**	**D**
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	1	4	4	4
5.	2	1	2	3
6.	2	2	1	4
7.	2	3	4	1
8.	2	4	3	2
9.	3	1	3	4
10.	3	2	4	3
11.	3	3	1	2
12.	3	4	2	1
13.	4	1	4	2
14.	4	2	3	1
15.	4	3	2	4
16.	4	4	1	3

Run	**Parameters = 4, Levels = 4**			
	A	**B**	**C**	**D**
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	1	4	4	4
5.	2	1	2	3
6.	2	2	1	4
7.	2	3	4	1
8.	2	4	3	2
9.	3	1	3	1
10.	3	2	4	3
11.	3	3	1	2
12.	3	4	2	4
13.	4	1	4	2
14.	4	2	3	1
15.	4	3	2	4
16.	4	4	1	3

In Table 4, we see two design arrays with four parameters - each with 4 levels, where we test each level 4 times. The two tables above are both fractional factorial experiments where instead of 256 runs we smartly designed the experiment to only require 16 runs.

Now are these arrays Taguchi design arrays? If we look at the two rules that have to be fulfilled, we can see that only the array on the left fulfils both of them. The first rule is met by both arrays – each level of every parameter is represented the same number of times (4 times to be specific). The second rule is only met by the array on the left – if we look at the levels of any pair of parameters in any row – that particular combination or its segment of length 2 or more is never repeated again. For example, in the row 14, if we take parameters *C* and *D* and their levels which are 3 and 1 we won't be able find any other row that also has *C* and *D* on levels 3 and 1. This is however not the case for the right array – highlighted are two cases of a pair of rows with repeated segment of the combination. We can therefore conclude that the array on the left is a Taguchi design array whereas the array on the right is not. [26] [27] [28]

8.2.3. Taguchi orthogonal arrays – definition and properties

Now that we defined Taguchi arrays we can finally move to Taguchi orthogonal arrays (sometimes called full orthogonal arrays). In order for a Taguchi array to be an orthogonal one, it needs to follow one rule (in addition to the two rules already mentioned for Taguchi arrays). [29]

> **At every level of a given parameter, all levels of every other parameter are tested at least once.**

To demonstrate this rule take another example with 3 parameters and 3 levels. Let us consider two cases: one where we test each level of each parameter 3 times (left) and one where we test each level of each parameter 2 times (right). We are going to use Taguchi arrays for both of these cases and we will see whether any of them fulfils the condition to be an orthogonal Taguchi array. In the first case, we are going to need 3*3 = 9 runs and in the second case, we are going to need 3*2 = 6 runs. [26] [29] [28]

Table 5.** Design of experiment arrays for 3 parameters each with 3 levels - on the left each level tested 3 times - on the right each level tested 2 times **[26]

Run	**Parameters = 3, Levels = 3**		
	A	**B**	**C**
1.	1	1	1
2.	1	2	2
3.	1	3	3
4.	2	1	2
5.	2	2	3
6.	2	3	1
7.	3	1	3
8.	3	2	1
9.	3	3	2

Run	**Parameters = 3, Levels = 3**		
	A	**B**	**C**
1.	1	1	1
2.	1	2	2
3.	2	3	3
4.	2	1	2
5.	3	2	3
6.	3	3	1

We can see that both of these arrays meet the criteria of Taguchi arrays. As for the criteria for Taguchi orthogonal arrays, only the left case meets the rule. If we take any level of any given parameter – for example parameter *A* on level 1 – we see that in those rows parameters *B* and *C* are tested at levels 1, 2 and 3 (once on each level). Therefore, the rule is met – array on the left is an orthogonal Taguchi array. The right array on the other hand does not meet the rule – for parameter *A* on level 1 – *B* and *C* are only tested on levels 1 and 2 (not on 3) and as the rule states: all levels of every other parameter are tested at least once – the right array is not orthogonal Taguchi array, but it is a Taguchi array.

8.2.4. Taguchi Orthogonal Arrays – examples

There is one obvious problem when it comes to Taguchi orthogonal arrays – their construction/creation is not easy. If every time we wanted to perform a simplified experiment (meaning fractional factorial experiment), so that we would not have to perform the full number of runs while still getting the most amount of information possible, then it would be quite difficult to figure out how that given Taguchi orthogonal array might look. Luckily, Taguchi himself has done this – he already designed a number of perfected orthogonal array templates.

These were designed for the most common industrial and academical experiments. Some of them might have special restrictions or built-in multiple levels and they can be found in many books and other literature – for reference see [24] [30] [20] [31].

To easily describe these arrays we use the notation of L_p or L-p[2] where *p* indicates the number of rows in the array. For example, L-4 is used to study a case with two or three factors each with two levels. The notation can also be followed by a number in brackets describing the exact number of factors and their levels, e.g. L-4(2^3) which would describe an array of four rows used for three factors with two levels each. [24]

---

[2] L stands for Latin squares

Table 6. *L-4(2^3) Taguchi orthogonal array, the bold numbers represent the individual factors, the numbers inside the table represent their levels* ***[24]***

	Column		
Run	**1**	**2**	**3**
1.	1	1	1
2.	1	2	2
3.	2	1	2
4.	2	2	1

In an experiment, each factor is assigned to one of the columns seen in Table 6 (TOA usually display parameters as numbers and not as capital letters). Each row then represents one run of the experiment where the numbers in the row represent the way the factors should be set for each experiment. The number in the bracket in the notation of the array helps us to see how much the experiment has been simplified compared to a FFE – in this case, we have 4 runs instead of the full $2^3 = 8$ runs. Other commonly used Taguchi orthogonal arrays:

Table 7. *Taguchi orthogonal arrays L-4(2^7) top, L-8(2^4 4^1) bottom, L-9(3^4) next page* ***[27]***

L-8 (2^7)	**Column**						
Run	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1.	1	1	1	1	1	1	1
2.	1	1	1	2	2	2	2
3.	1	2	2	1	1	2	2
4.	1	2	2	2	2	1	1
5.	2	1	2	1	2	1	2
6.	2	1	2	2	1	2	1
7.	2	2	1	1	2	2	1
8.	2	2	1	2	1	1	2

L-8 (2^4 4^1)	**Column**				
Run	**1**	**2**	**3**	**4**	**5**
1.	1	1	1	1	1
2.	2	2	2	2	1
3.	1	1	2	2	2
4.	2	2	1	1	2
5.	1	2	1	2	3
6.	2	1	2	1	3
7.	1	2	2	1	4
8.	2	1	1	2	4

L-9 (3^4)	Column			
Run	**1**	**2**	**3**	**4**
1.	1	1	1	1
2.	1	2	2	2
3.	1	3	3	3
4.	2	1	2	3
5.	2	2	3	1
6.	2	3	1	2
7.	3	1	3	2
8.	3	2	1	3
9.	3	3	2	1

Let us take a closer look at the middle array in Table 7 – its notation shows two numbers in the bracket – 2^4 and 4^1. This is an example of a multiple-level orthogonal array, generally called a mixed level array. It can be used for a four factors each with two levels – in this case, we would be using the first four columns while leaving out the fifth. The other option is to use it for one factor that has four levels – we would be using only the last column while leaving out the first four.

Another thing that might seem obvious but definitely should be mentioned regarding orthogonal arrays – each row in the array represents an experiment with the factors set at certain levels. This experiment should be run at least once but can be run more times for increased accuracy of the information. So in the end if we have L-8 array shown in Table 7 on the top it does not necessarily mean that we will be running only 8 experiments. The final value of the watched parameter for each run is then averaged from all the runs with that particular setting.

8.3. Calculating the influence of factors on a quality parameter using Taguchi orthogonal arrays

Up until now, we talked about the experiments themselves and how to do them, in this section we will be looking at how to interpret the data obtained after finishing the said experiments. Raw data obtained need to be evaluated and calculated in different ways before we can get the information we want. How much does a certain factor influence the quality parameter we chose (in other words how much does a certain factor influence quality of the product we are inspecting). All these processes/operations together are called data analysis, which can be split into two parts.

8.3.1. Analysis of variance vs. simple analysis

In the simple analysis, we can determine basic values that can help us calculate other more complex results and support our final findings and observations. [24]

Following values can be calculated:

1. Average influence of factor levels (also called main effects)

To calculate the average effect of factor A at a given level, all results – rows (each row will produce one result) where A is at that give level are taken and averaged.

2. Optimum conditions for achieving the best value of the quality parameter

After obtaining the average influence for each factor level, we can take these values and plot them against their corresponding levels for each factor, see example below in Figure 9.

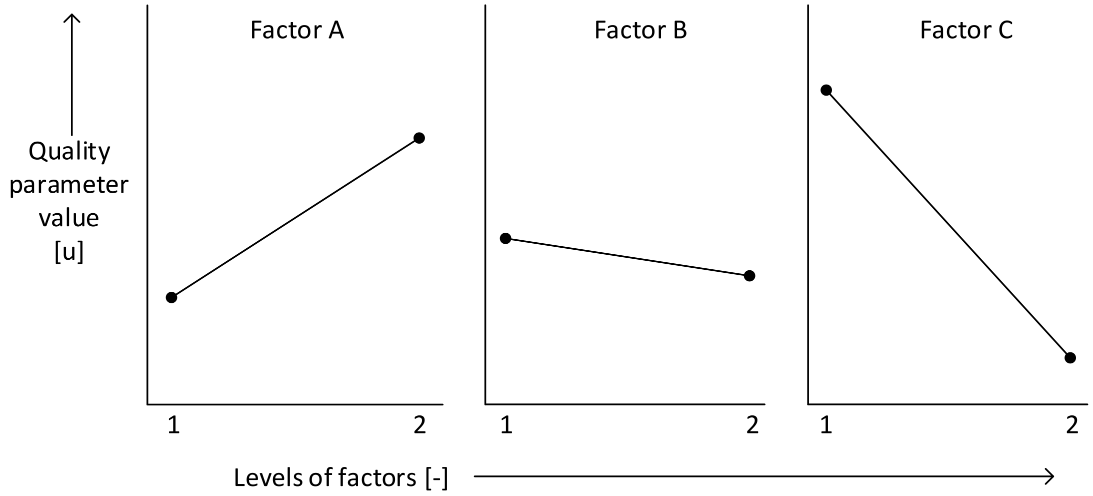

Figure 9. *Plotted average effects of three factors on a quality parameter when changing from level 1 to level 2*

In Figure 9, we can see a scenario where we have three factors A, B and C each with two possible levels (2^3). We are going to assume that the quality parameter measured in units *u* needs to be maximized – the bigger it is the better quality we achieve (real world scenario would be the production of insulators where the quality parameter would be their resistivity). It is clear that the optimum conditions are achieved when factor A is on level 2, factor B is on level 1 and factor C is on level 1 (we are not considering factor interactions here – simplified example)

3. Expected value of quality parameter when optimum conditions are met

Before conducting another run of the experiment using the optimum conditions we can actually calculate what the result should be – an estimate of performance [24] [20]

$$Y_{\mathrm{opt}} = \overline{T} + (\overline{A_2} - \overline{T}) + (\overline{B_1} - \overline{T}) + (\overline{C_1} - \overline{T}), \tag{43}$$

$$\overline{T} = \frac{Y_1 + Y_2 + Y_3 + Y_4}{4}. \tag{44}$$

Quantities Y_i in equations (44) represents the quality parameter that we get when running an experiment in one row of the array. The T with an overbar represents an average of all results from all runs (in this case, we are assuming an L-4 array so four rows). A_2, B_1 and C_1 (with overbars) represent the average optimum main effects for optimum levels. All averages have an overbar over their character as is custom. Y_{opt} is then the expected value when optimum conditions are met.

The second part of analysis is called the analysis of variance (ANOVA). Calculations here are a lot more complicated compared to the simple analysis. It can lead to a number of other useful information but it usually requires a wide knowledge of statistical mathematics to perform. The following information can be used using variation of analysis. [24]

1. Relative influence of the factors and their relation to variation of results
2. Significance of each factor and its testing
3. The interval of confidence regarding the optimum performance
4. The interval of confidence regarding the main effect of factors
5. Error factor

Some of these are out of scope of this work; others will be described later on in the following chapters. To summarize, analysis of variance can be quite useful for obtaining various information. Our use of it will be described in the following section.

8.3.2. Influence of an individual factor on the quality parameter

The influence of each factor on the final output parameter is crucial. We will try to describe each factor with a percentage that describes it. To describe this in a more simplistic way let us again take a look at Figure 8 – the normal distribution (or any other) shows us the variation in the final performance (value of quality parameter) that we want to reduce. Each factor considered (let us say there are three factors A, B and C) contributes to this variation with its own variation. In other words, we want to know how much variation each factor causes relative to the total variation in the final quality parameter. Taking the variation caused by one factor and dividing it by the total variation caused by all factors together. The problem is quantifying the variation. [24]

The total variation caused by all the factors in a set of runs corresponds to the deviations from the mean for each run. The problem here is that some deviations will fall to the right side of the mean and some to the left – which will be represented by the plus and minus sign. This can lead to some deviations canceling each other out so to speak. To avoid this we will be squaring each deviation before adding them all up.

This leads us to the sum of squared deviations from the mean formula [20]

$$S_T = \sum_{i=1}^{N}(Y_i - \overline{Y})^2 , \tag{45}$$

where N represents the total number of runs. Y_i is a result from the i-th run (row) and Y with the overbar represents the mean of the results. It can be rewritten as follows

$$S_T = \sum_{i=1}^{N}(Y_i - \frac{T}{N})^2 , \tag{46}$$

where T is the sum of the results from each row added together and N is the total number of rows/runs/experiments. This equation can then be edited into the following form

$$S_T = -\frac{T^2}{N} + \sum_{i=1}^{N} Y_i^2 , \tag{47}$$

where T^2/N here is referred to as the correction factor (CF). In statistical literature, it is described to be an estimation of the grand mean. [24] [20] [32]

The sum of squared deviation can be interpreted as a variance (mean squares are often referred to as variance in various statistical literature) caused by all the factors.

Considering the variation of an individual factor, we can use the factor sum of squares. For factor F with two levels, we have the formula

$$S_F = \frac{F_1^2}{N_{F1}} + \frac{F_2^{\ 2}}{N_{F2}} - CF\,, \tag{48}$$

where N_{F1} is the number of runs where factor F is on level 1 (similarly for N_{F2}). F_1 and F_2 are the sums of results with F on level 1 and 2 respectively.

We can now easily calculate the influence of an individual factor (let us call it F again) using our definitions from equations (47) and (48)

$$P_F = \frac{S_F}{S_T}\,. \tag{49}$$

The problem is, that the above formula does not take into account the error term (often called error factor – we already mentioned this at the end of section 8.3.1). This term takes into account all the remaining factors that were not included in the study and the experimental error. In order to consider this let us write the following equation

$$P_F = \frac{S'_F}{S_T}\,. \tag{50}$$

In order to calculate (50) we need to define and look at some commonly used terms from statistical mathematics [24] [20]

$$V_F = \frac{S_F}{f_F}\,, \tag{51}$$

$$F_F = \frac{V_F}{V_e}\,, \tag{52}$$

$$S'_F = S_F - (V_e * f_F)\,. \tag{53}$$

The first term in (51) is the variance or mean squares, which is the sum of squares per each degree of freedom (DOF – we are using the classical notation now) – f_F is the degree of freedom of factor F. DOF is as mentioned previously in chapter 7.2.1 a common statistical term used to describe the number of parameters in a system that can vary. To simplify it – if we want to know which object is the biggest one out of three total objects then DOF represents the number of comparisons necessary to determine this – in this case it would be two. More in depth description of DOF is out of the scope of this work. For our purposes, we can write

$$DOF = N - 1. \tag{54}$$

Equation (54) is true for DOF of a factor, column, array and experiment where N represents the number of levels of factor, levels in a column, columns in array and the number of results in all the runs respectively. [24]

F_F is the F-ratio, which has been talked about in chapter 7. V_e is the “error term” of the total variance term, which is calculated in the same manner as (51) only with the quantity DOF of the error term this time.

This then leaves us with the final value that interests us – P_F (whether calculated with or without considering the error term).

9. Preparation, measuring and application of climatic load onto a set of adhesive joints

In the theoretical part of this work we went through the basics of ECDs, the basics of quality management and two statistical methods used in experimenting that come from it. In the practical part of the thesis, we will be performing an experiment with ECA joints and evaluating it using FFES and TOAs.

The goal the practical experiment is to take a larger number of conductive adhesive joints, look at their quality parameter, then apply a certain predefined climatic conditions (climatic load) that should worsen this parameter and then measure it again. After, we will use the previously described statistical tools in the form of FFEs and TOAs to determine what kind of influence the climatic conditions had on the quality parameter. We should then be able to compare which of the two (FFEs vs TOAs) is better suited for experimenting with ECAs.

The quality parameter will be the electric resistance. When comparing conductive joints (usually solder/adhesives) we could say that there are other factors (beside their resistance) to consider – like the temperature that the joint can withstand (often needs to be quite high in many real world applications). But we are only comparing ADCs so the resistance on its own should suffice – also what interests us is not mainly the quality of each joint but what will happen to quality in general when subjected to a climatic load, which can be perfectly demonstrated on only one quality parameter. We will be trying to minimize the resistance (the lower the better).

For a climatic load, we will be applying thermal shocks (quick changes from very low temperatures to very high temperatures and vice versa). We are not aware of any work where thermal shocks have been applied to joints formed of ADCs and therefore hope that this experiment will provide useful and interesting results. The thermal shocks will be applied in a device that consists of two chambers each with different temperature – in our case one will be -40 °C and the other +80 °C. The samples with the joints will stay in one chamber until the temperature balances and then quickly move to the other compartment – this will be done a certain number of times. The second climatic load will be a subjection of the samples to a temperature of +80 °C and the relative humidity of 80 % for longer periods of time (168 hours first batch and 336 hours second batch).

9.1. Samples of adhesive joints

The samples have been prepared on small (about 8 cm x 7 cm) PCBs where the conductive tracks are made of gold or copper (both shown in Figure 10 below).

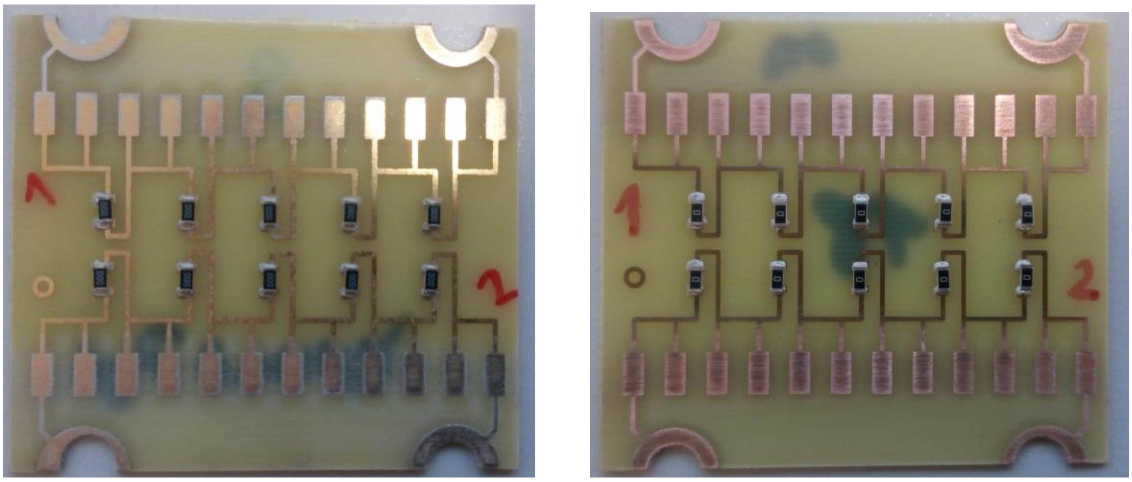

Figure 10. PCBs with ECA joints used in our practical part. Left - Permacol on gold, Right - 15S on copper

Each PCB contains 10 zero-ohm surface mounted resistors. These have been mounted using ECAs. Therefore we get 20 ECA joints (for each zero-ohm resistor there are two joints) per each PCB.

In total, we will be testing three types/brands of conductive adhesives each on a golden and on a copper PCB (referring to the conductive tracks). In total, this will give us six sets of samples.

9.1.1. ECAs used – 15S, 70, Permacol

Out of the three ECAs we are going to be using, two are from the polish manufacturer Amepox Microelectronics Ltd. (AXMC) [33]. The ELPOX SC 70MN (referred to in our work only as “70”) is a single component adhesive and ELPOX AX 15S (referred to in our work only as ”15S”). The third ECA comes from a company called Permacol® B.V. residing in the Netherlands [34]. The PERMACOL 2369/2 is a one component adhesive (referred to as “Permacol“).

9.1.1.1 PERMACOL 2369/2

The Permacol is a one component ECA with good heat and moisture resistance after curing. The technical data have been taken from the official site of the manufacturer. [35]

- Binder : epoxy
- Filler (conductive) : silver
- Particle size : under 50 μm
- Curing temperature : above 125 °C (6 min.)
- Application : dispensing or stencil printing
- Volume resistivity : <3x10-4 Ω.cm
- Viscosity : 30 000 mPa.s

9.1.1.2 ELPOX AX 15S

The 15S is a two component ECA with silver flakes. It is meant for service and short production series using manual application. The technical data have been taken from the official site of the manufacturer. [36]

- Binder : epoxy
- Filler (conductive) : silver flakes
- Mixing ratio : 1 to 1
- Percentage of silver : 60 %

- Curing temperature : from 20 °C (24 hours) to 150 °C (15 min.)
- Volume resistivity : from 0,00018 to 0,001 Ω.cm
- Viscosity “A” : from 25 000 to 28 000 mPa.s
- Viscosity “B” : from 120 000 to 140 000 mPa.s
- Viscosity “A+B“ : from 28 000 to 30 000 mPa.s

9.1.1.3 ELPOX SC 70MN

The 70 is a single component ECA with epoxy-phenolic resin filled with silver. It should be especially good for connection to copper materials. The technical data have been taken from the official site of the manufacturer. [37]

- Binder : epoxy-phenolic
- Filler (conductive) : silver
- Percentage of silver : 70 %
- Curing temperature : from 20 °C (60 minutes)
- Electrical resistivity : (1.0 –2.5) x E(-6) Ωm

9.2. Measurements before the climatic load

The measurements on the samples shown in Figure 10 are usually done via a 4-terminal sensing where we put the current-carrying electrodes on the two pads below/above the zero-ohm resistor that we measure (which contains two ECA joints) as shown in Figure 11.

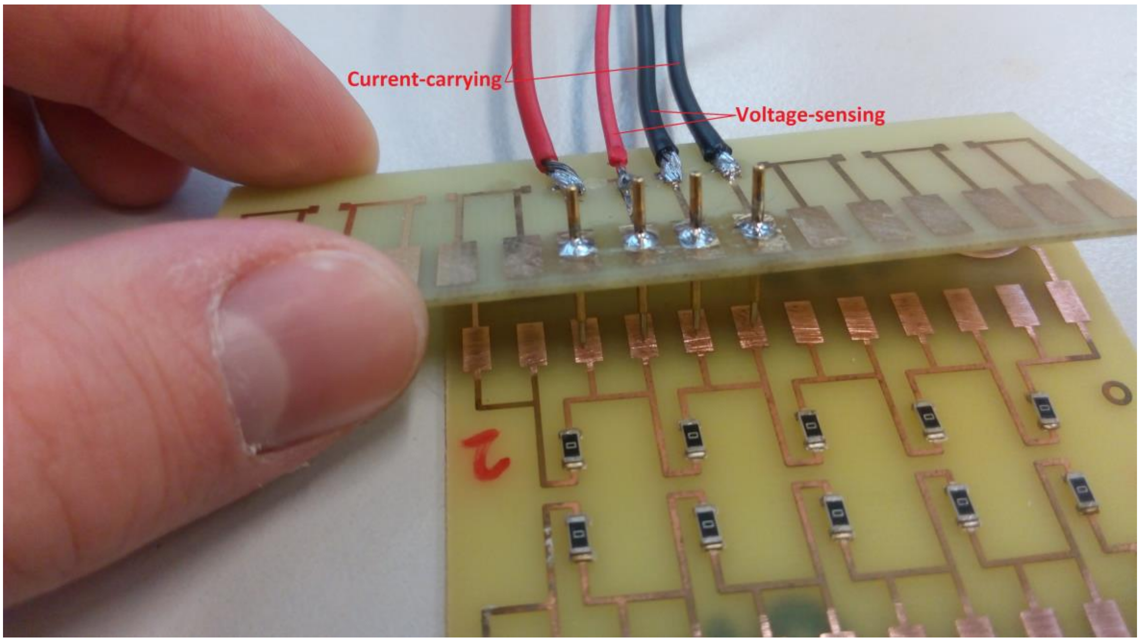

Figure 11. *Example of Four-terminal sensing method for measuring the resistance of ECA joints*

The obvious problem with this measuring method is the following: ECA joints are generally of lower quality than soldered joints – we will therefore need to measure all the samples before we do any climatic load and we need to omit all the joints that do not fulfill a certain resistance limit. After consulting my supervisor, we have decided to set the limit to 600 mΩ. If the joint is below this limit, any time before or after the climatic load it will be included! With the method in Figure 11, we always measure two joints at once – we can get one with 1500 mΩ and one with 100 mΩ - that would be interpreted as 1600 mΩ together, therefore 800 mΩ each. Using this method we would not include either of these.

Because of this we decided that the measuring method used needs to be able to measure each joint individually, giving us better and more accurate data. This method is shown in Figure 12 below.

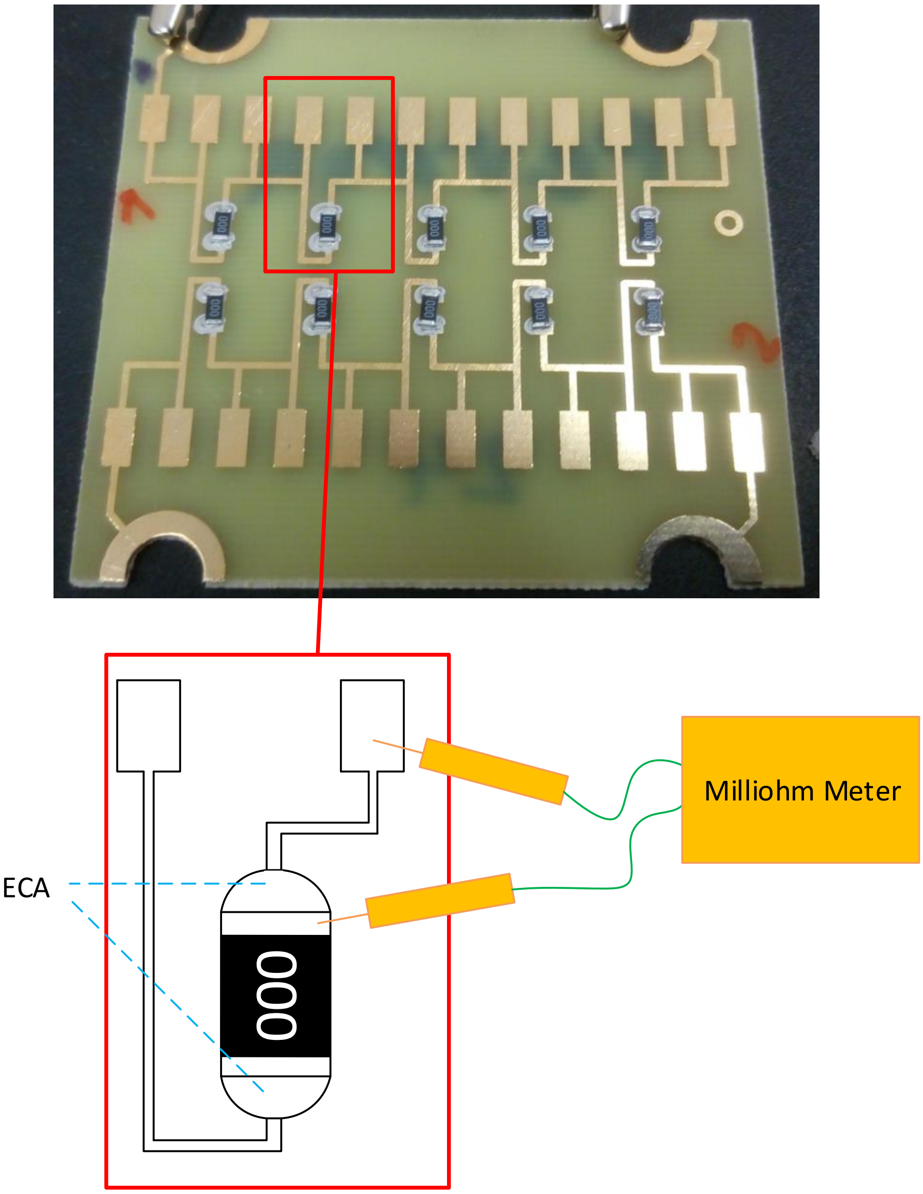

Figure 12. *Four-terminal sensing method used to measure each individual ECA joint separately*

In the upper part of Figure 12, we can see the current-carrying electrodes attached to the upper part of the PCB sample – the yellow electrodes then represent the voltage-sensing ones.

9.2.1. Milliohm meter used – Agilent HP 4338B

The milliohm meter used to obtain all the data was the Agilent HP 4338B at Faculty of Electrical Engineering CTU in Prague shown in Figure 13 below.

Figure 13. *Milliohm meter Agilent HP 4338B used for resistance measurements*

The resistance measure for each joint was usually between 100 mΩ and 1 Ω. Since we are going to be evaluating the effect of the climatic load on the resistance, we do not need the measured values to be as accurate as possible – as long as we have the error of equal magnitude before and after the climatic load, it will technically cancel each other out. Nevertheless, we should mention the measurement error for our data. It can be calculated using the table from the official manual shown in Appendix A – Milliohm measuring error.

We used the short/medium mode for measuring and the current level was usually at 100 μA (given our 100 mΩ and 1 Ω resistance range). According to the table, we then get

$$\text{Short mode: } 0{,}85 + \frac{1{,}001}{R} = \text{around +- } 2\%\,, \tag{55}$$

$$\text{Medium mode: } 0{,}4 + \frac{0{,}151}{R} = \text{around +- } 0{,}7\%\,, \tag{56}$$

where R in equations (55) and (56) represents the measured value of resistance in Ω. The percentage value gets higher with lower values of resistance.

9.2.2. Examples of measured values

We already mentioned that we are measuring three types of adhesives. All of them on PCBs with gold and copper meaning we get 6 sets of samples – our aim was to have for each set an 2^2 experiment with four columns of data, each column containing around 25 measured samples that fulfil the 600 mΩ mentioned above.

This way we measured 75 PCBs in total each containing 20 joints – meaning we individually measured 1500 joints. Out of these, around half was above the 600 mΩ limit. Example of the data measured is given in Table 8 below.

***Table 8.** Measured resistances of ECA joints on 4 PCBs - 2 for Permacol on gold and 2 for Permacol on copper. Measurements done before the climatic load*

	Permacol gold samples [mΩ]		Permacol copper samples [mΩ]	
1	65	430	360	670
2	150	250	225	660
3	728	85	476	407
4	1090	420	523	450
5	922	40	473	382
6	454	430	1048	550
7	2000	1170	750	860
8	198	428	1540	4500
9	1570	128	180	201
10	6400	9000	172	202
11	580	750	350	313
12	440	604	187	229
13	274	992	2700	510
14	920	2000	1460	526
15	170	38	3890	960
16	508	3264	384	551
17	425	135	14900	1600
18	870	292	20000	16400
19	274	96	710	832
20	203	105	89	176

As we can see, the resistances vary quite a lot. Around half of these can be deemed as nonfunctional due to too high resistance values. This variation can be caused by poor non-consistent construction of these joints (they were created using screen-printing) and by not completely accurate measurements – any slight change in movement when attaching the electrodes to the samples can cause the resistance to go up or down even up to a 100 mΩ.

Out of all the 1500 values measured, around half was above the 600 mΩ, some were not measurable (unable to get any value). All the remaining values can be reviewed in Appendix B – Resistance values before the climatic load at the end of this work.

9.3. Climatic load

We used thermal shocks as the first factor and relative humidity together with high temperature as the second factor.

9.3.1. Thermal shocks

The first factor considered when stress testing our samples will be the thermal shocks. We used the Thermal shock test cabinet type TSS-70/66, which is available at CTU. It contains two chambers – heat chamber (+50 °C to +200 °C) and cold chamber (-80 °C to +100 °C). [38]

Technical specifications [38]:

- Nominal Voltage : 400V 3/N 50Hz
- Nominal output : 8,8 kW
- Nominal current : 14 A

Cooling-Compressor	: TFH2511Z / TFH2511Z
Refrigerating agent	: R404A/R23
Constructed on	: 23rd November 2015
Manufacturer	: CTS GmbH

Figure 14. *Thermal Shock Test chamber (TSS series) used for stress testing our ECA samples* ***[38]***

We used temperatures -40 °C (cold chamber) and +80 °C (heat chamber) with the samples staying 15 minutes in each chamber to balance the temperature – then the samples quickly moved to the other chamber causing the thermal shock.

The level of this factor was the number of shocks. We considered two levels – we split all the samples in half and shocked one group 10 times and the other 40 times. We selected 6 PCBs (120 joints) and shocked those 20 times – we will be testing our mathematical model on these – they will not be included in the classic FFE (and Taguchi) data.

9.3.2. Relative humidity and temperature

The second factor will be the effect of a high relative humidity and a high temperature for longer periods of time. We chose RH 80 % and the temperature 80 °C since those are the values used for testing according to a technical standard. We are going to be using the Climatic test cabinet type C+10/200, which is available at CTU. [39]

Technical specifications [39]:

- Nominal Voltage : 230V 1/N 50Hz
- Nominal output : 3,2 kW
- Nominal current : 14,5 A
- Cooling-Compressor : SC18CLX
- Refrigerating agent : R404A

- Constructed on : 28th October 2016
- Manufacturer : CTS GmbH

Figure 15. *Climatic (RH and temperature) test cabinet (C series) used for stress testing our ECA samples* ***[39]***

This factor has again two levels – one half of the samples was left in the cabinet at 80 % RH and 80 °C for 168 hours (one week) and the other for 336 hours (two weeks). The 6 special PCBs that were shocked 20 times were taken out after 200 hours (and again were not considered in our FFE (Taguchi) data).

9.4. Measurements after the climatic load

After all the climatic stress testing has been done, we again measured all the joints in the same way as before in section 9.2. Below in Table 9 we can see some of the values measured after the climatic load (we can already see that the table takes the form of an FFE) – only a selected handful of values is shown, the rest can be viewed in Appendix C – Resistance values after the climatic load.

Table 9. *Measured resistances of ECA joints on 4 PCBs - Permacol on gold each combination of factors. Measurements done after the climatic load*

Perma gold samples [mΩ]			
10 shocks		40 shocks	
168 hours	336 hours	168 hours	336 hours
73	860	14	58
139	800	86	35
340	280	17	149
n	730	n	107
99	27	26	38
n	295	480	174
490	284	24	90
312	213	103	25
632	1056	40	450
430	655	44	16
477	17	221	704
178	120	93	45
598	100	371	62
220	24	56	157
750	22	93	560
240	90	101	213
320	n	17	53
525	n	210	173
620	115	22	340
48	890	63	105

Character *n* in the table represents a non-measurable joint (we could not obtain a value).

10. Use of FFEs and Taguchi arrays on measured data, mathematical model, results

Having the measured values, we can evaluate the effect of the factors using the FFE methodology and TOA methodology that was summarized in the theoretical part of this thesis.

For both FFEs and TOAs, we have two factors of two levels, which gives us 2^2 types of tables. We will therefore be doing 6 times 2^2 type FFEs and Taguchi arrays and we will also try to construct a mathematical model using FFEs that we will then test with our special set of samples (6 PCBs that have been shocked 20 times and left in 80%/80°C temperature for 200 hours). Unfortunately for 2^2 (two factors and two levels) Taguchi arrays are quite similar to FFEs (they only differ in the mathematical approach, but the tables are the same). We will therefore also do a 2^3 type FFE and Taguchi arrays with the third factor being material – two levels: copper and gold. In the case of 2^3 we will only compare FFE and Taguchi arrays and we will not be looking at mathematical model (since the third parameter is not quantifiable).

10.1. Data preparation

If we look at Table 9, we can see that the resistance values range from 10^1 to 10^3 mΩ. Assuming that 10 shocks decreased the resistance of every joint by approximately 10 % – this information could be lost because of the wide range of resistance.

Because of this we decided to work not with the absolute resistance values but with the increments in percent. Each value will be calculated in the following way

$$\text{final value in the table} = \frac{R \text{ after climatic load}}{R \text{ before climatic load}} . \tag{57}$$

This way the final results and observations are more accurate.

10.2. FFEs 2^2

The 2^2 FFEs will be considering the number of thermal shocks as one factor (lower level = 10 shocks; higher level = 40 shocks) and the time the joints were exposed to RH + temperature 80%/80°C as the other factor (lower level = 168 hours; higher level = 336 hours). This FFE can be considered 6 times (3 ECAs for 2 materials each). Let us take a look at Perma ECA on gold as an example for the calculations, below. Values in the table were obtained using the method described above in equation (57).

Table 10. *FFE 2^2 table for Perma gold samples with relative values of resistance*

10 shocks		40 shocks		Perma gold [-]
168 hours	336 hours	168 hours	336 hours	
0,55	1,51	0,42	0,06	
2,53	1,43	0,45	1,48	
1,09	0,25	0,11	0,36	
0,29	2,24	2,16	0,78	
4,37	1,08	0,67	0,35	
1,58	2,59	0,44	8,00	
2,07	3,32	0,02	2,55	
0,33	1,83	0,43	1,35	
0,40	1,26	0,54	0,04	
1,23	0,58	1,30	0,05	
1,88	1,17	2,27	0,04	
0,25	2,98	1,07	0,60	
0,74	2,10	1,38	16,48	
0,22	0,36	0,10	9,78	
0,66	2,72	0,18	0,90	
0,40	2,85	0,57	0,12	
2,27	10,60	0,26	0,11	
0,50	1,38	0,04	0,08	
4,45	0,16	2,67	0,22	
1,22	1,00	0,92	1,25	
7,90	13,44	0,86	0,35	
5,61	5,85	0,20	0,83	
0,58	3,95	1,02	0,50	
1,04	0,74	0,19	2,52	
5,00	1,92	0,16	5,21	
0,77	6,55	0,50	0,97	
0,97	2,02	0,23	2,31	
2,82	2,20	3,32	8,05	
0,34	20,59	0,18	0,45	
3,14	10,77	0,12	0,35	
0,39	3,39	0,17	1,73	
1,00	7,26	2,24	1,71	
0,33	6,40	1,02	1,73	
0,17	2,00	1,00	6,62	
1,37	3,20	0,51	0,03	
0,26	3,29	0,49	4,72	
0,67	1,74	0,99	0,37	
0,22	0,68	1,64	1,68	
1,16	0,69	7,27	10,18	
0,24	0,50	0,94	2,34	
0,20	8,25	1,91	1,13	
0,57	0,58	0,41	0,85	
3,18	1,20	0,31	4,15	
4,50	8,48	4,20	0,56	

We can see that each column has 45 rows – the original aim was to get at least 25 for each column. There is a certain variation to how many rows each table has because of the 600 mΩ limit and because we were unable to obtain a value with some joints. Below is a table that shows how many rows each 2^2 table has (how many times was the experiment run). It is obvious that the more rows there is the more accurate the results (the bigger the statistical pool). **We have the same number of repetitions/rows for 2^2 Taguchi orthogonal arrays as well!**

Table 11. *Number of rows for each 2^2 FFE/Taguchi table (represents the number of repetitions) for each type of ECA/material*

	Perma gold	**Perma copper**	**15S gold**	**15S copper**	**70 gold**	**70 copper**
number of repetitions for each column	45	18	27	8	8	17

Having the FFE table, we want to know which factor (and interaction between factors) had most influence and what kind of influence it was. We already described the calculations in section 7.2. Let us now apply them for the data in Table 33 (only the left part).

For the calculations:

Factor A = number of shocks (A1 = 10 shocks; A2 = 40 shocks)

Factor B = hours in 80%/80°C (B1 = 168 hours; B2 = 336 hours)

Table 12. *Perma gold 2^2 FFE calculations and final influences of each factor/interaction*

Factor A	**10 shocks**		**40 shocks**	
Factor B	**168 hrs**	**336 hrs**	**168 hrs**	**336 hrs**
sums of columns - T	**T1**	**T2**	**T3**	**T4**
	71,07	254,73	46,63	104,17
estimates of influence - Z	**Za**	**Zb**	**Zab**	
	-175,00	241,19	-126,12	
mean of the whole tab - M	2,65			
SUM of squares of deviations - S	12335			
mean of each column	1,58	5,66	1,04	2,31
RSS	11753,30			
individual sum of squares of deviations	**Sa**	**Sb**	**Sab**	
	170,14	323,19	88,37	
DOF	176			
F-characteristics	**Fa**	**Fb**	**Fab**	
	2,55	4,84	1,32	
Final influences of each factor/interaction	**Pa**	**Pb**	**Pab**	
	0,292	**0,556**	**0,152**	

The influences in Table 12 can be displayed as a pie chart to better understand and show the influence of each factor/interaction. **The influence is an increase in resistance (can be seen form the means of each column in Table 12 above).**

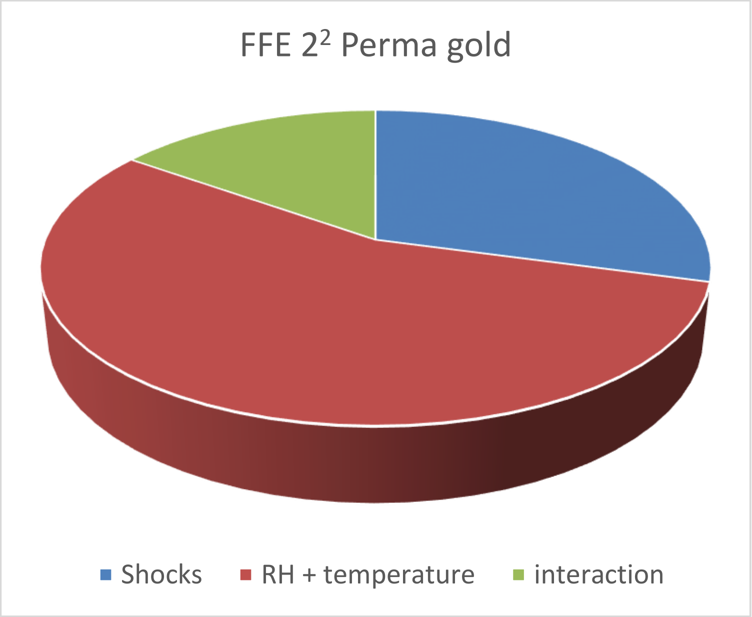

Figure 16. *Perma gold 2^2 FFE pie chart for each factor/interaction influence*

We can clearly see that the RH + temperature had a much larger effect compared to the thermal shocks. Not only that but from the estimates of influences in Table 12, we can actually see that the thermal shocks had a positive effect on the resistance of the joints (they decreased it).

The remaining five 2^2 FFE pie charts will be displayed and compared with Taguchi's approach in section 10.4. The FFE tables for the remaining five other sets of samples can be viewed in Appendix D – FFE/Taguchi tables with relative resistance values.

10.3. Taguchi orthogonal arrays 2^2

With Taguchi orthogonal arrays if we want to do an experiment with two factors that each has two levels we will be using the L-4(2^3) Taguchi orthogonal array, which can be either used for 2^2 or for 2^3. If we now apply Table 6 (shown in theoretical part) to our case, we get the following table.

Table 13. *L-4(2^3) Taguchi orthogonal array applied to our experiment - third column will remain unused*

	Column		
Run	**shocks**	**RH + temperature**	**C**
1.	10	168 hours	1
2.	10	336 hours	2
3.	40	168 hours	2
4.	40	336 hours	1

In Table 13, we can clearly see that the Taguchi orthogonal array for 2^2 will look exactly the same way as 2^2 FFE table shown in Table 10. We can therefore reuse it and just write the Taguchi's approach calculations here (this will be the same for all the six sets of samples – tables for them are shown in Appendix D – FFE/Taguchi tables with relative resistance values). The calculations are again shown on Perma ECA on gold. Description of calculations can be found in section 8.3.

Table 14. *Perma gold 2^2 Taguchi calculations and final influences of each factor*

Factor A	**Shocks**
Factor B	**RH + temperature**
SUM of squares of deviations - ST	12335,00
correction factor CF	1261,96
A1 (low) sum **(10 shocks)**	325,80
A2 (high) sum **(40 shocks)**	150,80
NA1 number of runs on A1	90
NA2 number of runs on A2	90
B1 (low) sum **(168 hours)**	117,71
B2 (high) sum **(336 hours)**	358,90
NB1 number of runs on B1	90
NB2 number of runs on B2	90
SA	170,14
SB	323,19
influence of A	0,014
influence of B	0,026

Just like in the case of FFE, we can put the final influences of the two factors – shocks and RH + temperature into a pie chart to demonstrate the effects.

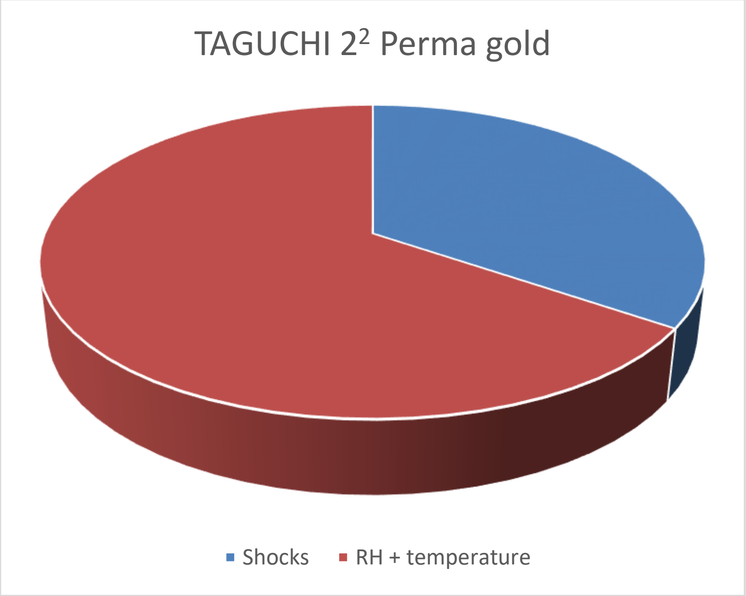

Figure 17. *Perma gold 2^2 Taguchi orthogonal arrays pie chart for each factor influence*

We can see a similar pie chart to the FFE one except without the interaction (see Figure 16). The remaining five pie charts for the other sets of samples will be discussed and shown in the following section 10.4.

10.4.Comparing results 2^2

The following pie charts are the comparison of six sets of samples (15S, 70 and Perma ECA on gold and copper each) that were looked at through the FFE approach and through the Taguchi's orthogonal arrays approach – total of 12 pie charts. **When showing the influence we mean the influence on the increase in resistance!**

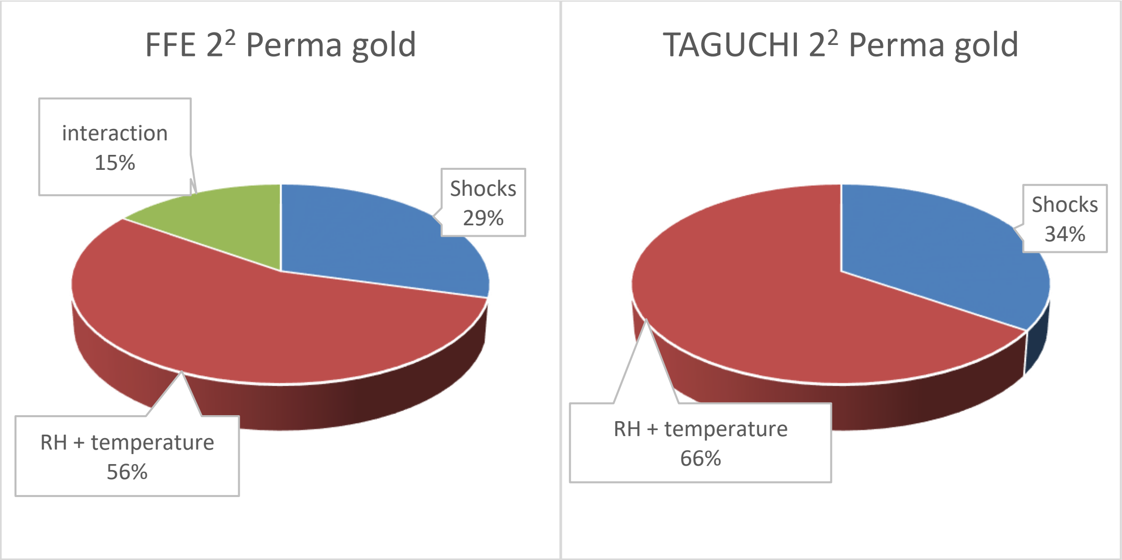

Figure 18. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - Perma on gold*

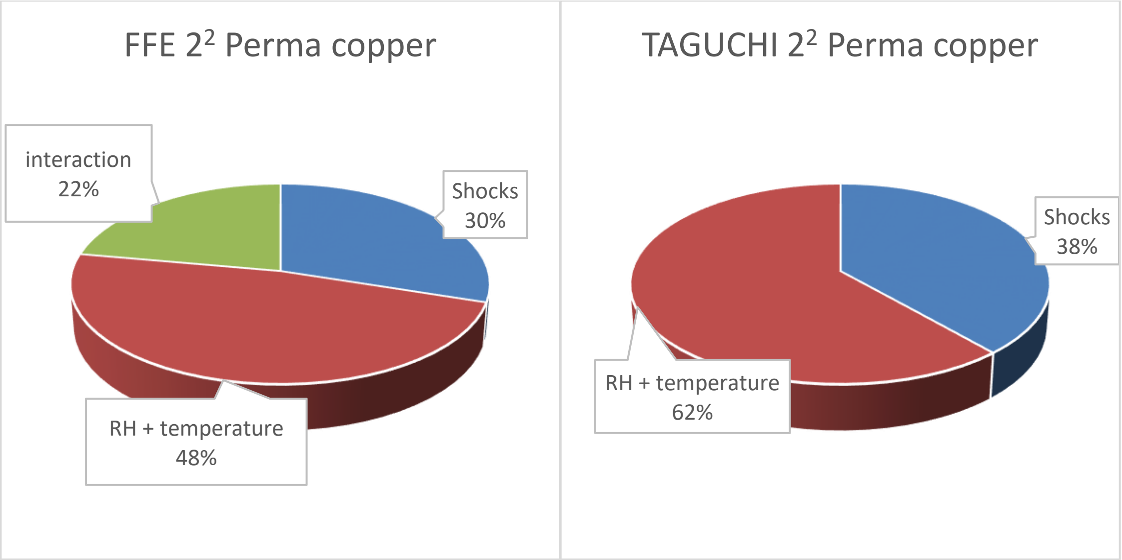

Figure 19. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - Perma on copper*

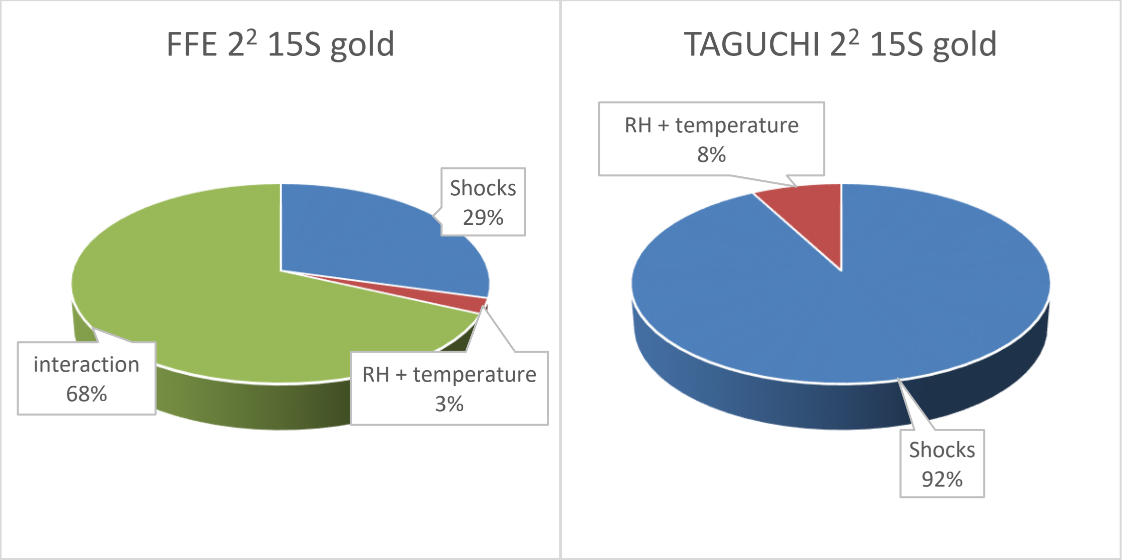

Figure 20. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - 15S on gold*

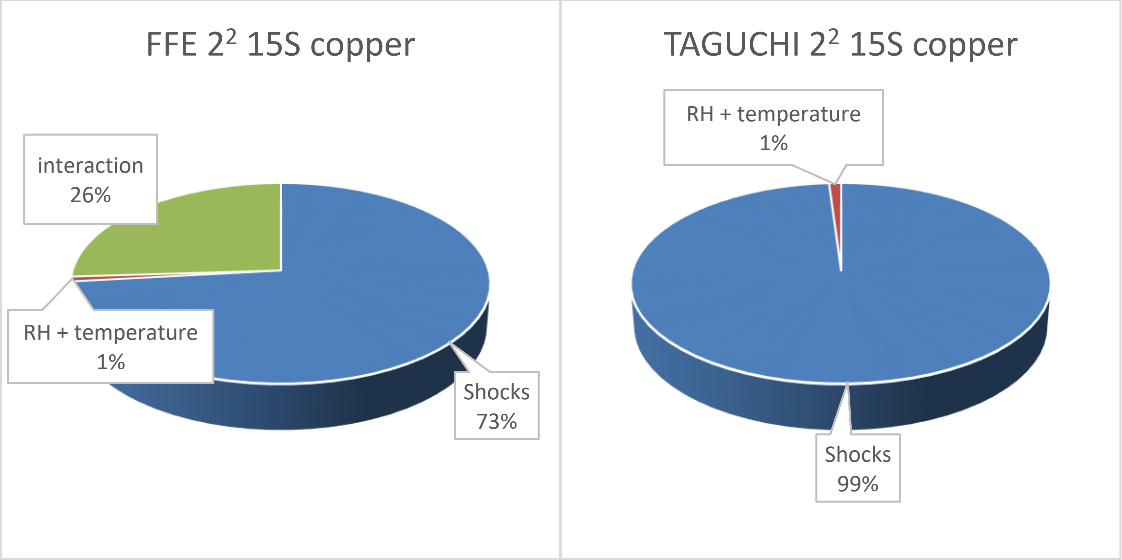

Figure 21. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - 15S on copper*

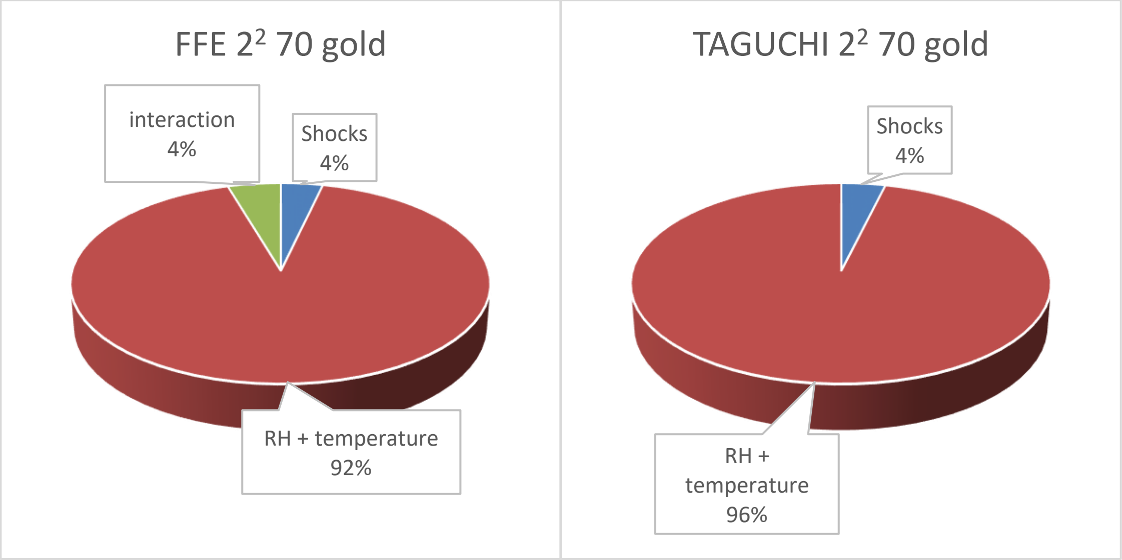

Figure 22. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - 70 on gold*

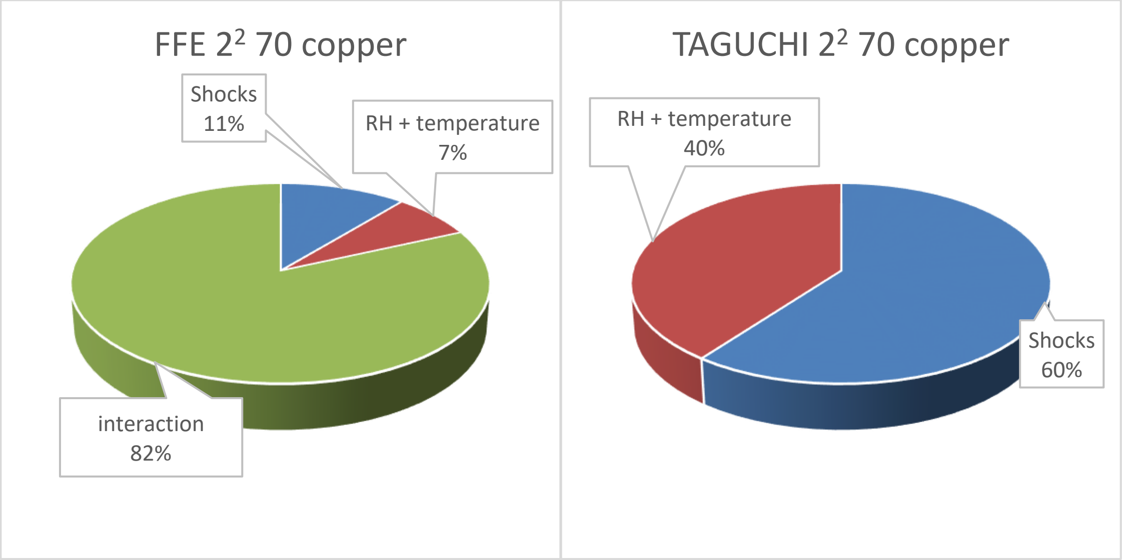

Figure 23. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (left) and Taguchi approach (right) - 70 on copper*

Discussion about the results in Conclusion.

10.5. Mathematical model of the climatic load process

Recalling section 7.3, we are now able to construct a linear model using the FFEs. Employing equations (23) to (35), we arrive at the general equation for a mathematical model

$$\text{relative } R = k_0 + k_1 * X_1 + k_2 * X_2 \ . \tag{58}$$

Constants k_0, k_1 and k_2 can be obtained using the data from the FFE tables (Appendix D – FFE/Taguchi tables with relative resistance values). X_1 and X_2 represent shocks and RH + temperature respectively (in dimensionless units that range from -1 to 1). Using the calculations form section 7.3 we can get the final mathematical models for each set of samples (6 in total). The resistance value will be in relative value as described in equation (57).

Table 15. *Constants for a linear mathematical model of a climatic stress test process with two factors - for six different types of ECA/material*

Constants	**Perma gold**	**Perma copper**	**15S gold**	**15S copper**	**70 gold**	**70 copper**
k0	2,65	3,83	8,12	24,44	16,49	12,51
k1	-0,97	-1,44	-2,93	-9,02	-0,96	0,58
k2	1,34	1,82	0,85	0,93	-4,81	-0,47

To test whether the mathematical models give good output values we prepared six PCBs that were shocked 20 times and left in RH + temperature for 200 hours. They were not used in the construction of the mathematical models – they were measured and averaged purely for testing purposes. Below we can see the measured values and the values from the models.

Table 16. *Measured data after 200 hours of RH + temperature and 20 shocks with calculated averages; bottom line represents values obtained from mathematical model*

Material	gold			copper		
ECA	**PERMA**	**15S**	**70**	**PERMA**	**15S**	**70**
	15	12	10	22	5	17
values [-]	0,27	x	1,26	8,75	5,43	x
	x	x	x	1,18	x	x
	0,25	0,97	3,01	3,89	17,85	3,28
	x	x	x	1,03	19,57	2,82
	0,70	1,05	x	6,34	x	x
	0,12	x	x	x	x	x
	0,81	1,40	x	x	x	2,15
	0,55	x	x	x	x	7,44
	4,78	x	x	8,33	x	x
	0,15	x	x	3,76	5,27	x
	0,57	2,71	7,79	12,00	6,00	x
	0,06	0,68	2,46	2,86	28,59	x
	0,35	x	54,86	x	4,87	x
	0,16	3,82	x	x	9,38	x
	0,17	x	x	x	12,97	x
	1,06	2,67	x	3,65	x	x
	14,71	5,01	x	x	1,60	3,55
	6,07	82,09	x	x	x	8,76
	x	x	x	x	11,45	x
	x	1,68	x	1,69	2,85	3,53
	16	10	5	11	12	7
MEASURED AVERAGES	**1,92**	**10,21**	**13,88**	**4,86**	**10,49**	**4,50**
MODEL	**2,06**	**8,52**	**20,07**	**3,07**	**26,81**	**12,64**

The character *x* in Table 16 again represents values above the limit or joints where we could not obtain any data. Given there is a large variation in the measured data the models actually give in our opinion a very good results if we compare them to the measured averages. Perma gold/copper and 15S gold are very close in values (measured and the calculated). The remaining three vary more – more discussion in the Conclusion.

10.6. FFEs 2^3

The reason for doing 2^3 (i.e. adding one more factor in the form of material – one level being gold and the other level being copper) is that with 2^2, TOAs are identical to the FFE tables. One of the goals of this work is to compare TOAs with FFEs and determine which is more suitable for ECA testing/experimenting. In order to properly compare which approach is better, we need to add a third factor so the TOAs and the FFE tables will differ.

The tables given in “Appendix D – FFE/Taguchi tables with relative resistance values” are for 2^2 FFEs but by just simply putting the left part together with the right (left is gold, right is copper) we obtain an ideal 2^3 FFE table.

The number of repetitions/rows in the tables will be lower – we have to lower each of the eight columns (2^3) to the lowest number we have. If we look at Table 11 with the number of rows/repetitions for 2^2 tables, we can easily transform it into a table that will give us number of repetitions/rows for 2^3 tables – shown below in Table 17.

Table 17. *Number of rows for each 23 FFE/Taguchi table (represents the number of repetitions) for each type of ECA*

	Perma	15S	70
number of repetitions for each column	18	8	8

Important note: **We have the same number of repetitions/rows for 2^3 Taguchi orthogonal arrays as well (but different number of columns)!**

The obvious problem when we look at Table 17 is the low amount of repetitions, which will give not as accurate results as previously due to the small statistical sample size.

The calculations will again be the same as described in 7.2. **However, there is one change in comparison to the notation in section 10.2. The factors A, B and C represent different factors!**

For the calculations:

Factor A = material (A1 = gold; A2 = copper)

Factor B = number of shocks (B1 = 10 shocks; B2 = 40 shocks)

Factor C = hours in 80%/80°C (C1 = 168 hours; C2 = 336 hours)

Example of final results is given for Perma ECA below.

Table 18. *Perma 2^3 FFE calculations and final influences of each factor/interaction*

Factor A	**gold**				**copper**			
Factor B	**10 shocks**		**40 shocks**		**10 shocks**		**40 shocks**	
Factor C [hours]	**168**	**336**	**168**	**336**	**168**	**336**	**168**	**336**
sums of columns - T	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**
	21,54	83,23	27,44	48,94	39,72	149,93	32,49	53,42
estimates of inf. - Z	**Za**	**Zb**	**Zc**	**Zab**	**Zac**	**Zbc**	**Zabc**	
	-94,41	132,12	-214,3	-75,34	112,93	-129,4	15,91	
mean of the table - M	3,17							
SUM of squares of deviations - S	2402,12							
mean of each column	1,20	4,62	1,52	2,72	2,21	8,33	1,81	2,97
RSS	1709,84							
individual sum of squares of deviations	**Sa**	**Sb**	**Sc**	**Sab**	**Sac**	**Sbc**	**Sabc**	
	61,89	121,22	318,99	39,42	88,57	116,41	1,76	
DOF	176,00							
F-characteristics	**Fa**	**Fb**	**Fc**	**Fab**	**Fac**	**Fbc**	**Fabc**	
	4,92	9,64	25,37	3,14	7,04	9,26	0,14	
Final influences of each factor/interaction	**Pa**	**Pb**	**Pc**	**Pab**	**Pac**	**Pbc**	**Pabc**	
	0,08	**0,16**	**0,43**	**0,05**	**0,12**	**0,16**	**0,002**	

The final influences (influences on the increase of resistance – can clearly be seen from the mean of each column). The results from Table 18 can be displayed in a pie chart.

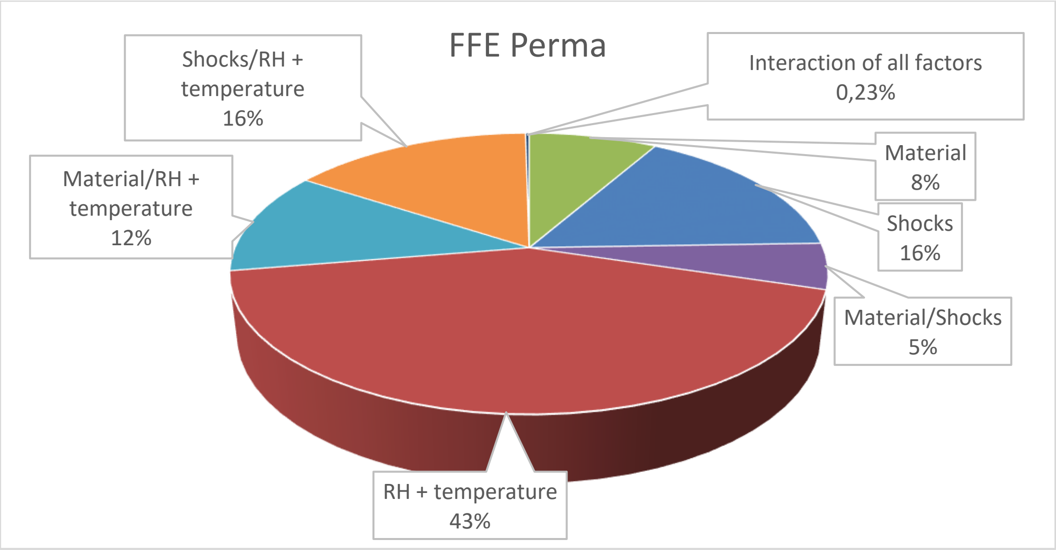

Figure 24. *Perma 2^3 FFE pie chart for each factor/interaction influence*

We see that again the RH + temperature factor has the largest influence as was shown in our 2^2 FFE calculations. For Perma it seems that material does not play a major factor in the climatic stress testing.

10.7. Taguchi orthogonal arrays 2^3

With Taguchi's approach, we will again use the L-4(2^3) orthogonal array but this time to its full extent. We will again take the full FFE table from Appendix D – FFE/Taguchi tables with relative resistance values (by combining the two tables – left and right – together) but we will only take some columns from it using the logic displayed in Table 6. To clarify, let us show the full L-4(2^3) array for Perma ECA with three factors below (values are again resistances in relative values calculated using equation (57))

Table 19. *L-4(2^3) Taguchi orthogonal array with 18 repetitions of each experiment used on Perma ECA (resistances in relative values)*

Perma [-]			
gold		**copper**	
10 shocks	**40 shocks**	**10 shocks**	**40 shocks**
168 hrs	**336 hrs**	**336 hrs**	**168 hrs**
0,97	2,31	7,91	0,47
2,82	8,05	5,10	1,97
0,34	0,45	0,70	0,72
3,14	0,35	1,47	1,03
0,39	1,73	1,45	2,67
1,00	1,71	7,35	1,13
0,33	1,73	20,78	0,86
0,17	6,62	14,81	4,16
1,37	0,03	4,30	1,00
0,26	4,72	27,78	0,54
0,67	0,37	14,25	1,76
0,22	1,68	12,89	0,74
1,16	10,18	2,77	4,29
0,24	2,34	2,76	1,29
0,20	1,13	5,43	1,21
0,57	0,85	7,42	3,37
3,18	4,15	6,47	2,44
4,50	0,56	6,27	2,85

Taguchi's approach calculations below are done as described in section 8.3 and again shown for Perma ECA.

Table 20. *Perma 2^3 Taguchi calculations and final influences of each factor*

Factor A **Factor B** **Factor C**	**Material** **Shocks** **RH + temperature**
SUM of squares of deviations - ST	1666,52
correction factor CF	888,30
A1 (low) sum **(gold)**	70,48
A2 (high) sum **(copper)**	182,42
NA1 number of runs on A1	36
NA2 number of runs on A2	36
B1 (low) sum **(10 shocks)**	171,47
B2 (high) sum **(40 shocks)**	81,43
NB1 number of runs on B1	36
NB2 number of runs on B2	36
B1 (low) sum **(168 hours)**	54,03
B2 (high) sum **(336 hours)**	198,87
NB1 number of runs on B1	36
NB2 number of runs on B2	36
SA	174,03
SB	112,58
SC	291,34
influence of A - material	0,10
influence of B - shocks	0,07
influence of C - RH + temperature	0,17

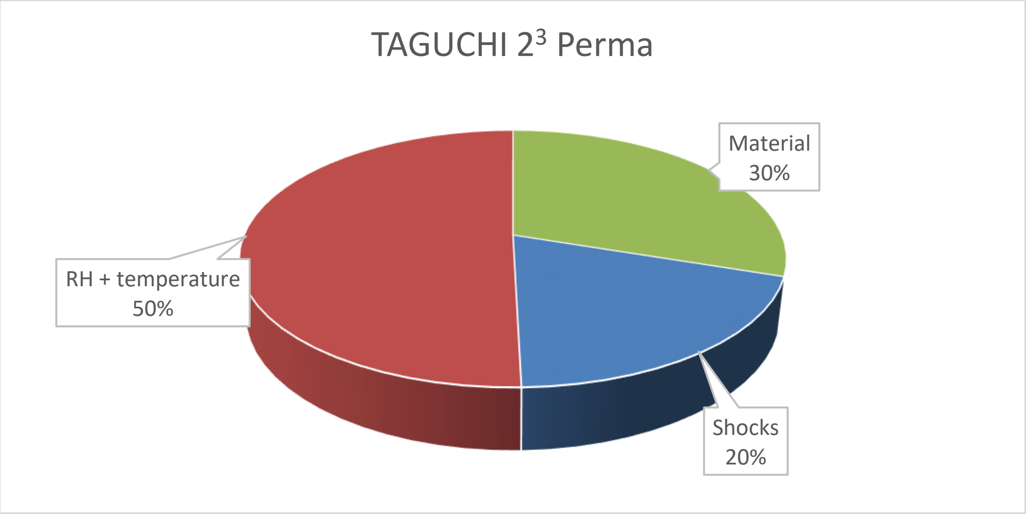

Figure 25. *Perma 2^3 Taguchi orthogonal arrays pie chart for each factor influence*

Taguchi array gives us a similar results to the one obtained by FFE when it comes to the RH + temperature factor, which seems to be the most influential one. However, the results differ for the other two factors, which is quite interesting.

10.8. Comparing results 2^3

The following pie charts give the comparison of the 3 sets of samples (15S, 70 and Perma ECA) that were looked at through the FFE approach and through the Taguchi's orthogonal arrays approach – total of 6 pie charts. The factors considered were the material (copper/gold), the thermal shocks (10/40) and the RH + temperature (168 hours/336 hours). **When showing the influence we mean the influence on the increase in resistance!**

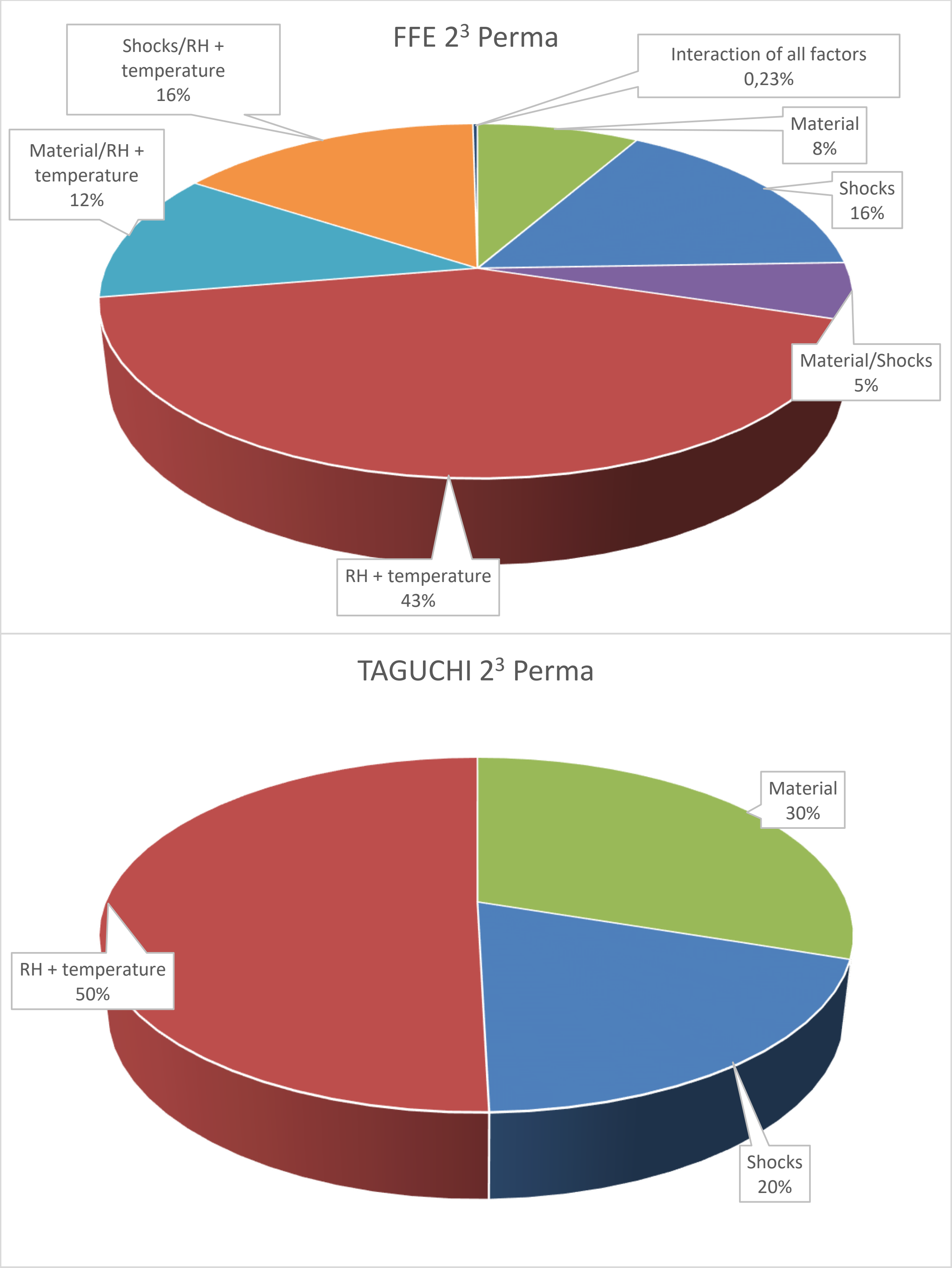

Figure 26. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (top) and Taguchi approach (bottom) - Perma ECA*

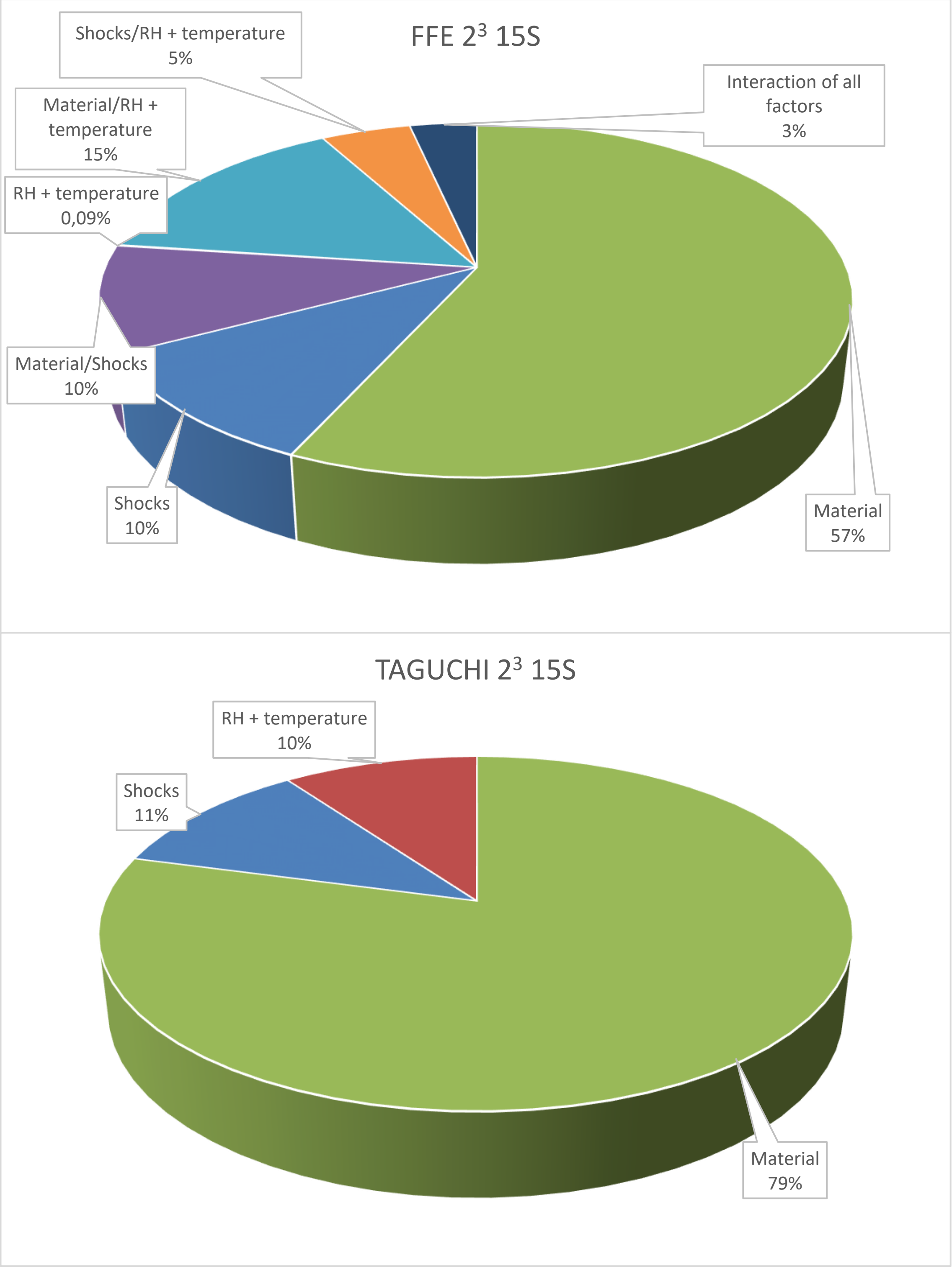

Figure 27. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (top) and Taguchi approach (bottom) - 15S ECA*

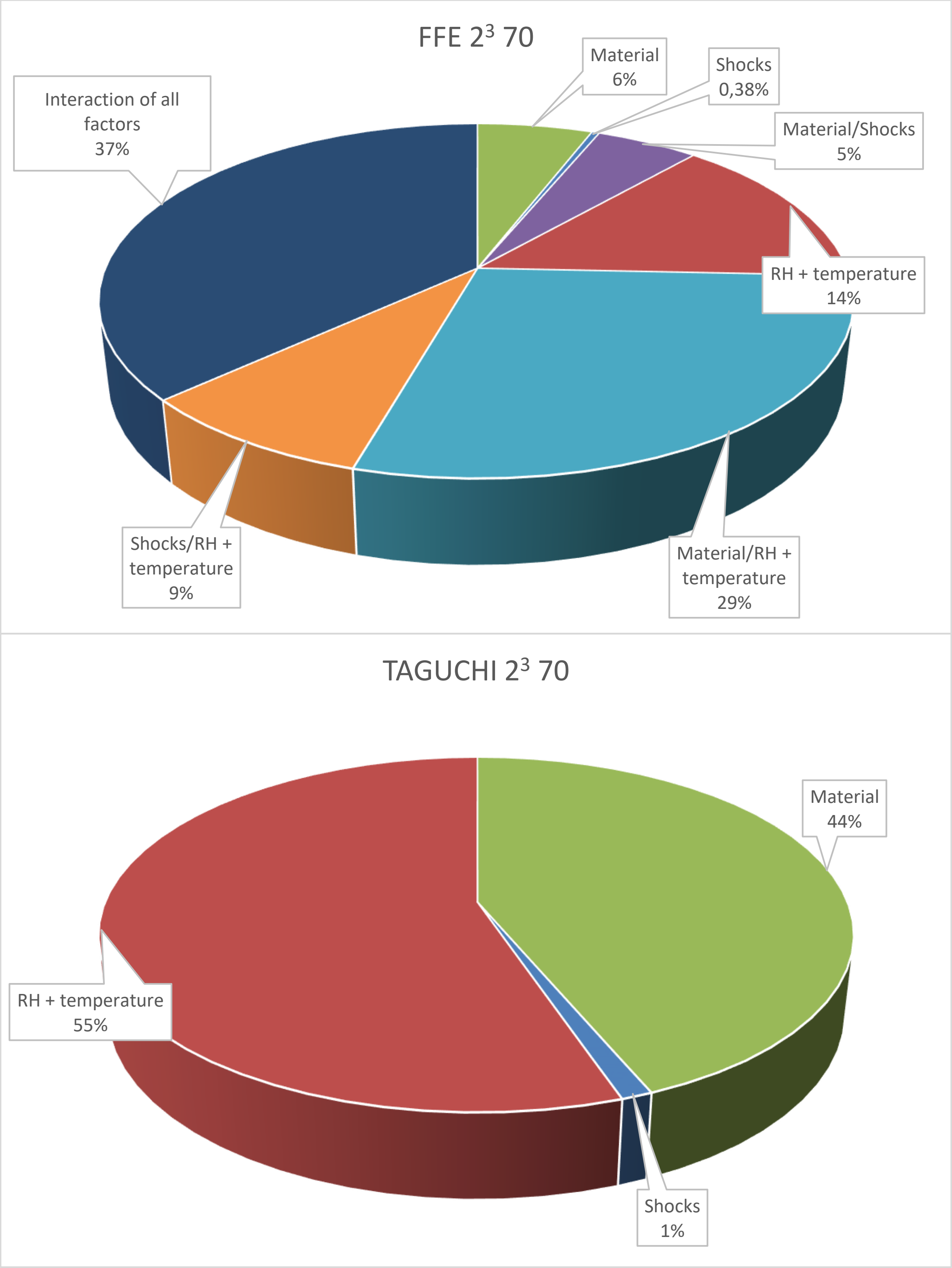

Figure 28. *Pie charts showing the influences of factors/interaction calculated using the FFE approach (top) and Taguchi approach (bottom) - 70 ECA*

Discussion about the results in Conclusion.

11. Conclusion

The goal of the work was to show the efficiency of using Taguchi orthogonal arrays and full factorial experiments for the evaluation of tests of electrically conductive adhesives.

In the theoretical part, ECAs in general together with some basics of quality engineering were given. At the end of the thesis practical usage of the FFEs and TOAs and is shown and described.

In the experimental part an experiment based on the adhesive assembly of 0R0 resistors on the test boards using different types of adhesives is presented. Three different types of ECAs and two different types of pads surface finishes (gold/copper) were used. This gave six sets of samples. The resistance of each of the joint was measured before and after the climatic treatment and the relative change the resistance was monitored. The joints having the resistance higher than 600 mΩ before the climatic treatment were not considered in the experiment. The climatic treatment (or climatic stress testing/aging) had the form of thermal shocks (acting as one factor with two levels – levels being the number of thermal shocks applied to the joint) and aging in a chamber with relative humidity of 80 % and 80 °C (acting as the second factor with two levels – levels being the time of the climatic treatment in the chamber). The whole experiment took around 60 (with the bulk of this time spent measuring individual resistance of each joint) hours in the span of two months.

Originally, an experiment with three factors (each with two levels) with the third factor being the material of the conductive tracks on the PCBs (two levels – gold and copper) was planned. However, this factor is a qualitative one unlike the previous two. One key difference between the FFEs and TOAs, is that The FFEs can lead to the calculation of a mathematical model of the process (for this purpose we have prepared special joint samples to test the model on). To construct such model, all factors need to be quantifiable, which is not the case if a third material factor is added in this thesis. Other problem is that TOAs and FFEs start to substantially differ only once you go above the two factors with two levels (i.e. we need at least three factors of two levels, two factors of three levels or any other “higher” combination). That is why it has been decided to go for a compromise and to evaluate both 2^3 and 2^2 TOA vs. FFE. The first gives the ability to properly compare the two approaches and the second gives the ability to fully utilize FFEs and to calculate a mathematical model of the process.

The final resistance of the joints after the first climatic load (thermal shocks) was mostly higher than before. We did do some measurements after the thermal shocks before the climatic RH/temp chamber and in some instances, especially for Permacol adhesive, it seemed to improve the resistance (lower it). This could mean that the thermal shocks actually “finished” the hardening of some of the joints or forced some of the metal particles closer to each other thus decreasing the final resistance.

However, it is possible to conclude, in general, that the resistance of the adhesive joints can not be improved by this type of the thermal treatment, because a low number of samples decreased their joint resistances. The test samples were, after the treatment by the thermal shocks, climatically aged at the temperature of 80 ^{o}C and at the relative humidity of 80 % The final values of the adhesive joint resistances are shown in Appendix C (relative values in Appendix D).

For the two-factor calculations, the interactions (contrasts) calculated using FFEs and TOAs are shown in Figure 19 to Figure 23. The first thing to notice is that the contrasts calculated using FFEs are almost identical to those calculated using TOAs. This is consistent with the fact that for 2^2 type of experiment both approaches are quite similar.

The big difference is the added influence of interaction considered in FFE. They clearly prevail in the case of adhesive 70 on copper and adhesive 15S on gold. Both types of adhesives, 15S and 70, were quite difficult to measure after the climatic load. It is possible to see from Table 11 that the amount of considered joints had to be reduced drastically because a lot of them got destroyed or were unmeasurable.

As for the mathematical model, we prepared six PCBs (each adhesive/material combination) that were tested using special third level of each of the two factors (data can be reviewed in Table 16). Even though we had limited data after the climatic tests to construct a linear model and a limited amount of data was available to test the model, a good quality model was calculated. In the bottom part of Table 16 are the compared measured results and results calculated using mathematical models (one model for each adhesive/material combination). For three of the six models the results were almost identical.

The conclusion for two factors with two levels type of experiments used for ECA testing is that FFE seems to be more viable in every way. Both TOA and FFE can be used but the added benefit of interaction influence and linear model from FFE means that this approach is strictly better. TOA does not lead to the reduction of the final number of experiments that must be done. The benefits of using TOA will be reflected in a higher number of factors and their levels.

For the three-factor type of experiment, we can view the final influences in Figure 26Figure 27 and Figure 28. For both Permacol and 15S adhesives very similar contrasts calculated using FFEs and TOAs were found. The drawback of the experiment of the type 2^3 is that only a limited number of measured values could be used for the calculations – 18 for Permacol and 8 for both 70 and 15S adhesives. The Permacol adhesive having the biggest statistical sample showed again the expected results of RH and temperature as a major influence. In the case of 15S there were lot of trouble measuring the joints formed on copper after the climatic load. Itis quite clearly shown in the pie chart – material had over 50 % influence. The adhesive of the type 70 shows the greatest differences between the TOA and FFE, which can be attributed to the low statistical sample and overall problems with the measurements of these joints. Since the third factor is not quantifiable, we did not get a mathematical model out of the FFE here. As for which method is more suitable, there does not seem to be any reason to use FFEs unless we aim to obtain a mathematical model or are set on finding out the influence of interactions. The results seem to be quite similar for 15S and Permacol and in the case of the adhesive of the type 70, they seem to not be correct.

The final conclusion is that TOAs seem quite viable for the testing purposes of ECAs above the 2^2 types of experiment – we did obtain very similar results with FFEs and with TOAs with our 2^3 experiment but in case of TOAs only had to conduct half of the number of experiments. In the case of 2^2 there is virtually no reason to use TOAs since the number of experiments that needs to be performed is the same as in the case of FFE. However, the added benefit when using the FFEs is the possibility to calculate a mathematical model together with the calculation of influences of interactions. Both approaches are viable when testing ECAs, but it needs to be on quite a large statistical sample when testing the climatic aging –many of the joints were destroyed. The reason is that the adhesives were used after their shelf time. As for the climatic load, it can be concluded that the climatic treatment at the higher temperature and relative humidity had a stronger effect on worsening (increase) the joint resistance than the thermal shocks. It can be explained by the fact that the modification of the epoxy resin by the thermal shocks is lower that by combination of the higher temperature together with the higher humidity. It is known that the epoxy resin is wetted under these conditions. This generates silver hydrides, which degrade contacts between the filler particles and thereby increases the resistance of the joints.

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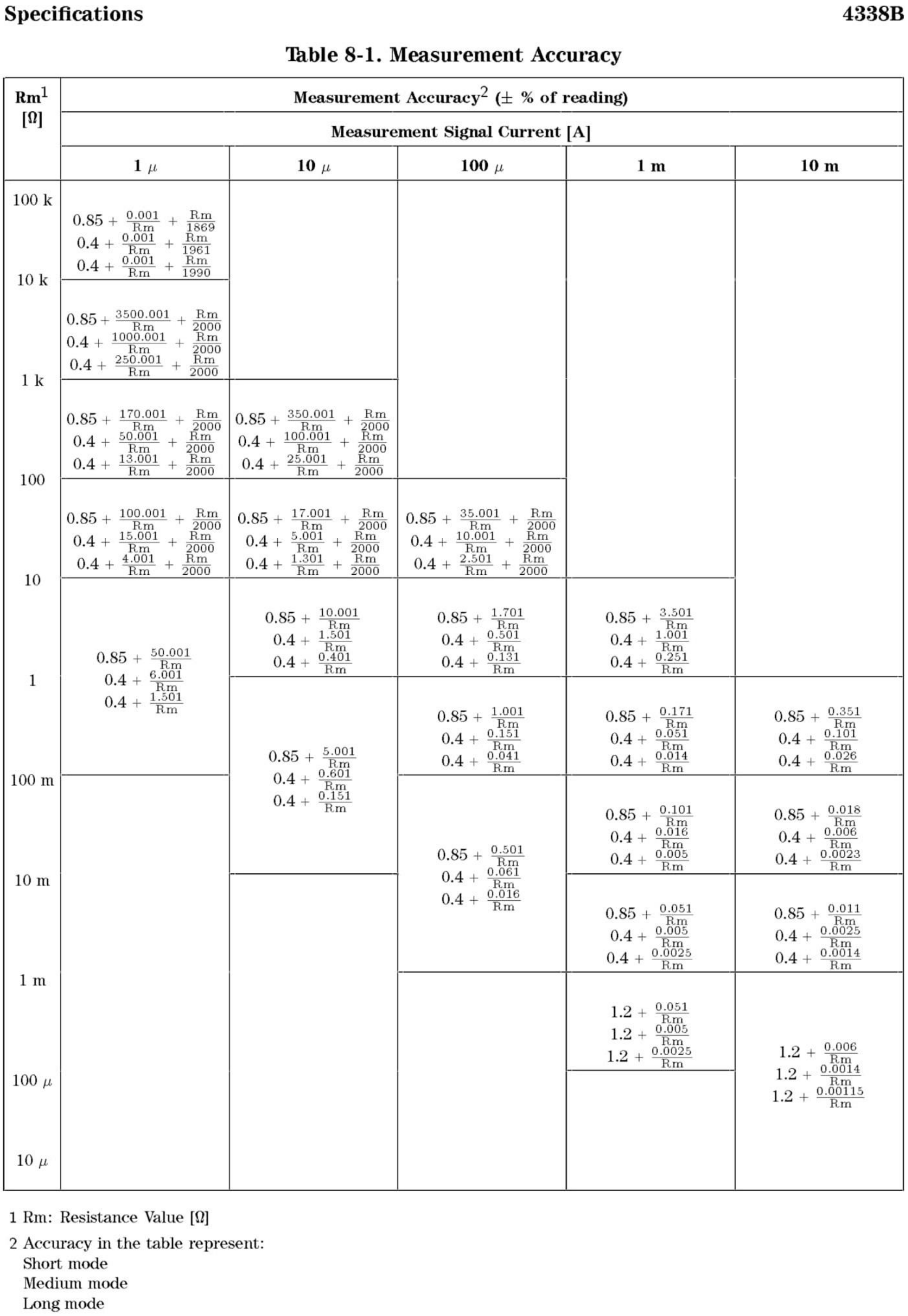
13. Appendix A – Milliohm measuring error

The table for calculating measuring error of the Agilent HP 4338B Milliohm meter taken from the official manual. [40]



Specifications **4338B**

Table 8-1. Measurement Accuracy

Rm[1] [Ω]	Measurement Accuracy[2] (± % of reading)				
	Measurement Signal Current [A]				
	1 µ	10 µ	100 µ	1 m	10 m
100 k – 10 k	$0.85 + \frac{0.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{1869}$ $0.4 + \frac{0.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{1961}$ $0.4 + \frac{0.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{1990}$				
10 k – 1 k	$0.85 + \frac{3500.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{1000.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{250.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$				
1 k – 100	$0.85 + \frac{170.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{50.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{13.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$	$0.85 + \frac{350.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{100.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{25.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$			
100 – 10	$0.85 + \frac{100.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{15.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{4.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$	$0.85 + \frac{17.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{5.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{1.301}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$	$0.85 + \frac{35.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{10.001}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$ $0.4 + \frac{2.501}{\mathrm{Rm}} + \frac{\mathrm{Rm}}{2000}$		
10 – 1	$0.85 + \frac{50.001}{\mathrm{Rm}}$ $0.4 + \frac{6.001}{\mathrm{Rm}}$ $0.4 + \frac{1.501}{\mathrm{Rm}}$	$0.85 + \frac{10.001}{\mathrm{Rm}}$ $0.4 + \frac{1.501}{\mathrm{Rm}}$ $0.4 + \frac{0.401}{\mathrm{Rm}}$	$0.85 + \frac{1.701}{\mathrm{Rm}}$ $0.4 + \frac{0.501}{\mathrm{Rm}}$ $0.4 + \frac{0.131}{\mathrm{Rm}}$	$0.85 + \frac{3.501}{\mathrm{Rm}}$ $0.4 + \frac{1.001}{\mathrm{Rm}}$ $0.4 + \frac{0.251}{\mathrm{Rm}}$	
1 – 100 m		$0.85 + \frac{5.001}{\mathrm{Rm}}$ $0.4 + \frac{0.601}{\mathrm{Rm}}$ $0.4 + \frac{0.151}{\mathrm{Rm}}$	$0.85 + \frac{1.001}{\mathrm{Rm}}$ $0.4 + \frac{0.151}{\mathrm{Rm}}$ $0.4 + \frac{0.041}{\mathrm{Rm}}$	$0.85 + \frac{0.171}{\mathrm{Rm}}$ $0.4 + \frac{0.051}{\mathrm{Rm}}$ $0.4 + \frac{0.014}{\mathrm{Rm}}$	$0.85 + \frac{0.351}{\mathrm{Rm}}$ $0.4 + \frac{0.101}{\mathrm{Rm}}$ $0.4 + \frac{0.026}{\mathrm{Rm}}$
100 m – 10 m			$0.85 + \frac{0.501}{\mathrm{Rm}}$ $0.4 + \frac{0.061}{\mathrm{Rm}}$ $0.4 + \frac{0.016}{\mathrm{Rm}}$	$0.85 + \frac{0.101}{\mathrm{Rm}}$ $0.4 + \frac{0.016}{\mathrm{Rm}}$ $0.4 + \frac{0.005}{\mathrm{Rm}}$	$0.85 + \frac{0.018}{\mathrm{Rm}}$ $0.4 + \frac{0.006}{\mathrm{Rm}}$ $0.4 + \frac{0.0023}{\mathrm{Rm}}$
10 m – 1 m				$0.85 + \frac{0.051}{\mathrm{Rm}}$ $0.4 + \frac{0.005}{\mathrm{Rm}}$ $0.4 + \frac{0.0025}{\mathrm{Rm}}$	$0.85 + \frac{0.011}{\mathrm{Rm}}$ $0.4 + \frac{0.0025}{\mathrm{Rm}}$ $0.4 + \frac{0.0014}{\mathrm{Rm}}$
1 m – 100 µ				$1.2 + \frac{0.051}{\mathrm{Rm}}$ $1.2 + \frac{0.005}{\mathrm{Rm}}$ $1.2 + \frac{0.0025}{\mathrm{Rm}}$	$1.2 + \frac{0.006}{\mathrm{Rm}}$ $1.2 + \frac{0.0014}{\mathrm{Rm}}$ $1.2 + \frac{0.00115}{\mathrm{Rm}}$
100 µ – 10 µ					

1 Rm: Resistance Value [Ω]

2 Accuracy in the table represent:
Short mode
Medium mode
Long mode

Figure 29. *The table for measurement error for the milliohm meter Agilent HP 4338B* ***[40]***

14. Appendix B – Resistance values before the climatic load

The bold numbers in the second line of the tab represent the numbered marks on each PCB board so we can tell them apart. *No resistor* in a cell means that the resistor fell off the PCB during manipulation. Small letter *n* represents that we were unable to obtain a value here (the value shown on the display usually did not make any sense).

Table 21. *Resistance values of Perma joints on gold PCBs before the climatic load*

PERMA	**gold**	**[mΩ]**											
24	**7**	**8**	**9**	**10**	**11**	**2**	**13**	**15**	**16**	**17**	**19**	**22**	**5**
627	110	400	42	185	65	430	45	545	72	143	533	49	130
225	350	440	76	314	150	250	320	1160	104	470	3290	28	100
120	150	140	180	670	728	85	56	595	70	30	382	95	850
660	320	4900	1110	725	1090	420	297	5200	925	224	234	30	710
95	200	95	135	148	922	40	97	57	50	100	25	18	22
1220	260	3950	252	105	454	430	174	220	650	1650	1610	29	102
135	110	85	185	87	2000	1170	30	86	214	589	110	33	52
325	256	1410	440	598	198	428	42	74	470	1050	118	70	1610
465	80	590	96	460	1570	128	85	27	56	15	13	45	68
740	1015	7426	338	1160	6400	9000	470	78	98	48	343	22	549
213	85	242	7822	210	580	750	340	609	140	258	410	no R	149
310	305	930	535	207	440	604	290	254	410	458	88	no R	122
60	574	1380	870	448	274	992	45	82	827	5220	45	no R	37
98	1680	1520	590	958	920	2000	27	193	225	2520	44	no R	8610
90	150	230	460	1150	170	38	90	294	95	91	47	no R	55
92	312	96	1250	5350	508	3264	92	94	2110	536	206	no R	91
168	330	998	177	475	425	135	445	102	60	105	179	no R	47
125	950	218	350	87	870	292	1256	280	15	418	207	no R	203
190	220	292	66	835	274	96	261	980	277	95	205	no R	82
545	140	35	20	180	203	105	220	1420	156	19	45143	no R	188

Table 22. *Resistance values of Perma joints on copper PCBs before the climatic load*

PERMA	**copper**	**[mΩ]**											
13	**14**	**17**	**20**	**21**	**22**	**23**	**1**	**9**	**12**	**4**	**2**	**3**	**10**
337	1600	1190	200	950	360	670	307	438	397	386	681	n	249
736	1200	253	95	1270	225	660	763	190	990	570	502	n	267
1870	320	342	380	340	476	407	370	437	374	529	1170	n	1014
510	153	950	890	7510	523	450	1000	354	573	908	925	n	660
355	256	2400	340	770	473	382	270	230	1700	366	990	n	2660
520	237	1270	725	480	1048	550	690	340	1280	842	371	n	951
570	1500	890	248	841	750	860	472	924	785	902	501	n	1960
1900	4700	1900	55	1618	1540	4500	846	1600	1150	1650	299	n	1520
720	570	620	385	135	180	201	570	478	640	695	205	n	1250
410	370	3900	540	907	172	202	201	702	1000	458	559	n	681
330	670	660	680	860	350	313	570	1300	844	962	257	542	1290
242	423	45	430	377	187	229	82	1140	317	290	490	245	592
950	1060	731	540	1330	2700	510	400	608	2380	2160	1240	425	3050
760	1050	4040	2300	840	1460	526	645	623	494	2580	1920	472	1290
890	350	760	690	890	3890	960	336	893	1710	1017	1330	333	1450
920	335	59080	270	276	384	551	266	504	630	1060	1830	517	831
910	1300	825	900	1000	14900	1600	906	507	2730	766	373	365	824
990	401	220	4800	872	20000	16400	1400	211	1540	2170	458	3250	585
570	659	2600	1900	120	710	832	900	534	650	1300	678	339	937
450	250	495	2000	525	89	176	631	279	261	1045	495	244	397

Table 23. *Resistance values of 15S joints on gold PCBs before the climatic load*

15S	**gold**	**[mΩ]**									
14	**15**	**20**	**21**	**17**	**13**	**2**	**5**	**7**	**8**	**12**	**11**
651	870	3200	754	4500	1760	2480	10600	950	600	18000	755
432	396	500	3900	540	1150	3800	350	702	1200	891	1406
635	560	2600	520	310	697	8200	368	1240	500	390	540
8000	540	540	680	328	320	470	186	475	280	853	929
950	740	1060	274	226	610	660	330	460	400	363	2900
480	370	530	616	269	420	1100	430	135	490	806	353
210	860	324	530	962	1580	959	335	6570	3400	342	441
5200	410	397	1330	410	580	1400	489	250	335	1400	452
527	270	1320	4700	385	230	790	445	700	543	657	600
1030	400	819	375	440	260	977	420	440	1070	725	3045
2000	550	373	770	620	880	2000	1010	548	1240	207	685
1200	300	7100	410	500	6000	505	513	1000	9600	425	499
260	328	415	820	240	1290	790	381	4300	790	932	473
143	4780	149	303	564	1350	310	700	1100	1800	288	841
242	381	2400	107	80	6100	415	149	3300	1900	1200	365
448	190	195	251	333	420	249	498	260	215	421	618
2540	255	390	430	410	870	380	290	1070	1200	399	194
280	1020	305	1080	740	712	217	625	870	750	268	459
520	359	490	770	1700	3000	390	2700	1450	555	975	1110
1870	791	240	840	360	4000	650	130	797	290	400	326

Table 24. *Resistance values of 15S joints on copper PCBs before the climatic load*

15S	copper	[mΩ]								
4	**24**	**5**	**6**	**10**	**9**	**11**	**14**	**18**	**20**	**22**
3000	550	230	1850	732	583	903	834	322	2330	1360
1170	1017	32000	605	1430	n	280	360	254	373	570
340	820	610	324	728	38	1070	185	1600	1280	550
610	4200	299	221	329	445	830	460	402	194	418
262	420	1090	490	595	347	461	214	291	123	401
1025	960	785	499	193	132	619	239	330	390	407
770	306	7100	516	442	370	298	230	640	281	13100
487	428	2300	541	341	189	590	500	n	565	590
426	276	4500	307	338	816	437	406	288	246	310
1760	4150	376	2860	502	642	790	660	244	195	252
650	280	510	399	91	599	158	274	677	1840	329
212	1220	85	656	304	778	520	298	351	1080	2350
157	405	468	3260	615	293	102	770	267	220	444
458	413	465	891	n	2400	209	930	395	164	259
420	351	364	450	n	1300	771	727	536	276	202
345	324	1042	580	n	78	487	4500	2900	615	618
135	670	40	1025	n	225	500	90	128	195	804
232	338	981	834	n	414	246	701	287	525	299
260	902	359	471	n	534	242	243	280	940	396
632	596	476	283	n	548	2330	481	626	437	369

Table 25. *Resistance values of 70 joints on gold PCBs before the climatic load*

70	gold	[mΩ]										
13	**15**	**16**	**17**	**20**	**14**	**23**	**21**	**10**	**9**	**5**	**4**	**3**
7200	895	418	n	328	795	358	730	385	210	420	197	362
748	363	158	n	245	168	2990	138	6700	2330	223	75	1420
1980	960	639	165	n	258	60	263	193	2150	93	663	833
217	2380	806	205	n	330	177	492	1620	266	356	2360	90
1360	761	1900	990	2740	207	278	155	184	6950	933	121	827
280	93	480	80	380	495	304	357	590	3934	910	238	163
2440	1290	7000	713	210	1100	50	151	434	957	743	12000	289
295	2310	233	390	305	452	188	245	545	525	110	254	411
2740	519	131	n	n	695	360	170	246	127	427	346	3260
946	579	590	n	n	598	5500	1050	933	1003	279	329	402
215	479	918	n	90	240	327	no R	240	2530	n	287	212
1100	224	310	n	122	514	258	no R	290	4500	n	358	320
762	2170	5030	185	475	482	177	no R	319	454	n	541	206
590	172	723	310	130	256	129	no R	2990	381	n	112	326
415	644	2848	218	311	983	270	no R	247	811	n	184	415
161	504	715	219	306	1090	6100	no R	577	261	n	154	216
1140	277	635	150	336	235	238	no R	1570	3650	n	339	196
550	368	1013	1380	172	115	130	no R	493	1260	n	247	357
1160	420	354	n	814	1480	265	no R	906	n	n	148	2810
507	2500	190	n	290	420	252	no R	40	n	n	111	238

Table 26. *Resistance values of 70 joints on copper PCBs before the climatic load*

70	**copper**	**[mΩ]**								
18	**21**	**22**	**13**	**24**	**14**	**16**	**17**	**11**	**6**	**9**
n	382	231	n	no R	399	82	151	197	86	715
n	745	2250	n	no R	120	176	1960	684	75	2010
n	1030	142	n	190	138	207	61	132	140	112
n	9000	428	n	345	266	172	430	390	38	52
n	168	2600	n	75	382	181	227	304	704	153
n	183	409	n	223	240	451	130	1710	202	147
n	418	94	n	1477	223	209	79	158	226	132
n	1067	359	n	372	81	2200	25	199	67	257
n	12000	1170	n	3900	232	70	682	163	102	257
n	3700	468	n	426	273	129	1730	186	98	159
1370	504	384	1600	182	126	304	1550	62	187	377
2700	763	1280	432	143	117	190	1050	337	225	292
45	322	188	668	449	277	118	1120	128	165	1190
84	627	1240	111	620	6500	631	1078	669	143	597
34	976	318	204	470	300	59	905	205	4030	962
176	3300	1700	615	193	275	2900	258	663	49	3760
93	239	47	455	160	1570	287	332	1400	132	67
167	386	1800	680	122	687	416	274	113	2500	72
2800	132	575	557	no R	1382	157	1080	109	348	140
440	313	503	2300	no R	167	208	279	306	768	171

15. Appendix C – Resistance values after the climatic load

Below we can see the resistance values of all the joints after the climatic load. Small letter *x* represents values that did not fulfil the 600 mΩ limit. Letter *n* represents joints that we were not able to measure (we did not get any value or the value displayed did not make any sense). Red values represent joints that were above the 600 mΩ limit, but got below it after the climatic load. Blue values are joints where it was necessary to use the four-sensing method shown in Figure 11 and then divide the final value by two.

Table 27. *Resistance values of Perma joints on gold PCBs after the climatic load*

PERMA	**gold**	**[mΩ]**										
10 shocks							**40 shocks**					
168 hours			**336 hours**				**168 hours**			**336 hours**		
24	**7**	**9**	**8**	**10**	**11**	**2**	**16**	**17**	**19**	**13**	**22**	**5**
x	73	132	523	234	380	860	99	14	98	10	11	58
367	139	30	852	182	592	800	290	86	x	18	35	35
66	340	180	211	125	x	280	54	17	45	83	33	149
69	n	x	x	204	x	730	432	n	39	108	25	107
240	99	44	136	173	x	27	21	26	56	76	9	38
150	n	44	x	313	338	295	60	480	50	61	73	174
147	490	253	n	183	x	284	96	24	112	240	172	90
94	312	113	x	216	380	213	52	103	n	107	68	25
n	632	64	n	1250	x	1056	121	40	13	115	104	450
327	430	76	x	x	x	655	66	44	174	20	177	16
930	477	x	60	599	3800	17	62	221	200	17	x	704
490	178	620	x	22000	890	120	7	93	87	12	x	45
124	598	670	x	620	604	100	x	371	74	27	x	62
32	220	141	x	x	x	24	96	56	320	445	x	157
36	750	94	515	x	3500	22	51	93	44	880	x	560
113	240	52	104	x	5470	90	92	101	393	83	x	213
315	320	n	x	78	1440	n	78	17	74	55	x	53
31	525	200	565	87	x	n	34	210	64	176	x	173
140	620	210	970	x	1990	115	297	22	861	30	x	340
118	48	90	64	2420	1300	890	215	63	x	18	x	105

Table 28. *Resistance values of Perma joints on copper PCBs after the climatic load*

PERMA	copper	[mΩ]										
10 shocks						40 shocks						
168 hours			336 hours			168 hours				336 hours		
13	**14**	**21**	**17**	**20**	**23**	**4**	**2**	**3**	**10**	**1**	**9**	**12**
310	500	x	27000	140	x	1230	370	x	n	24000	658	600
250	1004	x	27000	140	x	125	n	100	n	x	1070	600
x	n	n	450	550	5800	248	x	516	x	1600	557	365
660	820	x	450	550	5800	521	x	x	x	x	1176	365
890	500	x	x	2500	n	720	x	180	x	2300	982	x
980	1000	n	x	2500	n	x	990	x	x	x	1390	x
880	x	x	x	n	x	x	n	x	x	2000	x	x
160	x	x	x	n	x	x	n	x	x	x	x	x
70	420	n	4800	8000	557	x	232	x	x	440	1500	x
n	n	x	4800	8000	557	330	480	x	x	300	x	x
740	x	x	14400	1850	1700	1045	1070	400	x	512	x	1000
840	n	377	14400	1850	1700	300	490	1050	n	540	x	1000
x	x	x	x	15000	3300	x	x	550	x	454	x	2340
x	x	x	x	15000	3300	x	x	570	x	x	x	2340
x	850	640	x	x	x	x	x	1122	84	634	x	x
x	800	1150	x	n	n	x	x	1260	x	2700	5000	x
x	x	860	1740	x	x	x	201	1040	x	x	250	x
x	n	x	1740	x	x	x	806	x	n	x	160	x
1080	x	104	2525	x	x	x	x	n	x	x	534	875
n	211	n	2525	x	n	372	n	n	n	x	1020	875

Table 29. *Resistance values of 15S joints on gold PCBs after the climatic load*

15S	gold	[mΩ]								
10 shocks					40 shocks					
168 hours		336 hours			168 hours			336 hours		
15	17	14	20	21	2	5	7	13	8	11
x	x	x	x	x	x	x	425	x	437	393
420	4500	220	x	515	x	6600	x	529	365	123
390	2900	x	254	x	x	12900	x	x	284	326
2100	4700	7500	x	x	n	11000	2200	240	218	330
x	1300	x	2190	x	x	1500	652	442	164	307
815	2900	22000	438	100	x	4700	680	250	3340	929
x	x	1800	1960	1330	x	902	720	x	210	686
1090	11000	3760	x	x	x	1400	110	960	360	382
1120	232	x	155	1500	x	2600	381	425	127	563
250	1000	x	1050	x	x	712	1580	616	160	709
2200	x	4200	x	x	x	x	1200	x	200	128
220	420	247	860	x	40000	160	x	x	470	324
1260	2700	2650	x	n	x	7300	305	x	165	2170
x	182	22000	3400	n	2400	380	x	535	433	x
10900	262	x	107	n	8500	190	x	x	x	906
890	305	23000	160	n	n	2800	2200	288	320	230
390	515	2500	575	1300	3000	722	x	580	x	835
x	x	8700	x	1600	354	621	x	240	325	617
418	x	1040	290	342	73	512	x	x	170	x
646	202	970	x	351	147	467	x	707	92	670

Table 30. *Resistance values of 15S joints on copper PCBs after the climatic load*

15S	**copper**	**[mΩ]**							
10 shocks					**40 shocks**				
168 hours		**336 hours**			**168 hours**		**336 hours**		
24	**9**	**4**	**6**	**10**	**20**	**22**	**11**	**14**	**18**
n	n	1400	x	x	x	x	505	1500	n
x	x	1400	x	x	n	n	640	1720	n
x	105	1800	n	x	x	n	600	n	n
x	7000	970	n	6000	n	n	600	n	n
n	n	2600	n	24000	n	n	461	1750	1420
x	n	2600	n	5200	n	n	x	1750	4500
n	n	x	n	50000	3000	x	n	n	730
n	n	1600	n	10000	880	n	n	n	x
n	x	1570	n	13000	1000	12500	500	5500	6900
x	x	x	x	n	1000	12500	500	2700	3400
4500	n	1940	n	4000	x	1800	550	n	x
2600	x	865	x	n	x	1800	550	n	n
n	n	996	x	x	n	8000	2000	2800	n
n	x	n	x	x	n	8000	2000	2800	n
n	x	1240	n	x	n	n	8000	750	2000
n	n	3900	n	x	x	x	8000	750	2000
x	20000	4200	x	x	n	x	13500	1150	n
n	18000	1300	x	x	n	n	13500	1150	n
6000	2000	2000	n	10000	x	1800	1300	2400	n
6000	20000	2000	n	10000	n	1800	1300	2400	x

Table 31. *Resistance values of 70 joints on gold PCBs after the climatic load*

70	**gold**	**[mΩ]**										
10 shocks						**40 shocks**						
168 hours			**336 hours**			**168 hours**		**336 hours**				
16	**17**	**20**	**13**	**15**	**14**	**4**	**3**	**23**	**21**	**9**	**5**
13400	x	n	x	140	x	1300	n	n	x	13000	74
13400	x	n	x	2700	n	1300	x	x	1130	4750	1670
x	2100	x	x	490	n	x	x	40000	121	x	77
x	2100	x	n	x	n	x	n	40000	5200	n	750
7500	2400	x	15000	x	7000	n	x	n	12000	x	x
7500	2400	n	15000	n	7000	n	n	n	1400	x	x
5000	x	2300	x	x	1350	x	n	2850	33000	x	x
5000	n	2300	n	x	1350	n	n	2850	1600	n	n
1750	x	x	x	n	10000	12500	x	n	1600	750	n
1750	x	x	x	n	10000	12500	n	x	700	750	n
x	x	7100	1500	n	592	5500	2750	13000	x	x	550
n	x	7100	350	n	140	5500	2750	13000	x	x	x
x	1050	2250	x	x	n	n	n	2900	x	n	494
x	1050	2250	n	n	n	n	n	2900	x	n	x
x	n	n	n	7000	n	n	n	n	x	x	77
x	n	n	n	7000	n	n	n	x	x	n	x
x	n	n	x	n	1700	n	n	1050	x	x	x
x	x	n	n	n	1700	n	n	1050	x	x	x
n	x	x	x	n	x	n	x	2100	x	x	x
n	x	n	n	x	n	n	n	2100	x	x	x

Table 32. *Resistance values of 70 joints on copper PCBs after the climatic load*

70	**copper**	**[mΩ]**							
10 shocks						**40 shocks**			
168 hours			**336 hours**			**168 hours**		**336 hours**	
22	**13**	**24**	**18**	**21**	**14**	**11**	**6**	**16**	**9**
n	x	x	x	2200	23000	n	1500	260	x
x	x	x	x	240	220	x	444	400	x
3150	3800	n	x	x	750	2900	325	1100	409
3150	3800	n	x	x	1600	2900	115	3900	126
x	1800	n	x	n	1450	n	x	n	586
n	1800	5400	x	n	380	x	2000	n	n
1400	x	x	x	n	270	46	1230	390	1160
1400	x	n	x	x	n	450	1217	4600	662
x	1400	x	x	x	n	900	564	174	34600
n	1400	n	x	x	1100	900	365	6800	9000
n	x	2900	x	n	n	1200	160	n	n
x	n	809	x	x	n	1200	7900	n	n
n	1000	14000	3100	n	n	1800	827	390	x
x	1000	x	3100	x	n	1800	2100	600	n
n	5500	8600	n	x	3000	n	x	n	x
x	5500	2080	n	x	1370	x	815	x	x
n	n	3500	900	1250	20000	x	1700	43000	3300
x	x	648	900	5800	1580	n	x	43000	310
4150	2700	x	6000	3500	1460	10000	5000	1200	1800
4150	2700	x	6000	800	420	10000	x	660	588

16. Appendix D – FFE/Taguchi tables with relative resistance values

Values in the table are calculated according to equation (57). Letter *x* represents values above the 600 mΩ limit or joints where we were not able to obtain a value**. We can form a 2^3 table by putting left and right table together (with “material” being the third factor – gold/copper)!**

Table 33. *2^2 FFE/Taguchi table for Perma gold (left) and copper (right) with relative resistances*

Perma gold			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
x	1,31	1,38	0,22
1,63	1,94	2,79	0,6
0,55	1,51	0,77	1,48
x	x	x	0,36
2,53	1,43	0,42	0,78
x	x	x	0,35
1,9	x	0,45	8
0,29	x	0,11	2,55
x	x	2,16	1,35
x	x	0,67	0,4
4,37	0,25	0,44	0,5
1,58	x	0,2	0,4
2,7	x	x	0,6
0,33	x	0,43	16,48
0,4	2,24	0,54	9,78
1,23	1,8	x	0,9
1,88	x	1,3	0,12
0,25	2,59	2,27	x
0,74	3,32	1,7	0,11
0,22	1,83	1,38	0,8
0,66	1,26	0,1	0,22
0,4	0,58	0,18	1,25
2,27	x	0,57	0,35
x	x	x	0,83
0,5	1,17	0,26	0,5
x	2,98	x	2,52
4,45	2,1	0,4	5,21
1,22	0,36	x	0,97
7,9	2,72	2,67	2,31
x	x	0,92	8,5
5,61	2,85	0,86	x
0,58	16,28	0,2	x
1,4	1,38	x	x
x	x	x	x
5	x	1,2	x

Perma copper			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
0,92	x	3,19	78,18
x	16,72	0,22	x
x	1,32	0,47	4,32
1,29	x	x	x
2,51	x	1,97	8,52
1,88	x	x	x
1,54	x	x	4,24
x	x	x	x
x	x	x	0,77
x	x	0,72	1,49
2,24	x	x	0,9
3,47	32	1,3	6,59
x	x	x	1,14
x	x	x	x
x	x	x	1,89
x	x	x	1,15
x	x	x	x
x	7,91	x	x
1,89	x	x	x
x	5,1	x	x
x	0,7	x	1,5
x	1,47	x	5,63
x	1,45	x	1,27
5,36	x	x	3,32
1,95	7,35	x	4,27
4,22	x	2,67	4,9
x	x	x	x
x	x	x	x
0,74	2,78	1,13	3,14
x	14,81	0,86	x
x	x	4,16	x
x	4,3	1	x
x	27,78	x	x
x	x	x	x
2,43	x	x	x

0,77	x	0,19	x		2,39	x	x	9,92
0,97	0,16	0,16	x		x	x	0,54	0,49
x	1	0,5	x		x	x	1,76	0,76
2,82	x	0,23	x		x	x	x	1
0,34	13,44	3,32	x		0,84	x	x	3,66
3,14	5,85	0,18	0,45		x	x	x	1,51
0,39	3,95	x	0,35		x	x	x	x
1	x	0,12	x		x	14,25	x	0,98
x	x	0,17	x		x	12,89	x	0,64
0,33	x	2,24	1,73		x	x	x	x
0,17	0,74	x	1,71		x	x	x	x
1,37	x	1,2	1,73		x	x	x	x
0,26	1,92	x	x		x	x	x	x
0,67	x	1	6,62		x	2,77	x	x
0,22	x	0,51	0,3		x	2,76	x	x
x	6,55	0,49	4,72		x	5,43	0,74	x
1,16	2,2	0,99	0,37		1	7,42	4,29	3,15
x	2,2	1,64	1,68		x	6,47	1,29	x
0,24	x	7,27	x		x	6,27	1,21	4,74
0,2	2,59	0,94	1,18		x	x	3,37	x
x	1,77	1,91	2,34		4,17	x	2,44	x
x	3,39	0,41	1,13		x	x	2,85	x
0,57	x	0,31	0,85		x	x	x	x
3,18	7,26	4,2	4,15		0,87	x	x	x
4,5	6,4	x	0,56		x	x	x	3,35
	2						x	
	3,2						x	
	3,29						x	
	1,74						x	
	0,68						x	
	0,69						x	
	x						x	
	0,50						x	
	8,25						x	
	x						x	
	x						x	
	x						x	
	x						x	
	x						x	
	0,58						x	
	x						x	
	x						x	
	x						x	
	1,20						x	
	8,48						x	

Table 34. *2^2 FFE/Taguchi table for 15S gold (left) and copper (right) with relative resistances*

15S gold			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
x	x	x	x
1,6	1,19	x	x
0,7	x	x	x
3,89	x	x	0,75
x	x	x	x
2,2	0,21	x	0,6
x	6,33	x	x
2,66	x	x	1,66
4,15	2,85	x	1,85
0,63	x	x	2,37
4	x	x	x
0,73	x	79,21	x
3,84	x	x	x
x	x	7,74	x
28,61	x	2,48	x
4,68	x	x	0,69
1,53	x	7,89	x
x	5,71	1,63	x
1,16	0,66	0,19	x
x	x	x	x
x	x	x	0,73
8,33	0,44	18,86	x
9,35	x	35,5	0,57
14,33	13,89	59,14	0,78
5,75	x	4,55	0,41
1,78	41,51	1,93	6,82
x	5,56	2,69	x
26,83	9,47	2,86	1,7
0,6	x	5,84	0,23
2,27	x	1,7	x
x	11,26	x	x
0,84	x	0,31	x
11,25	6,39	19,16	x
0,32	147,65	x	x
3,28	x	1,28	x
0,92	117,95	5,62	1,49
1,26	6,41	2,49	x
x	28,52	x	x
x	2,12	x	0,31
0,56	4,4	3,59	0,32
	x	x	x
	x	x	x
	0,49	x	0,6

15S copper			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
x	x	x	x
x	x	x	2,29
x	5,29	x	x
x	x	x	x
x	9,92	x	1
x	x	x	x
x	x	1,68	x
x	3,29	1,56	x
x	3,69	4,7	1,14
x	x	5,13	x
16,7	x	x	3,48
x	4,8	x	1,6
x	6,34	x	19,61
x	x	x	9,57
x	2,95	x	x
x	11,3	x	16,43
x	31,11	x	27
x	5,6	x	54,88
x	7,69	x	5,37
1,7	x	x	x
x	x	x	x
x	x	x	4,78
2,76	x	x	x
15,73	x	x	x
x	x	x	8,18
x	x	x	7,32
x	x	x	x
x	x	x	x
x	x	4,32	13,55
x	x	49,6	x
x	x	5,47	x
x	x	x	x
x	x	18,2	x
x	x	3,89	x
x	x	x	x
x	x	x	x
88,89	x	x	12,78
43,48	x	x	x
3,75	x	4,55	9,88
36,5	x	4,88	4,99
	x		x
	x		x
	x		x

x	4,63	x	18,24	x
7,99	1,42	x	4,34	4,88
x	5,4	2,63	26,94	13,64
3,7	x	1,56	113,12	x
x	0,44	0,85	29,33	x
x	x	0,94	38,46	23,96
2,8	3,59	x	x	13,93
x	2,19	x	43,96	x
2,1	x	0,65	x	x
x	x	4,59	x	x
11,22	x	x	x	x
1	x	2,48	x	3,73
0,64	8,46	x	x	x
1,34	x	4,3	x	x
x	x	1,34	x	x
x	x	x	x	x
x	x	2,6	x	x

Table 35. *2^2 FFE/Taguchi table for 70 gold (left) and copper (right) with relative resistances*

70 gold			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
32,6	x	6,6	x
84,81	x	17,33	x
x	x	x	666,67
x	x	x	225,99
x	x	x	x
15,63	53,57	x	x
x	x	x	57
21,46	x	x	15,16
13,36	x	36,13	x
2,97	x	37,99	x
x	6,98	19,16	39,76
x	x	15,36	5,39
x	x	x	16,38
x	x	x	22,48
x	x	x	x
x	x	x	x
x	x	x	4,41
x	x	x	8,8
x	x	x	7,92
x	x	x	8,33
x	x	x	x
x	7,44	x	8,19
12,73	x	x	0,46
1,24	x	x	1,57
x	x	x	77,42
3	x	x	3,92
x	x	x	218,54
x	x	x	6,53
x	x	x	9,41
x	x	x	x
x	x	12,97	x
x	x	8,59	x
5,68	x	x	x
3,39	x	x	x
x	x	x	x
x	13,89	x	x
x	x	x	x
x	x	x	x
x	x	x	x
x	x	x	x
x	x		61,9
x	x		x
x	x		x

70 copper			
10 shocks		40 shocks	
168 hrs	336 hrs	168 hrs	336 hrs
x	x	x	3,17
x	x	x	2,27
22,18	x	21,97	5,31
7,36	x	7,44	22,67
x	x	x	x
x	x	x	x
14,89	x	0,29	1,87
3,9	x	2,26	x
x	x	5,52	2,49
x	x	4,84	52,71
x	x	19,35	x
x	x	3,56	x
x	68,89	14,6	3,31
x	36,9	x	x
x	x	x	x
x	x	x	x
x	9,68	x	x
x	5,39	x	x
7,22	x	91,74	7,64
8,25	13,64	32,68	3,17
x	5,76	17,44	x
x	x	5,92	x
x	x	2,32	3,65
x	x	3,3	2,42
x	x	x	3,83
x	x	9,9	x
x	x	5,44	8,79
x	x	18,16	2,58
x	x	5,53	x
x	x	3,72	56,6
x	x	0,86	x
x	x	35,11	x
x	x	5,1	x
9,1	x	14,69	x
26,96	x	x	x
x	x	16,63	x
x	5,23	12,88	49,25
x	15,3	x	4,31
4,85	26,52	14,37	12,86
x	2,56	x	3,44
x	57,64		
x	1,83		
x	5,43		

x	x	x		x	6,2
x	33,82	x		x	3,8
x	14,14	x		24,22	1,58
1,95	x	x		x	1,21
7,54	2,99	x		x	x
x	x	5,91		x	x
x	16,72	x		x	4,3
78,89	2,47	x		15,93	x
58,2	0,27	x		5,66	x
4,74	x	x		31,18	x
17,31	x	x		x	x
x	x	x		18,3	1
x	x	x		1,78	4,98
x	7,23	x		21,88	x
x	14,78	x		5,31	x
x	x	x		x	x
x	x	x		x	2,51
		0,18			
		7,49			
		0,83			
		2,11			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			
		x			