University Politehnica Timișoara
Faculty of Management in Production and Transportation
Management Department

HABILITATION THESIS

Contributions on Development of Quality Engineering and Management with Applications in the Theory of Attractive Quality and Six Sigma Methodology

Research field: Engineering and Management

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A. REZUMAT

Conceptul de cadru didactic universitar implică atât o activitate didactică susținută cât și o activitate ştiinţifică validată prin cărți, studii, cercetări și lucrări ştiinţifice. Domeniul Ingineriei si Managementului Calității reprezintă un atribut esențial în dezvoltarea culturii inginerești și manageriale a viitorului inginer licențiat precum și a masterandului în inginerie și management.

Prezenta teză de abilitare relevă capacitățile și performanțele didactice și de cercetare ale candidatului dr.ing. Adrian Pavel Pugna, care ocupă în prezent o funcție didactică de conferențiar universitar în statul de funcțiuni al Departamentului de Management al Facultății de Manangement în Producție și Transporturi de la Universitatea Politehnica Timișoara, dezvoltate după susținerea publică a tezei de doctorat și până în prezent. Teza de abilitare se focalizeză, în principal, pe acele realizări care atestă capacitatea autorului de a desfășura și conduce activități de cercetare științifică în domeniul Inginerie și Management, cu aplicații în Teoria Calității Atractive și Metodologia Six Sigma.

În cei aproape 30 de ani de **activitate didactică**, candidatul și-a dezvoltat capacitățile și performanțele didactice, desfășurând toate tipurile de activități: seminar, laborator, proiect, curs, îndrumare la elaborarea de lucrări de diplomă și disertație etc., urcând scara ierarhică a funcțiilor didactice. Canditatul a contribuit la elaborarea de lucrări didactice, manuale universitare și îndrumătoare pentru lucrări aplicative.

În ceea ce privește **activitatea managerială**, candidatul a fost 5 ani membru în Consiliul Departamentului de Management, fiind membru al Biroului Consiliului Departamentului precum și coordonatorul comisiei pentru evaluarea și asigurarea calității și de asemenea, candidatul a fost 12 ani membru al Consiliului Profesoral al FMPT, unde a îndeplinit funcția de coordonator al comisiei pentru evaluarea și asigurarea calității. De asemenea, candidatul a fost (și este și în prezent) președintele Board-ului masterului Ingineria și Managementul Competitivității precum cum și membru în board-urilor masterelor Ingineria și Managementul Calității și Competitivității (limba engleză), Ingineria și Managementul Sistemelor Logistice, Management Antreprenorial în Administrarea Afacerilor.

Prezentarea rezultatelor obținute în **activitatea de cercetare** a candidatului ocupă cea mai mare parte a conținutului tezei de abilitare. Teza de abilitare este structurată pe 3 direcții de cercetare importante și de mare actualitate în domeniul Ingineriei și Managementului, așa cum rezultă din literatura de specialitate:

1. Teoria Calității Atractive;
2. Metodologia Six Sigma;
3. Aplicații moderne ale proiectării experimentelor.

În prima parte a tezei se prezintă bazele Teoriei Calității Atractive precum și contribuțiile candidatului la dezvoltarea de noi modele principiale și aplicative în acest domeniu. În 2015, candidatul a contribuit la realizarea unui nou model pentru proiectarea produselor și serviciilor noi . Modelul HWWP (Health – Weapon - Wealth – Prospect) face legătura între piramida lui Maslow (Maslow's hierarchy of needs), Modelul și metodologia Kano, importanța dorințelor clienților și coeficientul satisfacșiei clientului (SC). Acest model reprezintă o contribuție teoretică fundamentală la dezvoltarea modelului Kano și un punct de referință pentru cercetări ulterioare. În 2016 candidatul a contribuit la realizarea unui model HWWP rafinat, bazat pe partiția neuniformă cu curbe de elasticitate. În 2016, candidatul a contribuit la dezvoltarea unei abordări strategice pentru analiza variațiilor între nevoile potențiale ale clienților pentru o mai bună înțelegere ce "elemente de calitate" trebuie cultivate înainte de lansarea produsului sau serviciului, numită, " A Greenhouse Approach for Value Cultivation" sau modelul Greenhouse. În 2020, candidatul a contribuit la realizarea unui model HWWP generalizat. Tot în 2020, candidatul a contribuit la realizarea unui nou model pentru evaluarea "vocii studenților" în etapa de dezvoltare a unei aplicații pentru telefonul mobil, numit modelul HWWP – DDDI.

În partea a doua a tezei se prezintă elementele fundamentale ce stau la baza metodologiei Six Sigma. De asemenea se prezintă câteva din realizările candidatului în ceea ce privește aplicarea metodologiei Six Sigma în industria Automotive.

În partea a 3-a se prezintă elementele fundamentale ale proiectării experimentelor, cu accent pe metodologiile Taguchi și RSM (Response Surface Methodology). Sunt prezentate câteva din contribuțiile candidatului la utilizarea acestor metodologii la realizarea și încercarea pieselor din bazalt sinterizat precum și la realizarea nanopartipulelor de TiO_2 dopate cu argint.

Rezultatele activității de cercetare ale candidatului au fost prezentate în cadrul unor manifestări academice și științifice naționale și internaționale, prin articole publicate în reviste sau în volumele de lucrări ale conferințelor.

Candidatul a publicat un număr de 117 de articole. Distribuția pe categorii de publicaţii a acestor lucrări este după cum urmează:

- **4 în reviste indexate în baza de date Web of Science (Clarivate Analytics);**
- **29 la conferințe internaționale indexate în baza de date Web of Science (Clarivate Analytics).**
- 13 în reviste și volume indexate în alte baze de date internaționale (BDI);
- 71 în reviste sau volume neindexate în BDI;

De asemenea, candidatul este coautor la 1 carte la o editură internațională, coautor la 5 capitole în cărți la edituri internaționale, autor și coautor la 9 cărți la edituri naționale recunoscute și autor și coautor la 8 materiale didactice inclusiv în format electronic - suport de curs/îndrumare.

A doua parte a acestei secțiuni prezintă perspectivele de dezvoltare.

Ultima parte a acestei secțiuni prezintă referințele bibliografice.

A. ABSTRACT

The concept of University Professor involves both a sustained teaching activity and a scientific activity validated through books, studies, research, and scientific papers. The field of Engineering and Quality Management is an essential attribute in the development of the engineering and managerial culture of the future licensed engineer as well as of the master student in engineering and management.

The present habilitation thesis reveals the didactic and research capacities and performances of the candidate Adrian Pavel Pugna, Ph.D. who currently holds a teaching position as an Associate Professor in the staff of the Department of Management of the Faculty of Management in Production and Transport at the University Politehnica Timisoara, developed after the public defense of his doctoral thesis.

The habilitation thesis focuses mainly on those achievements that attest to the author's ability to conduct and conduct scientific research in the field of Engineering and Management, with applications in Attractive Quality Theory and Six Sigma Methodology.

In the almost 30 years of teaching activity, the candidate has developed his teaching skills and performances, carrying out all types of activities: seminar, laboratory, project, course, guidance in the elaboration of diploma and dissertation papers, etc. teaching functions. The candidate contributed to the elaboration of didactic works, university textbooks, and tutorials for applied works.

Regarding the **managerial activity**, the candidate was 5 years member of the Board of the Management Department, is a member of the Bureau of the Department Council as well as the coordinator of the commission for evaluation and quality assurance and also the candidate was 12 years member of the Faculty Council of FMPT, where he served as coordinator of the commission for evaluation and quality assurance. Also, the candidate was (and is currently) the chairman of the Board of the master's degree in Engineering and Competitiveness Management as well as a member of the boards of the masters of Engineering and Management of Quality and Competitiveness (English), Logistics Systems Management and Engineering in Business Administration.

The presentation of the results obtained in the research activity of the candidate occupies most of the content of the habilitation thesis. The habilitation thesis is structured on 3 important and highly topical research directions in the field of Engineering and Management, as it results from the specialized literature:

1. Theory of Attractive Quality;
2. Six Sigma Methodology;
3. Modern applications of experimental design.

The first part of the thesis presents the bases of the Theory of Attractive Quality as well as the candidate's contributions to the development of new and applied models in this research field. In 2015, the candidate contributed to the development of a new model for the design of new products and services. The HWWP (Health - Weapon - Wealth - Prospect) model which connects Maslow's pyramid (Maslow's hierarchy of needs), the Kano model and methodology, the importance of customer wants and the customer satisfaction coefficient (SC). This model represents a fundamental theoretical contribution to the development of the Kano model and a reference point for further research. In 2016 the candidate contributed to the realization of a refined HWWP model, based on the non-uniform partition with elasticity curves. In 2016, the candidate contributed to the development of a strategic approach to analyzing variations in potential customer needs for a better understanding of what "quality elements" need to be cultivated before launching the product or service, called "A Greenhouse Approach for Value Cultivation" or the Greenhouse model. In 2020, the candidate contributed to the realization of a generalized HWWP model. Also in 2020, the candidate contributed to the development of a new model for evaluating the "student voice" in the development stage of a mobile phone application, called the HWWP - DDDI model.

The second part of the thesis presents the fundamental elements underlying the Six Sigma methodology. It also presents some of the candidate's achievements in the application of the Six Sigma methodology in the Automotive industry.

Part 3 presents the fundamentals of experimental design, with emphasis on Taguchi and RSM (Response Surface Methodology) methodologies. Some of the candidate's contributions to the use of these methodologies in the production and testing of sintered basalt parts as well as in the production of silver-doped TiO_2 nanoparticles are presented.

The results of the candidate's research activity were presented in national and international academic and scientific events, through articles published in journals or the volumes of conference papers.

The candidate published 117 articles. The distribution by publication categories of these works is as follows:

- **4 in journals indexed in the Web of Science database (Clarivate Analytics);**
- **29 at international conferences indexed in the Web of Science database (Clarivate Analytics).**
- 13 in journals and volumes indexed in other international databases (BDI);
- 71 in journals or volumes not indexed in BDI;

Also, the candidate is co-author of 1 book at an international publishing house, co-author of 5 chapters in books at international publishing houses, author and co-author of 9 books at recognized national publishing houses, and author and co-author of 8 teaching materials including in electronic format - course support /guidance.

The **second part** of this section presents development perspectives.

The **last part** of this section presents the bibliographic references.

B. RESEARCH RESULT

1. Theory of Attractive Quality

1.1 Introduction

Voice of Customer (VOC) is the statement made by the customer on a particular product or service reflecting its voice, expectations, preferences, or comments (International Six Sigma Institute™, http://www.sixsigma-institute.org).

Capturing Voice Of Customer (VOC) is very important because customers are the ones who buy, use or transform either products or services and are the ones who receive the process output, regardless if they are internal customers (the ones who are internal to the organization, e.g Management, Employee(s) or Any Functional Department) or external customers (are not a part of the organization but use product(s) or service(s) or have invested interest in the organization, e.g. Clients, End-Users or Shareholders).

It is very important to distinguish between customer's "needs" and "wants". "Needs" are desires or expectations of a customer from a given product or service Unfortunately are expressed often vague and generally are "wants" from a product/service. It is important to separate "needs" and "wants" because the first ones are critical features of products or services and the second ones are expectations that are beyond "needs". If "needs" are not met by the products or services, the customers will be highly disappointed, and is a high probability they will switch to the competition. If "wants are" not met, the customers may only be highly displeased or dissatisfied but will remain loyal to the brand, products, or services. "Requirements" are attributes of the product or service which fulfill the "needs" of customers. From the customer's perspective, "requirements" are a "must" and therefore, as explained above, the customers may buy the products or services if "requirements" are met, even if the "wants" are met or not met. Voice of Customer (VOC) methodology can be used to capture the customer needs – both current (stated needs) and latent (unstated needs). VOC methodology helps capture the needs of the customer through stated verbatim comments (customer voices). It helps translate verbatim comments (customer voices) into customer needs to product/service output characteristics (customer requirements).

1.1.1 Kano Model

KANO Analysis is about prioritizing customer requirements once they are established. Noriaki Kano (Kano et al., 1984) is the one who developed the "Customer Satisfaction Model" or Attractive Quality Model" (known as the Kano Model) which by a simple hierarchical scheme distinguishes between the essential and differentiating attributes related to the customer quality concepts.

Thus, the Kano Model focuses on differentiating the attributes of the product and not how it was initially done on the needs of the customers. He also proposed a methodology for connecting customer responses to a special questionnaire. It is very important for organizations, especially those working on the development of new innovative products and services, to know the needs and requirements of their customers as quickly as possible.

The "Creating the Attractive Quality" approach, also known as the "Kano Model", came about as a result of questioning the traditional idea that by acting more intensively on a product or service, the customer will be even more satisfied. Noriaki Kano argued that the performance of a product or service is not equal in the eyes of customers, in the sense that the performance of certain categories of attributes of the products or services produces higher levels of satisfaction than others (International Six Sigma Institute™, http://www.sixsigma-institute.org).

Noriaki Kano improved the definition of quality by adding a new dimension to it, the previous definitions of quality up to that time were linear and one-dimensional (Figure 1.1.1). Noriaki Kano integrated the quality of a two-dimensional model, considering two dimensions: how a product or service behaves in terms of performance (X-axis), and the degree of user/customer satisfaction (Y-axis), as in figure 1.1.2.

Fig. 1.1.1 One-dimensional Quality

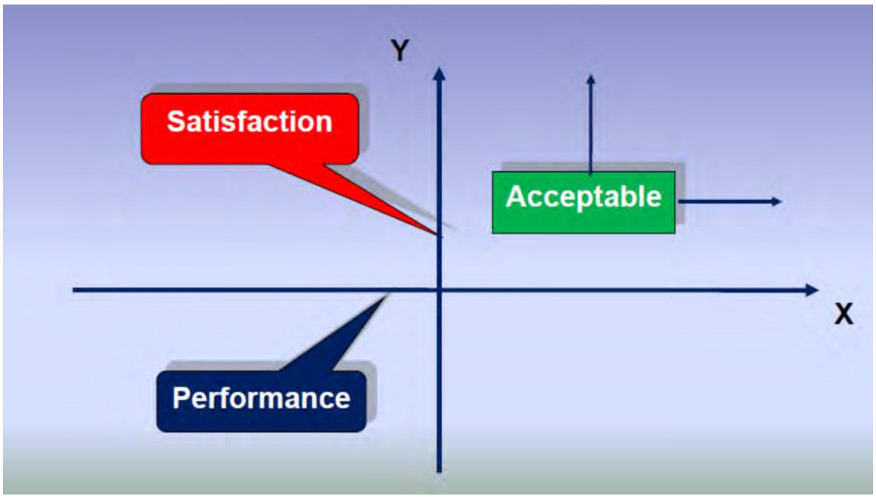


Fig. 1.1.2 Two-dimensional Quality

If customers are asked in the exploration phase only about their desires and the reasons for the purchase, the results are usually disappointing and the answers already are known. It is very important to analyze "*customer problems*" instead of analyzing "*customer wishes*". If customers are asked in the exploration phase only about their desires and the reasons for the purchase, the results are usually disappointing and the answers already are known. The expectations regarding the product, mentioned by the customers, are only the tip of the iceberg, being necessary to highlight the "hidden" needs and problems. A detailed analysis of the problems to be solved, the conditions, and the environment in which the product evolves can lead to information on further product developments (International Six Sigma Institute™, http://www.sixsigma-institute.org).

The elaboration of the Kano Model starts with a survey of customers based on questionnaires, they are asked about the attributes of the products and what perception they have so much that they have them sufficiently or insufficiently. A Kano survey asks 2 questions for each product attribute, resulting in the categories in table 1.1.1.

Tab. 1.1.1 Attribute categories according to the Kano Model

Physical state (degree of fulfiment)	Sufficient			
Insufficient	**User perception**	**Dissatisfied**	**Neutral**	**Satisfied**
	Dissatisfied	*Skeptic*	*Must Be*	*One-dimensional*
	Neutral	*Reverse*	*Indifferent*	*Attractive*
	Satisfied	*Reverse*	*Reverse*	*Skeptic* [385]

Basic Requirements are “Must-be’s”. They are the most important needs of customers. They are required and expected to be there. These are the needs the customer assumes will be met. When these requirements are unfulfilled, the customer is greatly dissatisfied and when fulfilled, the customer is neutral (i.e., they do not produce additional satisfaction).

For Performance Requirements there is a direct positive correlation that exists between satisfaction levels and the degree of presence. The more performance requirement elements needs are met, the better it is for the product or service. Indifferent elements are needs that result in neither satisfaction nor dissatisfaction whether they are present / met or not.

Reverse elements are needs that result in either dissatisfaction when they are fulfilled or satisfaction even when they are not fulfilled.

Delighter Requirements are “attractors” and their presence in a product/process is unexpected and fulfill the latent needs of a customer. They lead to great satisfaction if found present and the customer still is neutral (& not dissatisfied) when absent.

Skeptic (or Questionable) refers to the fact that there is some uncertainty in the customer's response. Noriaki Kano follows these categories with the phrase "*quality features*", meaning a high functional level of the requirements (Figure 1.1.3).

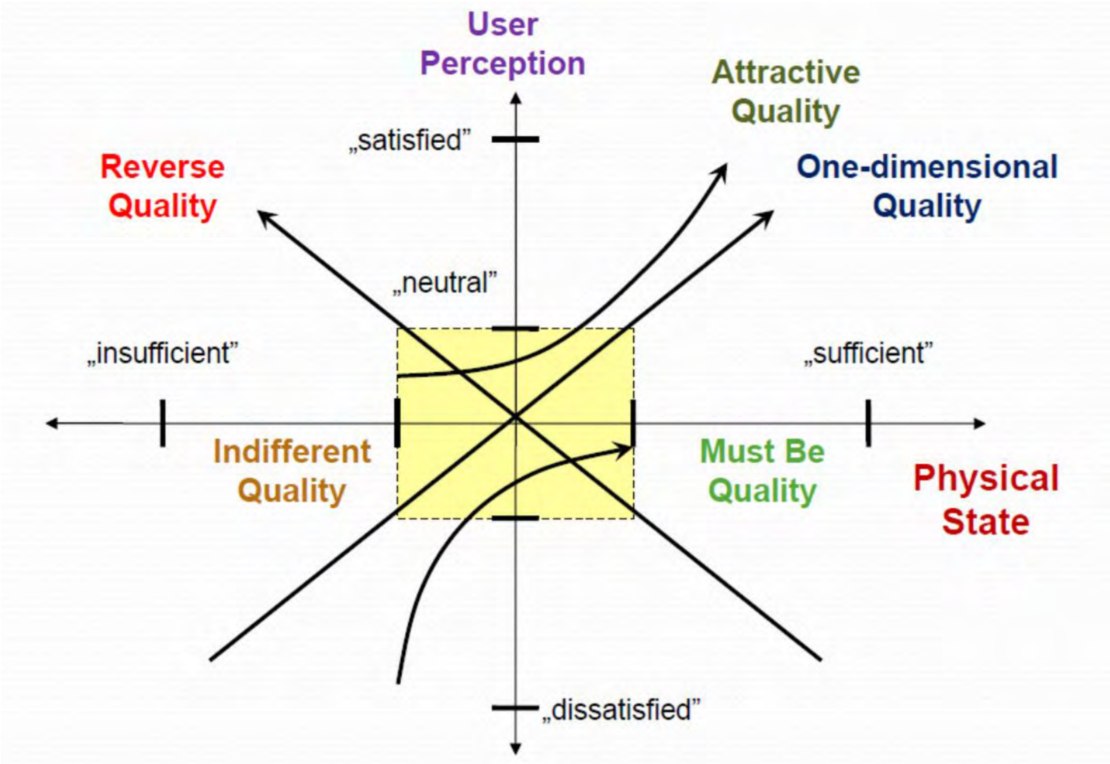


Fig. 1.1.3 Quality types according to the Kano requirements categories

It is accepted that the positions of the Kano requirements categories are changing over time (Figure 1.1.4).

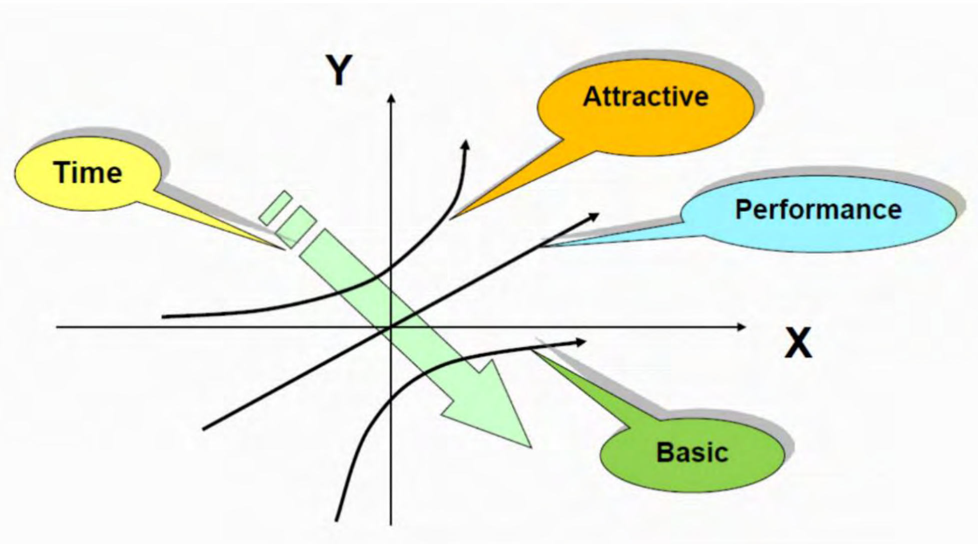


Fig. 1.1.4 Kano requirements categories over time

Another possibility to distinguish between the types of requirements that influence customer satisfaction is to answer in 5 different ways each pair of questions for each element of the product or service.

➢ *Construction of Kano questionnaires*

Table 1.1.2 presents functional/dysfunctional questions and five possible answers in the Kano survey and tables 1.1.3 and 1.1.4 presents the evaluation of pair questions in the Kano survey.

Tab. 1.1.2 Functional/dysfunctional questions and five possible answers in Kano survey

Functional form of the question	1. I like it that way 2. It must be this way 3. I'm neutral 4. It is acceptable in this way 5. I don't like it that way
Dysfunctional form of the question	1. I like it that way 2. It must be this way 3. I'm neutral 4. It is acceptable in this way 5. I don't like it that way

Tab. 1.1.3 Evaluation of pair questions in Kano survey

Customer requirements		Dysfunctional Questions (negative)				
		1.Satisfied	2.Must Be	3.Neutral	4.Acceptable	5.Dissatisfied
Functional Questions (positive)	1.Satisfied	*Skeptic*	*Attractive*	*Attractive*	*Attractive*	*One-dimensional*
	2.Must Be	*Reverse*	*Indifferent*	*Indifferent*	*Indifferent*	*Must Be*
	3.Neutral	*Reverse*	*Indifferent*	*Indifferent*	*Indifferent*	*Must Be*
	4.Acceptable	*Reverse*	*Indifferent*	*Indifferent*	*Indifferent*	*Must Be*
	5.Dissatisfied	*Reverse*	*Reverse*	*Reverse*	*Reverse*	*Skeptic*

Tab 1.1.4 Kano evaluation table

Customer Requirements → ↓		Dysfunctional				
		1. like	2. must-be	3. neutral	4. live with	5. dislike
Func-tional	1. like	Q	A	A	A	O
	2. must-be	R	I	I	I	M
	3. neutral	R	I	I	I	M
	4. live with	R	I	I	I	M
	5. dislike	R	R	R	R	Q

Customer Requirement is:

A: Attractive O: One-dimensional
M: Must-be Q: Questionable result
R: Reverse I: Indifferent

- *Testing Kano - type questionnaires*

When a Kano questionnaire is sent to multiple clients, it must be understood by all. First of all, ask the members who participate in the development of the Kano questionnaire to answer questions. Each member should think of a customer trying to predict what he or she would answer and what questions they might not understand. Then select people from within the organization and give them the questionnaire. Select a large variety of staff (managers, engineers, marketing staff, etc.). If the internal test signals something confusing, customers will likely notice the same thing. Review and retest the questionnaire by adding, if necessary, additional instructions.

- *Administration of Kano - type questionnaires*

Select the customers you want to interview, ensuring the representativeness of the sample. Decide how you want to send the questionnaires: telephone, fax, mail, e-mail, face-to-face, etc. The most used is the transmission by mail (if you opt for this mode, write a cover letter explaining the purpose of the survey and include supplemental instructions for clients). If you also use *Importance Questionnaires* with *Kano Questionnaires*, use the same sequence of questions in both to compare the two questionnaires more easily. Keep a log of the customers to whom questionnaires were sent and record the results as they arrive.

- *Processing the results*

Responses for each customer requirement in a Kano Questionnaire are tabulated according to figures 1.1.5.

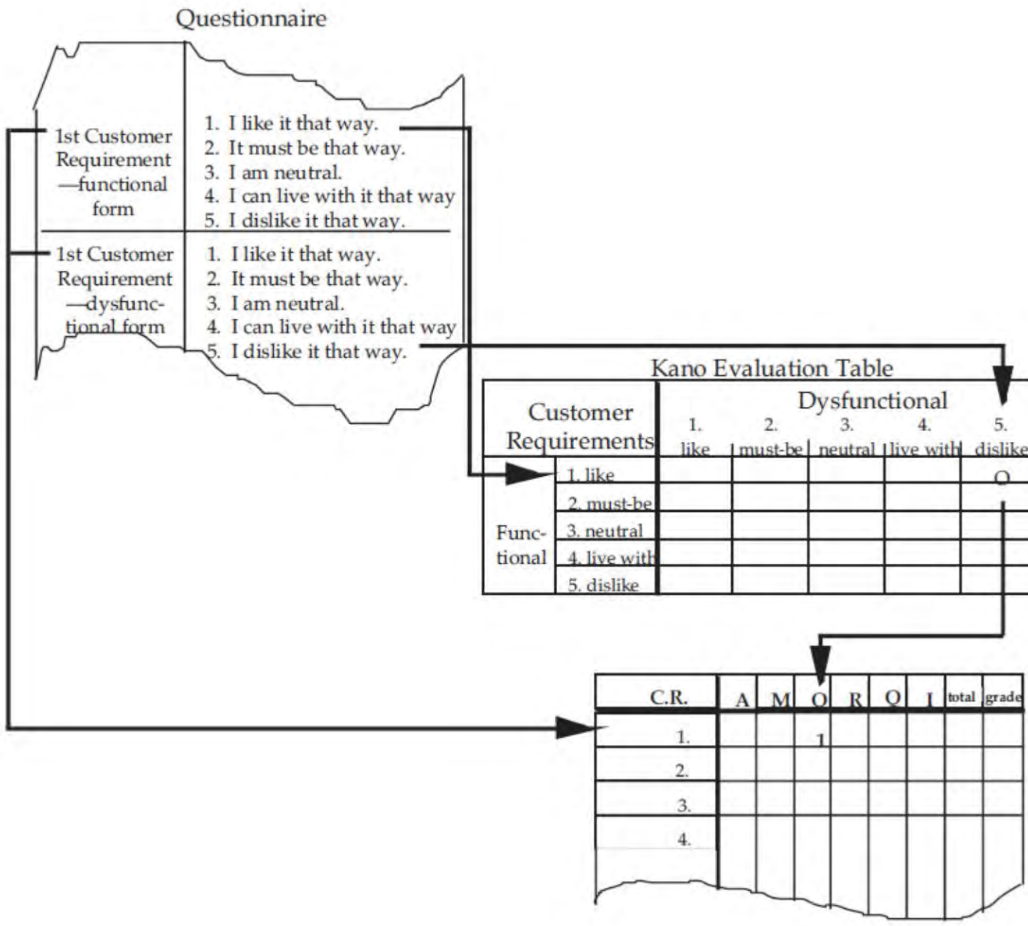


Fig. 1.1.5 Tabulation of Surveys

The easiest way to choose a category is to use the code that appears most often in the answers for a certain requirement (Customer Requirements – C.R.) - that is, the statistical mode of the answers is used. If any requirement receives a substantial number of Q (questionable) scores, the question must probably be temporarily removed from the analysis until the confusion with it is resolved or the respondents' thinking can be clarified. If most of the respondents give an R (reverse) scores to one of the requirements, this indicates that the market thinking about the question is opposed to the thinking of those who created the questionnaire.

- *Analyzing the results*

Benefits obtained by analyzing the data of the Kano questionnaire:

- ✓ A better understanding of customer requirements;

- ✓ Prioritizing the requirements for development activities;
- ✓ Detecting the characteristics of market segments;
- ✓ Helping the design process.

Answers should only be viewed as a guide, they do not provide exact answers as to which element should be included in the product or which requirement should not be fully met. It is usually desired to do a more in-depth analysis than the simple statistical mode.

When two Kano codes are equal in the evaluation of a question, it is considered:

- ✓ Contacting customers for additional information,
- ✓ Research for differences in market segmentation,
- ✓ Selecting the classification that will have the greatest impact on the product, using the order from relation (1.1.1).

$$\mathrm{M} > \mathrm{O} > \mathrm{A} > \mathrm{I} \tag{1.1.1}$$

Another way to study the data is to build a table with columns for the first, second and third most common responses (Table 1.1.5). Then the rows can be rearranged into groups according to the order according to relation (1.1.1) (Table 1.1.6).

Tab. 1.1.5 Spreadsheet of Most Frequent Responses to Customer Requirements

Customer requirement number	Most frequent response	Second most frequent response	Third most frequent response
1	A	O	
2	A	O	
3	M		
4	O	I	I
5	O	A	
6	M	A	
7	A	O	M
8	M		
9	O	M	I

Tab. 1.1.6 Spreadsheet of Customer Requirements Sorted in Order of Most Frequent Response

Customer requirement number	Most frequent response	Second most frequent response	Third most frequent response
8	M		
3	M		
6	M	A	
9	O	M	I
5	O	A	
4	O	A	
1	A	O	
7	A	O	M
2	A	O	I

If it is used in parallel with the Kano questionnaire a Self-stated Importance questionnaire, then the answers can be sorted based on it. If there are several requirements of customers whose rating was A, then the data from the Importance questionnaire can be used to sort in descending order of importance of these requirements.

As a general guide, it may be considered necessary:

- ✓ Meeting the M requirements,
- ✓ To be competitive with market leaders relative to O,
- ✓ To include for differentiation elements A.

➢ *The Self-stated Importance Questionnaire*

For each potential customer requirement included in the Kano questionnaire, a question is constructed in the Self-stated Importance Questionnaire in the general format:

"How important is it or would it be if: [requirement X]? (Table 1.1.7).

Tab. 1.1.7 Self-stated Importance Questionnaire

	Not at all important		Somewhat important		Important		Very important		Extremely important
How important is it or would it be if: The car has good gas mileage?	1	2	3	4	5	6	7	8	9
How important is it or would it be if: The car has good brakes?	1	2	3	4	5	6	7	8	9
How important is it or would it be if: The car has a long warranty period?	1	2	3	4	5	6	7	8	9
How important is it or would it be if: The car has a small turning radius?	1	2	3	4	5	6	7	8	9

➢ *Improvements in the Analysis of Results*

If the Kano questionnaire asks about very general functions, such as whether a machine must have 3 or 4 wheels or software must have a GUI (graphical user interface), each will have a specific opinion. However, if the Kano questionnaire asks about very specific functions, such as whether a machine must have ceramic valves or software must be compatible with a specific printer, then most respondents may be indifferent (I). Extremely detailed questions can increase the "*noise level*" to the level where all requirements are considered indifferent (**I**).

One way to change the simple statistical mode is if (**O** + **A** + **M**) > (**I** + **R** + **Q**), then the grade is maximum (**O**, **A**, **M**), if not, the grade is maximum (**I**, **R**, **Q**) (Table 1.1.8).

Tab 1.1.8 Modified Mode Statistic

C. R.	A	O	M	I	R	Q	total	grade
1.	19	18	18	20	2	3	90	A
2.	7	6	9	36	2	2	62	I
...								

There are some cases where the answers are "spread" over several categories or when divided differently into two categories, the grade is the same. In this case, the Mode Statistic is inadequate (Table 1.1.9). The idea is to reduce the data to 2 numbers, a positive one that gives the relative value of fulfilling the customers' requirements (customer satisfaction will increase by providing elements A and O) and a negative one, showing the relative cost of not meeting that requirement (customer satisfaction will decrease if elements O and M are not included).

Tab. 1.1.9 Example where Mode Statistic is inadequate

CR	A	M	O	R	Q	I	total	grade
1.	33	21	30			16	100	A
2.	90					10	100	A
3.	60					40	100	A

➢ *Customer Satisfaction Index – CSI*

The Customer Satisfaction Index (CSI) is a method (proposed by Berger et al. in 1993) to identify attribute classification according to the Kano model. It consists of the rate of customers who declare to be satisfied with the presence or sufficiency of attributes (SI - Satisfaction Index), as well as the rate of customers who declare to be dissatisfied with the lack or insufficiency of the attributes (DI - Dissatisfaction Index).

- ✓ If SI > 0.5 and DI < 0.5, the attribute is classified as A.
- ✓ If SI ≤ 0.5 and DI ≥ 0.5, it is classified as M.
- ✓ If SI > 0.5 and DI > 0.5, it is classified as O.
- ✓ If SI < 0.5 and DI < 0.5, it is classified as I (Neutral).

Coefficients of Customer Satisfaction (SC), Dissatisfaction (DC), and Total Satisfaction are presented in relation (1.1.2), (1.1.3), and (1.1.4).

$$SC = \frac{A+O}{A+O+M+I} \tag{1.1.2}$$

$$DC = \frac{O+M}{(A+O+M+I)\cdot(-1)} \tag{1.1.3}$$

$$TC = \frac{A-M}{A+O+M+I} \tag{1.1.4}$$

The (-) sign in front of the DC coefficient is to emphasize its negative influence on customer satisfaction if the quality level for this product is not reached. The positive coefficient SC takes values between “0” and “1”; the closer the value to “1”, the greater the influence on customer satisfaction. An SC coefficient approaching “0” means that there is very little influence. If DC approaches “-1”, the influence on customer dissatisfaction is very strong if the product attribute is not fulfilled. A value of approximately "0" means that that attribute does not cause dissatisfaction if it is not fulfilled.

- ✓ If TSC < 0, then the requirements are O,
- ✓ If TSC > 0.1, then the requirements are A,
- ✓ If TSC = 0, then the requirements are R.

➢ *Kano transformation table*

The Kano transformation table is presented in table 1.1.10.

Tab. 1.1.10 Kano transformation table

	I like	Must-be	Neutral	I live with	Dislike
Functional	4	2	0	-1	-2
Dysfunctional	-2	-1	0	2	4

The analysis form described in this section assumes the existence of Q pairs of questions, j = 1, ..., Q and N respondents, i = 1, ..., N. It is also assumed that the Kano Questionnaire is used in parallel with an Importance Questionnaire. Thus, there are three scores for each investigated customer requirement - Functional, Dysfunctional, and Importance. The 3 scores are coded as follows:

- **Functional**: Y_{ij} = -2 (Dislike), -1 (Live with), 0 (Neutral), 2 (Must-be), 4 (Like)

- **Dysfunctional**: X_{ij} = -2 (Like), -1 (Must be), 0 (Neutral), 2 (Live with), 4 (Dislike)
- **Importance**: W_{ij} = 1 (Not at all Important), ..., 9 (Extremely Important).

Note that X and Y take the values -2, -1, 0, 2, 4 The logic for the asymmetric scale (starting from -2, rather than from -4) is that "Must be" and "One-dimensional" are stronger answers than "Reverse" or "Questionable". That is why the scale should give less importance to less powerful responses to diminish their influence on the average. Reverse type answers are given less importance, being "drawn" to zero. The purest representations for the Reverse, Indifferent, One-dimensional, Must-be, and Attractive points are identified in this coordinate system with the points:

- Reverse: X = - 2, Y = - 2
- Indifferent: X = 0, Y = 0
- One-dimensional: X = 4, Y = 4
- Must-be: X = 4, Y = 0
- Attractive: X = 0, Y = 4

These points are shown in figure 1.1.6 (underlined and bold). All other combinations of XY points appear as interpolations between these points.

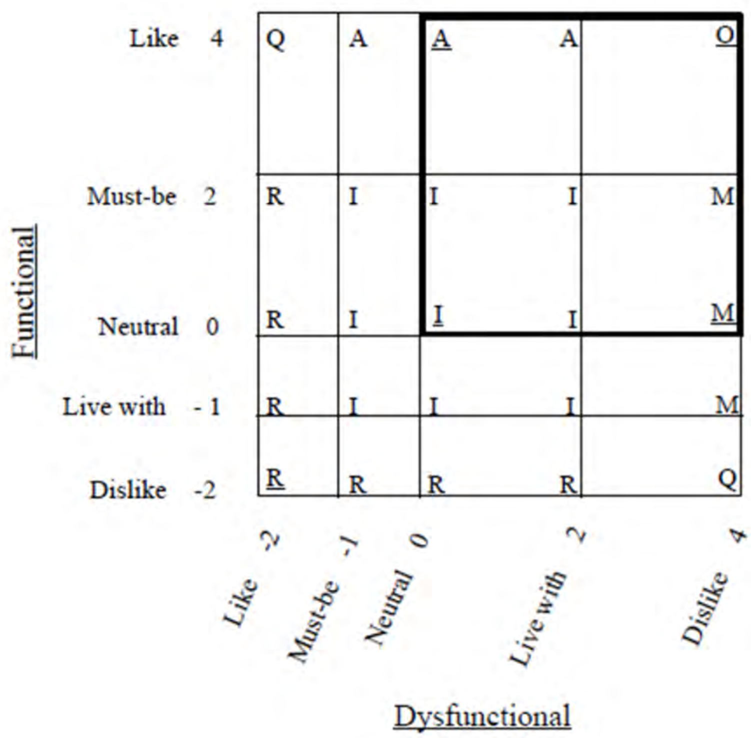


Fig. 1.1.6 Functional vs. Dysfunctional and Kano transformation

Calculate for all questions, j = 1, ..., Q, the mean of X (dysfunctional) and Y (functional) as in relations (1.1.5) and (1.1.6).

$$X_{avg}[j] = \frac{\sum_i X_{ij}}{N} \quad (1.1.5)$$

$$Y_{avg}[j] = \frac{\sum_i Y_{ij}}{N} \quad (1.1.6)$$

Represent the points Q (X_{avg} [j], Y_{avg} [j]), and use the number j as a symbol on the graph so that you can identify which question represents each point. Averages should fall between 0 and 4 because the negative values are either "Questionables" or "Reverses". "Questionables" will not be included in the media. "Reverses" can be transformed from this category by changing the meaning of the functional and dysfunctional questions for all the respondents. Otherwise, as described above, there will not be enough "Reverses" to "pull" the media to the negative.

In figure 1.1.7, the square in which Xave and Yave are between 0 and 4 is divided into quadrants, considering the prototype points Attractive, One-dimensional, Must-be, and Indifferent placed in the 4 corners. This square comes from the upper right corner of the figure 1.1.6.

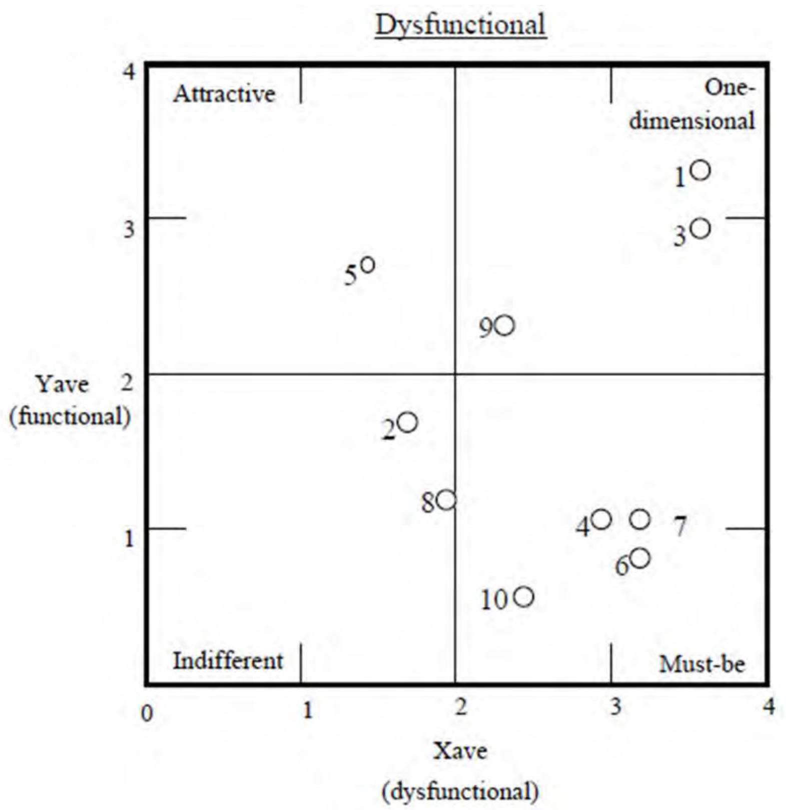


Fig. 1.1.7 Plots of Average Functionality and Average Dysfunctionality Points for Question J

From the Importance Questionnaire, the average importance is calculated for each question as in relation (1.1.7).

$$W_{avg}[j] = \frac{\sum_i W_{ij}}{N} \quad (1.1.6)$$

Represent the value near the points (Xavg [j], Yavg [j], as in figure 1.1.8. For example, draw a full circle, with the radius proportional to $(W_{avg}[j])^{1/2}$, so that the radius of the circle "j" will be proportional to W_{avg} [j]. As an alternative, represent the values of "j" used to identify the question in shades of gray, representing the value range for W_{avg}.

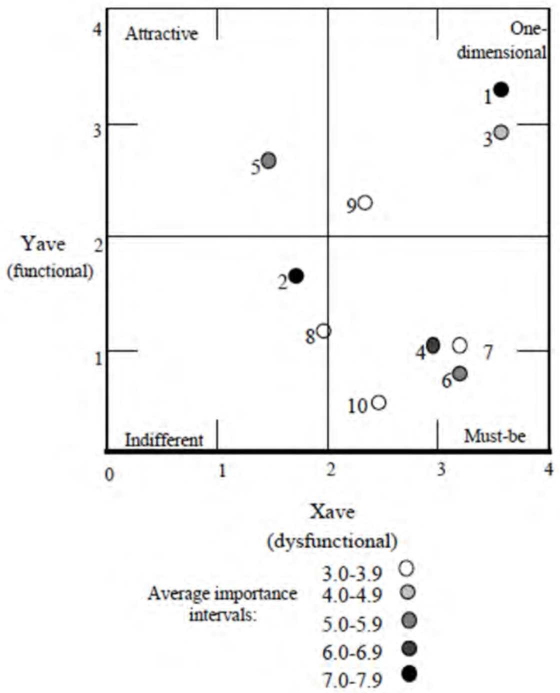


Fig. 1.1.8 Plots of Average Functionality and Average Dysfunctionality Points for Question *J* with Average Importance Indicated for Each Point

- *Hierarchy questionnaire*

An example of a Hierarchy Questionnaire is presented in figure 1.1.9.

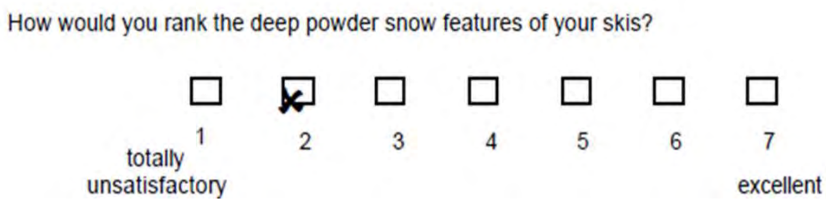


Fig. 1.1.9 Hierarchy questionnaire (example)

➢ *Quality Improvement Index*

It is very important for the strategy of product development, to know the quality of its product in relation to the strongest competitor. It is therefore useful not only to ask our customers to evaluate our product but also that of the competitor. The Quality Improvement Index (QI) is the ratio calculated by multiplying the relative significance of a product requirement (the Importance Questionnaire) with the difference between evaluating its product and that of the competitor through a Hierarchy Questionnaire.
QI = Relative importance x (own product evaluation - competition product evaluation).
An example of the Importance Questionnaire and Hierarchy Questionnaires (own and competitor's) is presented in figure 1.1.10.

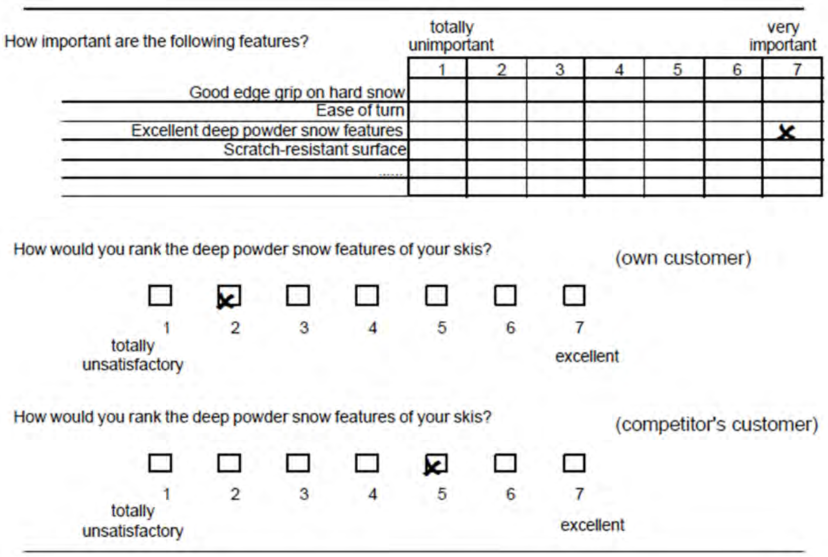


Fig. 1.1.10 Importance questionnaire and Hierarchy questionnaires (own and competitor's)

1.2 HWWP, a refined IVA - Kano model

Potra, Izvercian, **Pugna,** and Dahlgaard (2017), proposed a refined IVA-Kano model for designing new delightful products or services. This model was first initiated in 2015.

For the last decade, companies have tried to survive in a continuous competitive global marketplace with informed and demanding customers for first-time-right delightful products and services. The present paper tries to answer the simple corporate question 'How to design a new product for customer delight?' by exploring the relevant design requirements managers need to take into consideration for corporate strategic decision-making. After examining the ongoing debate regarding the theory of attractive quality, the Health Weapon Wealth Prospect (HWWP) model is proposed for a new product or service design, which relates Maslow's hierarchy of needs with the Kano methodology, importance of customer wants, and the customer satisfaction coefficient. The result represents a theoretical contribution to the further development of the Kano model and a starting point for future explanatory research.

1.2.1 Introduction

Customer satisfaction is one of the key elements of a company's financial performance and profitability (Anderson & Fornell, 1994). It is also related to the fulfillment of implicit and explicit customer needs by a product or service attributes (Tontini, Søilen, & Silveira, 2013). Transforming the voice of the customer (VOC) into design requirements for satisfying the target group may help the company capture the largest share of the market (Yang & El-Haik, 2008). In an extremely competitive global marketplace, a firm's success resides in not only satisfying customers, but delighting them (Oliver, Rust, & Varki, 1997) for exceptional behavioral consequences such as loyalty or positive word-of-mouth, through the creation of value (Yang & Sung, 2011). Managers cannot start the design process without having a clear image of the attributes which will differentiate and create added value for their new product or service in the marketplace. Therefore, the needs and expectations of future clients need to be listed, properly visualized, and discussed before transforming them into design requirements. This list is usually realized by applying the Kano, Seraku, Takahashi, and Tsuji (1984) model of product attributes, which influences customer satisfaction and the Kano questionnaire for classifying customer requirements.

In the last 30 years,we have witnessed an exploration and an explosion phase of research in the area of the theory of attractive quality. Witell, Löfgren, and Dahlgaard (2013) argue that further development of the Kano methodology is necessary for creating new and attractive products. In this line of reasoning, after a thorough analysis of the literature presented in the next chapter, the authors propose a theoretical contribution to the ongoing debate about the Kano methodology. The Health Weapon Wealth Prospect (HWWP) model measures customer quality attributes for a new product or service successful design in the light of customer importance of wants and customer satisfaction. It visually outlines customer quality attributes situated in four different domains, which help specialists understand their position in the customer's mind. At the same time, this proposed model represents a useful tool throughout the new product's lifecycle. The model's theoretical foundation is explained with the help of a case study which envisages its practical usability for business performance. The methodology, results, and discussions of the case study expose the HWWP's implications in managerial strategic decision-making. The last section concludes the main contributions of the paper and paves the way for future research in the area of the theory of attractive quality. Theory of attractive quality debate Kano et al.'s (1984) theory of attractive quality started as an attempt to better explain the roles that different quality attributes play for customers when desiring a product or service. A methodology was constructed for theory application which classifies quality attributes in one of six quality dimensions based on customer questioning regarding the presence or absence of a product or service feature. If the feature finds itself in the A – attractive category, the customer has not thought about this characteristic but he likes the idea if it comes as a surprise. Attractive features are the ones that differentiate renowned brands from the competition. If attractive means not expected, O – one-dimensional refers to desired features the user is willing to pay for. The M – must-be category is an expected feature, the consumer assumes it as a basic requirement. The I – indifferent category represents a feature that does not influence customer satisfaction or dissatisfaction and the R – reverse category expresses a backward influence on customer satisfaction. As pointed out by Witell et al. (2013), research in this area has seen three different phases: an emergence, an exploration, and an explosion of research articles and debates regarding the Kano model. We consider ourselves remaining in the explosion phase, where several debates have taken place regarding the classification of quality attributes. Quality attributes – assignment in a category In the analysis phase of the Kano questionnaire when two categories were seen as close to one another for a single attribute, researchers developed different solutions. Matzler (1996) used a special evaluation rule M > O > A > I for a clear quality attribute category assignment. Newcomb and Lee (1997) classified the attributes in this situation as a combination, and Kano (2001) proposed a new approach regarding an attribute with two strong categories, talking for the first time about quality attributes' dynamics. Thus, the lifecycle of a quality attribute states that it will change in time from being indifferent, to attractive, one-dimensional and ultimately must-be (Lo¨fgren & Wittel, 2005). Each new Kano refined model must take into consideration this lifecycle, even when designing a new product from scratch. Quality attributes – classified based on importance It has been observed that quality attributes affect customer satisfaction differently. Although the Kano model has many uses, Yang (2003) considered it inefficient in identifying the rate of importance for each specific attribute. Martensen and Grönholdt (2001) classified quality attributes emphasizing the importance of customer wants. The Importance–Satisfaction model (Importance–Performance Analysis (IPA)) has also identified the importance degree of each attribute as one criterion for its matrix. By keeping the importance degree customers give to specific attributes, we can understand which attributes are minimum requirements and which can be ignored. Tontini et al. (2013) argue that it is extremely important to avoid customer dissatisfaction by achieving an adequate performance of must-be attributes before offering attractive or one-dimensional attributes. Only in this manner, the one-dimensional and attractive attributes will positively affect customer satisfaction. At the same time, Moorman (2012) suggests that smart money is invested in one-dimensional and attractive features because those are the attributes that capture the hearts and minds of customers, triggering delight. The question appears: 'How to order and understand customer quality attributes and not dissatisfy customers but delight them?'

1.2.2 Refined attractive quality models

In the attempt to answer this question, Yang (2005) has developed a refined Kano model categorizing quality in four domains (attractive, one-dimensional, must-be, and indifferent), each with two subcategories. This approach was a step closer to a Kano methodology development because the traditional six categories have been reduced to four, discarding reverse and questionable elements with no strategic importance. Kuo, Chen, and Deng (2012) proposed a mix between the Kano model and the IPA. Nevertheless, the IPA–Kano model has limited practical usability since the three series of attributes (must-be, one-dimensional and attractive) are introduced in a two-variable diagram (importance and performance) as circles. The circle with the highest perimeter is represented by attractive attributes, this implying that they can have higher importance than must-be attributes, which is not the case. The HWWP model for a new product or service design The refined attractive quality models discussed, even though interesting, are not suited for a product or service design from scratch where we do not have previous performance knowledge. Since we are not able to measure previous performance for a new product or service attribute, we must take into consideration its value-added potential, Berger et al.'s (1993) positive better numbers concerning customer satisfaction. Value-added activities or product/service characteristics enhance customer delight because this positive emotional state results from having one's expectations exceeding to a surprising degree (Rust & Oliver, 2000). Therefore, value triggers satisfaction and delight, becoming critical for success. All attributes researched for a specific new product or service will therefore pass through the reading glass of its customers regarding their importance degree and the value it adds for their satisfaction, taking into consideration the quality attributes lifecycle for strategic design. Therefore, the proposed model is introduced in a two-variable diagram formed by the importance of customer wants and the value-added potential of specific quality attributes.

1.2.3 The origin of the HWWP model in Maslow's hierarchy of needs

We have compared Yang's (2005) four main quality elements and Kuo et al.'s (2012) series (health, war, and treasure) with Maslow's (1943) hierarchy of needs, and the outcome envisages the main domains of our model and the guidelines for future quality attributes assignment (Figure 1.2.1). Extrapolating, each firm can become a warrior on the global battlefield for market share. Must-be attributes represent the corporate product's basic needs for survival, the functional needs envisaged by Salado and Nilchiani (2013) as the expression 'I want it to work' and Kano et al.'s (1984) necessity factors. These basic needs were related to psychological health by Lester, Hvezda, Sullivan, and Plourde (1983). Without must-be features, the product or service manifests sickness and potential death. A normal state is assured by meeting these needs. Without this level fulfilled, we cannot enrich the offer and scale success. Thereby must-be features do not offer customers what they desire and demand, but are important and necessary for ascending to a higher degree in the hierarchy of needs. D'Addario (2013) argues that individuals, and likely organizations, are not capable of successful development before meeting their primary security needs. Salado and Nilchiani (2013) are referring to this type of needs as related to performance and define them by the expression: 'Now that it works, I would like that .

. . ' Similarly, Kano et al. (1984) call them performance factors. In light of the earlier-mentioned research, security is considered a protection from the risk of being injured or killed through performance. Therefore, safety or security needs are translated into one-dimensional attributes, representing a firm's weapons against rival companies. These attributes provide customer satisfaction. But in such a competitive global environment, sustainable companies need to delight their customers for a secure and desired market share. Weapons wear out, and the firm must provide enough wealth to sustain a new weapon division because we already know that the feature which delights users today becomes what they demand and expect tomorrow (Moorman, 2012). Indeed, in time, customers will start to consider the elements that triggered delight as normal. When you have attractive attributes you possess wealth; when you have wealth (money and fame), you have assured market acceptance (love needs) and respect (esteem needs). What about self-actualization needs?

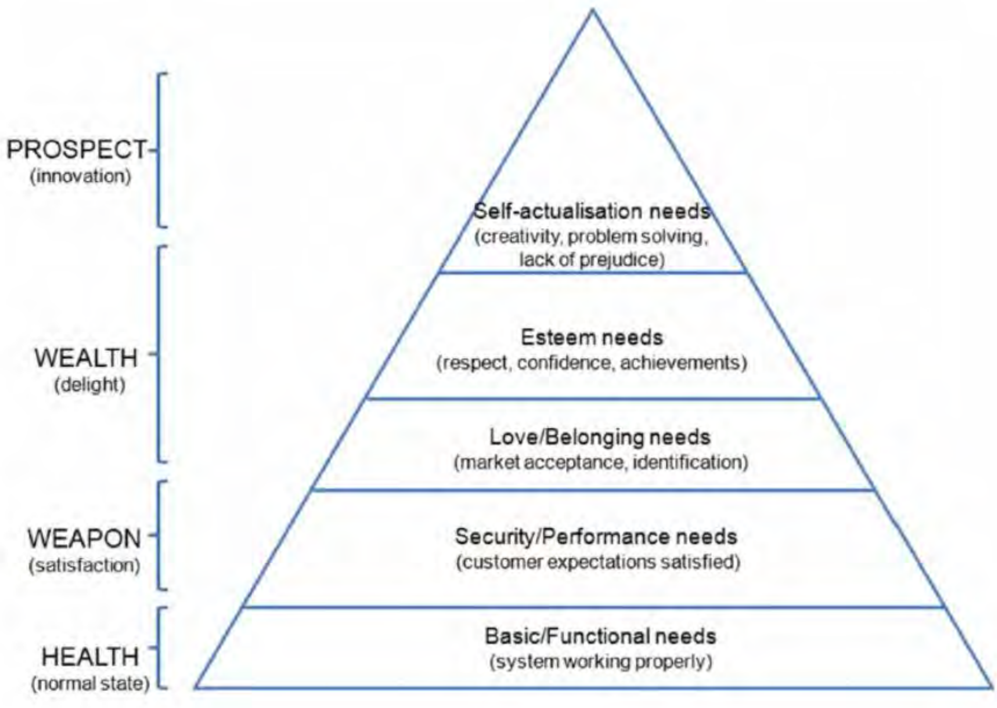


Fig. 1.2.1 The HWWP's domains and Maslow's hierarchy of needs

Even if we find ourselves in the design stage of a new product or service, we must think about the future. A firm can reach the top of the pyramid with creative and adaptable thinking regarding prospect attributes because successful attributes are often indifferent before they become attractive (Nilsson-Witell & Fundin, 2005). Thus, time dynamics consume a company's wealth, wear out its weapons, and endangers its health. Firms must think about the future even when designing a new product and should maintain prospect features in a continuous research and development stage. Due to quality attributes' dynamics, an attribute will change over time from being a satisfier to a 'dissatisfier' (Lo¨fgren &Wittel, 2005), from an attractive to a must-be feature. This lifecycle can be applied to Maslow's hierarchy of needs. A photo camera on a mobile phone was an attractive attribute determining an esteem need in the early 2000s, becoming quickly one-dimensional and then a must-be functional feature. Nowadays most mobile phones, even inexpensive ones, are sold with a camera. It is considered a must-be feature that assures a certain degree of health for the producing company. Quality attribute categories change with time as customer needs change with different offerings and lifestyles. In the same way, a company must adapt its weapons and wealth to respond quickly to market needs.

1.2.4 The four domains of the HWWP model

The complexity of each domain is revealed by the stages it comprises (Figure 1.2.2). The HWWP model measures customer importance on a 3–5–9 scale where 1 – 'Not at all Important' and 9 – 'Extremely Important', and value-added characteristics with the help of the customer satisfaction coefficient (SC) (Berger et al., 1993).

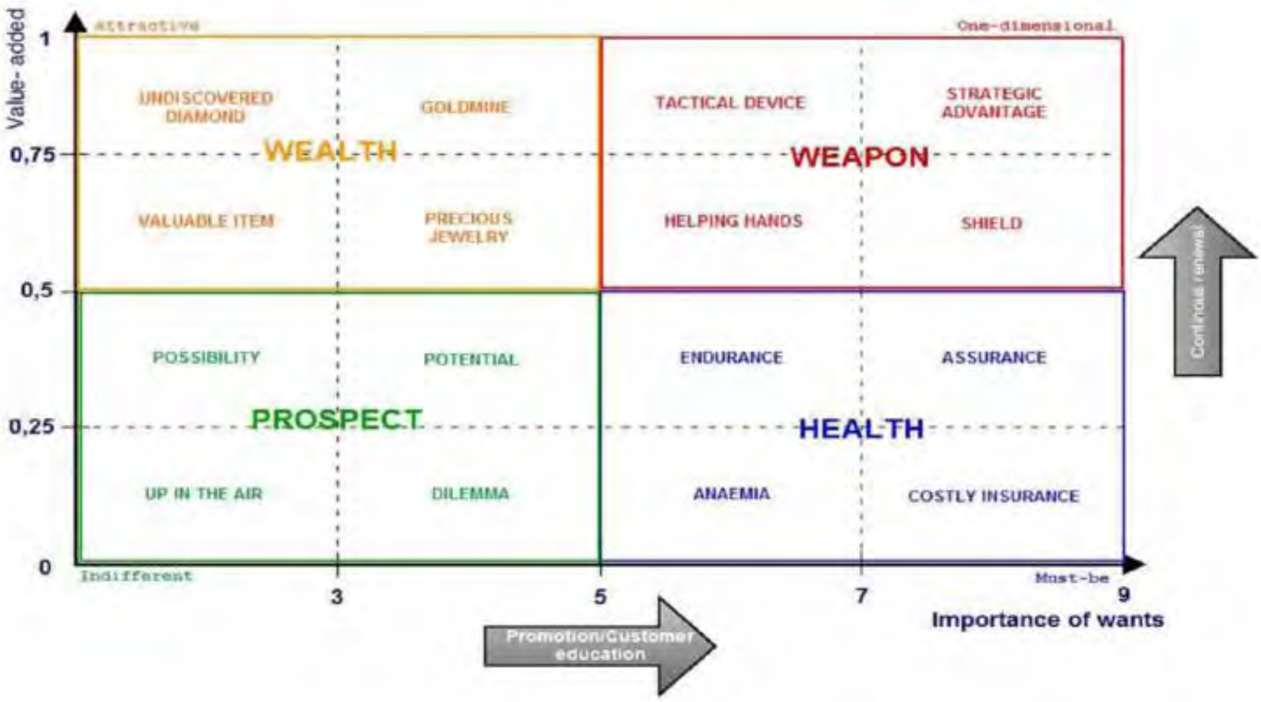


Fig. 1.2.2 The HWWP, a refined IVA-Kano model

- *Health domain (high importance, low value-added and must-be characteristic)*

This first domain refers to Herzberg, Mausner, and Snyderman's (1959) 'motivation-hygiene theory' and represents, as Kuo et al. (2012) suggest, attributes essential to enterprises as health is to the human body. Depending on the importance and value-added variables, these must-be characteristics are classified into four groups:

- *costly insurance* (7–9 very high importance and 0–0.25 very low value-added) – a product or service characteristic situated in such a category has to be maintained or insured at all costs solely because insufficiency may lead to problems which could disturb the new service's potential success. It does not supply enough value to assure company growth, representing only a costly requirement for existence;
- *anemia* (5–7 high importance and 0–0.25 very low value-added) – because these attributes do not cause extensive dissatisfaction and do not provide enough value, the investment in them may cause a sickly state and may exhaust resources. It is advisable to avoid such category attributes for new products and services;
- *assurance* (7–9 very high importance and 0.25–0.5 low value-added) – must-be characteristics from this category guarantee a basic level of efficiency. With some sort of value and high importance, their provision is extremely important for the soundness of the newly designed business;
- endurance (5–7 high importance and 0.25–0.5 low value-added) – do not affect the service or product future survival because they are not a fatal quality, but they may be important if the value-added variable is promising and the cost is reasonable.

- *Weapon domain (high importance and high value-added)*

The second domain describes the four main strategies a company can use for a new product or service differentiation. They represent weapons against possible competitors that secure a good position in the marketplace. These attributes are important and provide value for the customers, the perfect mix to ensure future gains.

Depending on the importance for customers and the value they add to the service, the categories of this one-dimensional domain are:

- *shield* (7–9 very high importance and 0.5–0.75 high value-added) – the very high importance of these attributes ensures a comfortable place of the product or service regarding possible competitors. They safeguard attributes, which cannot win a war by themselves, but keep the product or service affront;
- *helping hands* (5–7 high importance and 0.5–0.75 high value-added) – these specific attributes advocate customer's desires. Even if importance is not critical, they are appreciated and their fulfillment is welcomed, producing value and satisfaction. The significant concern regarding users produces a comfortable state and ensures a place at the rich man's table in the mind of the consumer;
- *strategic advantage* (7–9 importance and 0.75–1 very high value-added) – this strategy comprises the product or service main development reason, the idea from which the new offer originated. Without at least one such attribute, a company's new product or service is doomed to failure. The very high importance and the value it adds to the service make this category the most relevant of the entire model;
- tactical device (5–7 high importance and 0.75–1 very high value-added) – brings value to the product or service, satisfying customers in a way in which it supports the strategic advantage.

➢ *Wealth domain (low importance and high value-added)*

The third domain of the Importance Value Added (IVA)-Kano model can be easily represented as a treasure-hunt experience because, as Kuo et al. (2012) argue, people can live without jewelry, but are happier when they find and own some. In the same way, insufficient attractive characteristics do not lead to customer dissatisfaction but they reserve a delightful experience for the one who finds and exploits them. And because the loyalty curve is relatively flat within the zone of satisfaction and climbs rapidly as a result of delight or exceptionally high satisfaction (Dick & Basu, 1994), attractive high-valued characteristics represent the wealth of an offer. The four categories it comprises are:

- *precious jewelry* (3–5 low importance and 0.5–0.75 high value-added) – this category depicts attractive attributes, which add value to customer experience and therefore induce an emotional state, engaging the user with the new product or service in the same way in which precious jewelry triggers an emotional response in the person it is offered to;
- *valuable item* (0–3 very low importance and 0.5–0.75 high value-added) – the valuable item category represents attractive characteristics that are limited to the conception of the product or service, but with time they may be developed and lead to future success. These attributes constitute the basis of continuous renewal of the newly designed product or service;
- *goldmine* (3–5 low importance and 0.75–1 very high value-added) – fascinate customers. With adequate promotion and customer education, attributes from this category can literary become a goldmine. When designed, the company specialists must estimate the impact of such an attractive option and invest adequately to transform it into a strategic advantage in years to come. This represents real strategic thinking in the conception phase of a new product or service;
- undiscovered diamond (0–3 very low importance and 0.75–1 very high value-added) – if resources allow, an unimportant attribute with high value may be turned into a radical innovation which in time can develop tactical or strategic advantages as a weapon in the marketplace. A new product needs not only well-defined and acknowledged characteristics but also undiscovered or raw attributes in a continuous renewal path for competitive advantage. Thus, we must conceive something suitable today which will develop into something extraordinary tomorrow.

➢ *Prospect domain (low importance and low value-added)*

The last domain envisages a quadrant with four prospective categories. These items do not represent a priority, some may not be taken into consideration in the conception and design stage of a new product or service, but a small amount with the right corporate strategy can become future competitive weapons. The categories of the prospective domain are:

- dilemma (3–5 low importance and 0–0.25 very low value-added) – these characteristics have a certain amount of importance for the customer but lack value-added advantages. In the designing stage of the new product or service, there will be no dilemma whether to include this attribute or not. It is not advised to spend money on something with so little worth, but with adequate promotion or renewal strategies, the respective attribute can become a possible weapon in the future;
- *up in the air* (0–3 very low importance and 0–0.25 very low value-added) – such an attribute can be easily excluded in the majority of cases because it triggers neither satisfaction nor dissatisfaction. In extremely rare situations, such an 'up in the air' characteristic can gain some value;
- potential (3–5 low importance and 0.25–0.5 low value-added) – potential attributes represent the most interesting items of this domain because they can easily be transformed into weapons or wealth. If not costly to implement, it is advised to include them in the new product or service design;
- possibility (0–3 very low importance and 0.25–0.5 low value-added) – the scarce added value of these attributes and the very low importance for customers makes them easy to neglect in the conception of the product, but have possible importance in future development ideas.

The horizontal arrow below the importance of wants variable – 'promotion/customer education' – represents a possible improvement strategy which, as Kuo et al. (2012) have argued, may help the newly developed product or service to maintain its Six Sigma efficiency standard and the educated and informed customer to appreciate valuable experiences. It also envisages a considerable marketing and Public Relations (PR) effort. With the help of this strategy, the present detected attractive or prospective attributes can become valued and extremely useful weapons against the competition. Even if we are in the design stage of a new product, managers must always consider potential improvements for sustainable growth in years to come. Therefore, the vertical arrow – 'continuous renewal' – serves as the main strategic objective of smart companies. They must always come up with something new or improved to delight customers through value-added processes. Continuous renewal may transform costly insurance in assurance or a shield attribute in strategic advantage. The HWWP model not only provides an overview of the new product or service's relevant attributes but also facilitates managerial strategic thinking. For a better understanding of the model, we have implemented it in the design stage of a new shoe customization service for a local shoe manufacturing company.

1.2.5 Implementing the HWWP model for a new customization service

In an attempt to add value to its offer, a shoe manufacturer aims to develop a customization service for customer delight. The company wishes to address a younger target group and therefore needs an adequately designed service for selling and customizing shoes.

- *Methodology*

The target customer requirements regarding a possible customization option have been identified starting from questionnaire-based market research: ease of use, time optimization, interesting design, interactivity, a large number of options for customization, a large number of shoes to be customized, and several payment options. Since the identified features were too general for an adequate understanding of the VOC, several possible service attributes have been developed, reaching a total number of 14.

The Kano questionnaire has been built, based on a pair of two questions for each specific service characteristic to which the customer could answer in one of five different ways (Yang & El-Haik, 2008). Thereby, one question from each pair had a functional form (concerning the reaction of the customer if the product had that feature) and the second question had a dysfunctional form (concerning the customer's reaction if the product did not have that feature). The standard importance questionnaire has been used with the following scale: 1 (Not at all Important) . . . 9 (Extremely Important).

Before applying these questionnaires, optimal proportional sample size has been established. People with ages ranging from 19 to 45, persons who demonstrate an increased online buying behavior, have responded to the questionnaires, both by mail

(1/3 of cases) and by standard face-to-face oral interviews (2/3), totaling 164 individual valid responses. Based on the Kano questionnaire, after taking into account the entire amount of responses, each service attribute was granted a category stated in a general table of results evaluated according to frequencies. The classification of quality attributes was tested through a t-test to compare the proportions of customers classifying a quality attribute to a specific quality category. The classification of the attributes is statistically significant, that is, 12 of them at $p < .01$ and 2 of them at $p < .05$. The value-added criteria for the first variable of our model were analyzed based on Berger et al.'s (1993) positive better average numbers, which state whether customer satisfaction can be increased by meeting a certain quality attribute (customer SC). We consider that the SC coefficient represents the value an attribute adds to service and therefore we analyze it according to relation (1).

$$\mathrm{SC} = \frac{\mathrm{A+O}}{\mathrm{A+O+M+I}} \tag{1.2.1}$$

The positive SC coefficient ranges from 0 to 1; the closer the value to 1, the higher the influence on customer satisfaction. But if it approaches 0, there is very little influence. For the last variable of our model, we have developed the importance of the wants questionnaire, which has been distributed along with the Kano questionnaire.

Table 1 presents the Kano categories which emphasize the four main domains of our model, with the customer satisfaction results (SC) which outline the value-added of each new service attribute and the average importance intervals (we have computed the importance answers across all 164 respondents).

Based on the results in Table 1.2.1, we have constructed the HWWP model for the shoe customization service as stated in Figure 1.2.3.

The first customer requirement, information clarity, and concision do not have a very consistent influence on customer satisfaction, but if not fulfilled, it causes customer dissatisfaction especially in an online environment where information ambiguity determines a user to quit the platform in the majority of cases. Therefore this must-be attribute is placed in the health domain where it assures a steady condition. In future years, the company can maintain this health attribute by cost-efficiency strategies. The ease of use is desired and represents a one-dimensional feature because consumers consider it important.

Gadgets, links, and other tools must be easy to use by usual individuals with the medium online experience. Besides, it provides also increased value, becoming a relevant weapon in the battle for survival and excellence. In the future, by promoting the ease of use of their service, this attribute can become an effective shield against similar services. Loading time optimization is a one-dimensional feature that every customer desires, situated in the future service's 'weapon department' as a helping mechanism for customer satisfaction. Once you click on a web page, you wish it loads instantly. But when designing a product as a whole, attribute interactions are critical. For the customization option, we must take into consideration the fact that many images with high resolution may jeopardize the loading optimization.

Tab. 1.2.1 Table of results

Table 1. Table of results.

Customisation requirements	A	O	M	I	R	Q	t-test	Category	Value-added (SC)	Stated importance
Information clarity and concision	7.4	29.2	47.6	14.5	0.6	0.6	$p < 0.01$	M	0.37	7.3
Ease of use	18.4	49.7	20.8	11	0	0	$p < 0.01$	O	0.68	7.2
Loading time optimisation	13	43.8	21.6	19.1	1.2	1.2	$p < 0.01$	O	0.58	5.7
Fast order confirmation	13.7	43.5	25.4	16.7	0.6	0	$p < 0.01$	O	0.57	6.1
Modern design	57	13.1	0	25.6	3.1	1.2	$p < 0.01$	A	0.73	4.6
Product 3D format	64.8	4.9	3.7	18.6	1.2	6.8	$p < 0.01$	A	0.75	4.9
Image rotation	50	20.1	6	20.2	0	3.7	$p < 0.05$	A	0.72	4.4
Customisation storage	33	28.6	9.2	26.2	1.2	1.8	$p < 0.01$	O/A	0.63	3.9
View of other's customised orders	30.2	12.3	4.3	50	2.5	0.7	$p < 0.01$	I	0.43	3.7
Large number of customisable shoes	45.3	16.6	4.3	25.7	3.7	4.3	$p < 0.01$	A	0.67	3.8
Customising colour	39	34.1	15.3	9.2	0.6	1.8	$p < 0.01$	O→A	0.74	7.7
Customising leather material	35.6	31.3	7.4	24.5	0.6	0.6	$p < 0.05$	O→A	0.67	7
Customising accessories	39.6	29.3	7.9	20.8	0.6	1.8	$p < 0.01$	O→A	0.70	6.3
Payment options	32.9	23.2	20.1	23.2	0.6	0	$p < 0.01$	O→A	0.56	6.4

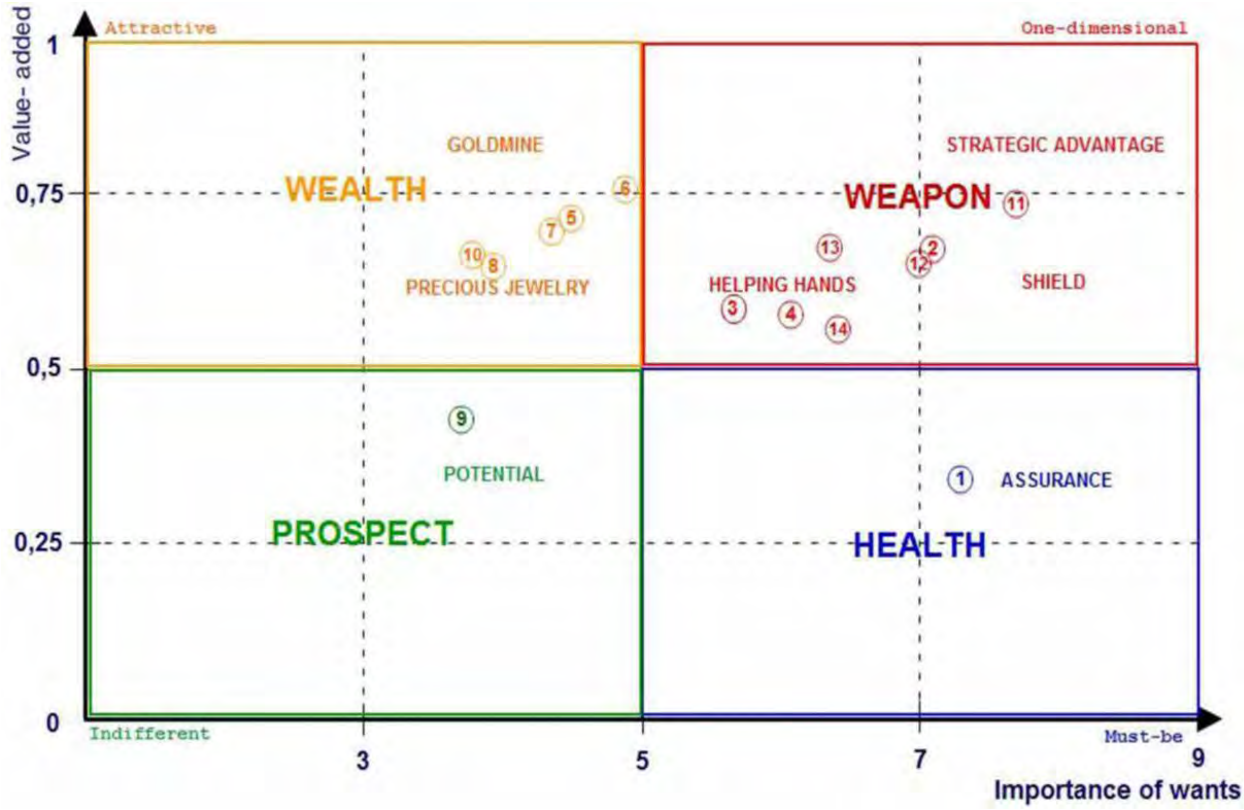


Fig. 1.2.3 The HWWP model for the new shoe customization service

When ordering a pair of shoes on the Internet, the customer desires a quick confirmation and also very fast delivery. This service attribute must be standardized into a time frame that is optimal for both the company and the customer, but it must not exceed one day. If adequately designed and implemented, the service will satisfy and differentiate the service from the competition, as a 'helping hand' for the client. A modern design of the web page where the customization will take place is considered an attractive requirement, being situated in the wealth domain of our model as a precious attribute similar to jewelry. Therefore the customer will be delighted to visualize a fresh and innovative design, which will be pleasing to work with. But if the company does not provide such a modern design, the customer may be satisfied with a classic one as well. The medium importance and pretty high value it adds to the new service are reason enough to include this characteristic to the new corporate offer if costs are low. When customizing a pair of shoes, a 3D format is extremely attractive, as if finding a goldmine. The customer can see the model's details and its color or material can easily be changed. It would be a plus for the company and especially for the new service to provide such a feature. Nevertheless, the increased cost with its implementation may trigger debates. For understanding all the specificities of a model, an image rotation option is very attractive. Combining the 3D format with a rotating image and a modern design, the service will be unexpected and surprising. Viewing other's customization orders influences customer satisfaction, adding value to the experience. The majority of customers are indifferent to viewing other customer's customization orders. This prospect attribute can be improved and implemented further on into the service, when weapons wear out, for a fresh new wealth element. The possibility of customizing all collections of the company is seen as attractive because it supplies wealth and delight. But we can easily notice that this attribute holds a low level of importance; this leads us to think that the company has a maneuvering space, and it can provide for customization of only shoes that are designed for promotion and not the entire collection. When customizing a pair of shoes, having the possibility to change their color is seen as attractive in 39% of cases and desired by 34%. Therefore, it represents an attribute commuting from an attractive to a one-dimensional category. This weapon, when wisely used, can become a steady strategic advantage, retaining customers and satisfying their needs. In the same way, customizing leather material and adding accessories to a pair of shoes represent weapons and more specifically helping hands for passionate users. In a few years, with adequate promotion and improvement, these attributes can become the firm's strategic advantage. Last but not least, the multiple payment options attribute is considered one-dimensional, being situated in the weapon domain of the HWWP model. This feature may bring dissatisfaction if the company does not provide two or three payment possibilities. With increased ease of use options, the firm can transform it into a tactical advantage.

When designing a brand new product or service, companies want to have a first-time-right success. Therefore, they need to assess the VOC and visualize its quality attributes simply and suggestively. Even if the majority of recent studies have failed to determine significant explanations of the theory of attractive quality, the authors have learned to merge interesting ideas from the 'explosion phase' (Witell et al., 2013) and build on the foundations of the Kano methodology. The recent focus on Kano categories introduction and evaluation perspectives (Ipek & Çikiş, 2013) on quality category transformation (Borgianni & Rotini, 2013), and on the need to create customer loyalty through delight (Högström, 2011) made the authors rethink the Kano methodology for a delightful product or service design from scratch with an evaluation perspective (importance of wants and value-added quality for customer satisfaction), which adapts to category lifecycle transformations for continuous organizational strategic thinking. Since current measuring models for the VOC were not suited for the conception of a new corporate offer, the proposed HWWP model represents a managerial tool with easy to understand domains and suggestive categories for business excellence strategic thinking. Future research will focus on the degree to which the model can be used for the improvement of already launched products or services. In this case, we must take into consideration key performance indicators related to a customer, marketing, and operational perspective.

1.3 A refined HWWP model

Pugna, Potra, Negrea, and Mocan (2016) proposed a refined HWWP model based on a non-uniform partition with elasticity curves.

In the present extremely competitive business environment, successful companies must differentiate their offer and provide a valuable and desired output. Quality is not enough anymore. The starting point of product design resides in consumer requirements (Bilgili et al., 2011). Thus, understanding customer demands determine the need to differentiate and manage them. Consumers have certain intrinsic or extrinsic requirements but want also to be surprised by an offer. This situation has led to the development of the theory of attractive theory which tries to classify the different role quality attributes play for customers. The presumed linearity of this theory considered that consumer assessment increases or decreases linearly as a product attribute is improved or worsens. However, Anderson and Mittal (2000) state that linear modeling of performance-satisfaction link can incorrectly estimate attribute importance weights and (Linares & Page, 2011) present literature cases that have proven otherwise, where attributes which produce satisfaction are not the same as those which produce dissatisfaction The Kano model (Kano et al., 1984) has demonstrated co-existing linear and non-linear attributes, being the first to thoroughly address the non-linear relationship between quality attribute performance and overall customer satisfaction (Lin, Yang, Chan & Shen, 2010). Thus, this model can comprehensively analyze user demands and obtain the relevant requirements for product design (Liao, Yang & Li, 2015). Raharjo (2007) argues that the Kano model provides a unique way of distinguishing the impact of different customer needs (also known as the voice of the customer – VOC) on total customer satisfaction in the early stage of product or service development, leading to a much higher degree of effectiveness and efficiency in the subsequent processes.

Over time the Kano method has been widely used, analyzed, and critiqued. Xu, Jiao, Yang, Helander, and Halimahtun (2009) address some weaknesses, and Yang (2003) argues a certain degree of inefficiency of the model in identifying the rate of the importance of each quality attribute. Regarding the need to assess quality attributes in relation to the importance for customers, Martensen and Grönholdt (2001) classified quality attributes emphasizing the importance of customer wants. Yang (2005) redefined Kano categories by transforming the four traditional categories into eight: highly attractive and less attractive, high value-added and low value-added, critical and necessary, and potential and care-free. He also discarded reverse and questionable categories with no strategic importance. Kuo, Chen, and Deng (2012) proposed an IPA-Kano model with three series of attribute dimensions: must-be, one-dimensional, and attractive. After understanding the qualitative nature of the Kano model, Xu, Jiao, Yang, Helander, and Halimahtun (2009) suggested an analytical Kano (A-Kano) model that introduces Kano indices, Kano classifiers, and evaluation criteria for quantification of customer satisfaction.

As a first deduction, we see a wide variety of Kano related models trying to refine the methodology for a better quality attribute classification. The majority of the work is focused on discussing customer satisfaction with a requirement (quality attribute) versus the performance of the same attribute. Thus, the relationship between the degree of sufficiency and customer satisfaction can be classified into five categories of perceived quality: attractive, one-dimensional, must-be, indifferent and reverse quality. The performance (sufficiency) factor and the perceived quality indicate an earlier customer assessment of quality attributes after consumption of a product/service. But little research has been undertaken regarding new products and services which do not benefit from earlier consumption assessment. In this situation, we do not have previous performance or customer satisfaction (perceived value), but possible added-value and importance of quality attributes (desired value). In this line of reasoning, the HWWP model has been developed for new product and service first time right design, not taking into consideration previous performance (Potra, Izvercian, Pugna, & Dahlgaard, 2015). Founded on Maslow's hierarchy of needs and introduced by two variables: the value-added potential and importance of customer wants for new attribute offerings, the HWWP model responds to managerial demand for relevant and easy to understand the value of possible new product/service attributes. It is constructed on four main domains: Health (eloquent for functional needs), Weapon (envisaging performance needs), Wealth (expressing delight needs), and Prospect (mainly research and development needs), each with four suggestive dimensions, as it can be seen in Figure 1.3.1. Wherever quality attributes are first located, the model offers future improvement strategies for enhancement of the importance degree through promotion/customer education and increased value added to the offer through continuous renewal.

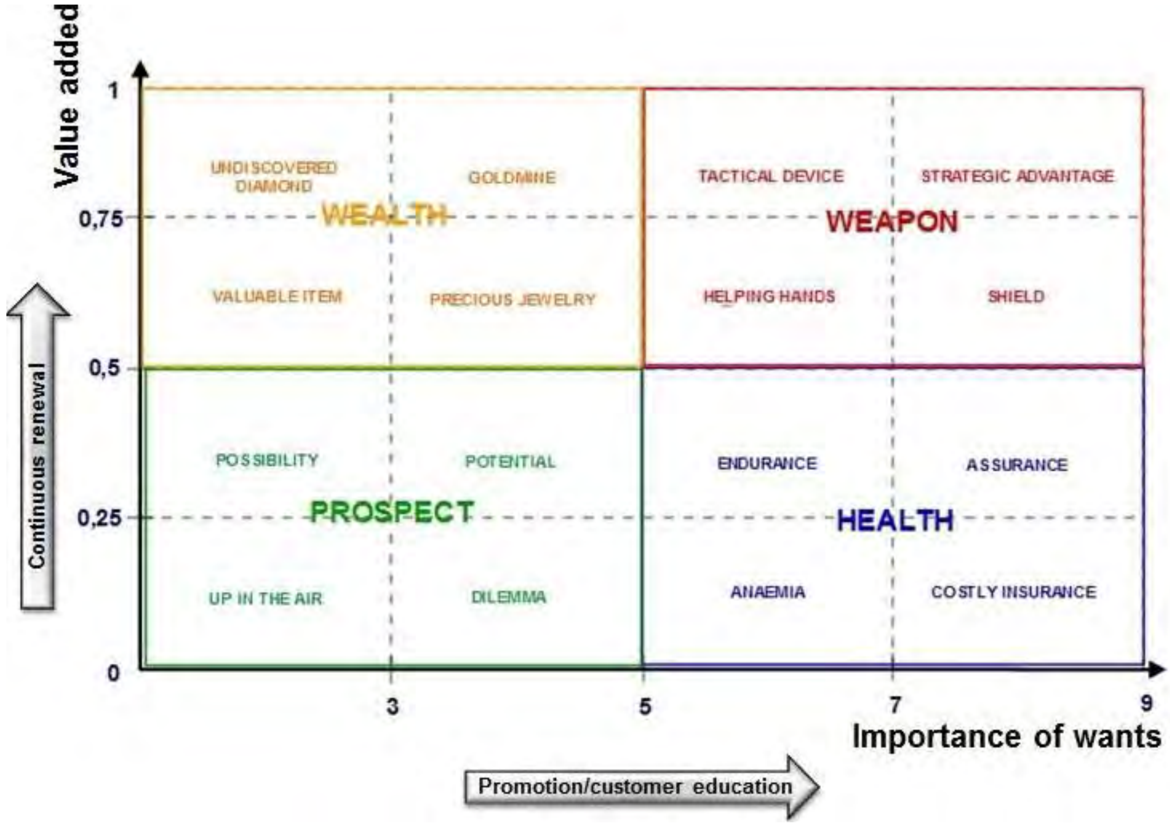


Fig.1.3.1 The HWWP model (Potra, Izvercian, Pugna, & Dahlgaard, 2015)

The voice of potential customers is identified through a standard importance questionnaire which uses the following scale: 1 (Not at all Important)... 9 (Extremely Important), and a Kano questionnaire which provides the basic information for appreciating the value-added characteristics with the help of the customer satisfaction coefficient (Berger et al., 1993). However, the current HWWP model has a uniform partition without a transition phase. For example, two quality attributes situated in the weapon quadrant, associated with the shield dimension, one in the upper left and the other in the lower right are considered equal, which is not entirely correct. By discussing three statistical techniques the present paper rejects the uniform hypothesis of the current HWWP model and proposes a refined one separated by several elasticity curves, an idea extracted from the economic domain of price elasticity. Through elastic and inelastic areas, the quality attributes are more clearly separated and adequately classified for a strategic understanding of their future dynamics.

1.3.1. The HWWP non-uniform distribution

In an attempt to explain why the HWWP model should be refined, three statistical techniques are furthermore studied because they are known to be representative when analyzing the concentration of records in the unit square and rejecting the hypothesis of uniformness.

a) Interquartile range

In descriptive statistics, the interquartile range (IQR), also called the mid spread or middle fifty, is a measure of statistical dispersion, being equal to the difference between the upper and lower quartiles, IQR = $Q3 - Q1$. In other words, the IQR is the first quartile subtracted from the third quartile. These quartiles can be seen on a data box plot. It is a trimmed estimator, defined as the 25% trimmed range, and is the most significant basic robust measure of scale. For establishing if the HWWP model should have a non-uniform distribution, the concentration of the statistical series should be tested. Thus, if we encounter a concentration of results, the uniform distribution is proved to be incorrect (a uniform distribution means no concentration; all points have the same quota). The analyst should check if the amplitude is greater than the semi-interquartile range – IQR/2, and then take the decision based on the distribution seen as a concentration (Zwillinger & Kokoska, 2000).

b) Gini coefficient

Thie Gini coefficient measures the inequality among values of a frequency distribution (Gini, 1936). To test the concentration of a statistical distribution (and then, to test the non-uniform aspect of the HWWP model) we should compare the Gini coefficient to 1/3 which represents the value of this coefficient for the uniform distribution (Dorfman, 1979).

c) Concentration of measure

If previous techniques are not widely used for a bi-dimensional space, the concentration of measure presents an important argument against the HWWP bi-dimensional uniform model. In mathematics, the concentration of measure (about a median) is a principle that is applied in measure theory, probability, and combinatorics (Talagand, 1996). Informally, it states that "a random variable that depends in a Lipschitz way on many independent variables (but not too much on any of them) is essentially constant". From a
probabilistic perspective, let us agree that a random variable Z defined on some probability space satisfies a concentration inequality if, for some constant m, which will typically be EZ or the median of Z, we have for every u $\geq$ 0, as in relation (1.3.1):

$$P[|\mathrm{Z}-\mathrm{m}|] \leq \mathrm{c}\cdot\exp\left(-\frac{\mathrm{u}^2}{2\cdot\mathrm{v}}\right) \tag{1.3.1}$$

or equivalently, as in relation (1.3.2)

$$P[|\mathrm{Z}-\mathrm{m}| \leq u] \leq 1-\mathrm{c}\cdot\exp\left(-\frac{\mathrm{u}^2}{2\cdot\mathrm{v}}\right) \tag{1.3.2}$$

where the constant v is usually related to the variance of Z, and where c > 0 should be a small numerical constant (Berestycki & Nickl, 2009). From a more geometric perspective, we can say that a measure μ on some metric space (X, d) satisfies a measure concentration principle if, for any set A such that μ(A) ≥ 1/2, we have, as in relation (1.3.3).

$$\mu(A_r) \geq 1-\mathrm{c}\cdot\exp\left(-\frac{\mathrm{r}^2}{2\cdot\mathrm{v}}\right) \tag{1.3.3}$$

where A_r denotes the r-enlargement of A: that is, points x € X within distance r of A. This point of view should be of some use to the combinatorics and analysts (Berestycki & Nickl, 2009). For a uniform distribution on a unit square, the concentration measures is the half square root of 2, hence, a non-uniform distribution can be found for a concentration measure less than this value. All three techniques have been computed for the HWWP model in a previous practical example, providing statistical arguments to reject the uniform hypothesis, as we will furthermore see. Therefore, a correction of the classical model is necessary and any development of a new model must begin with a non-uniform partition of a unit square.

1.3.2 The refined HWWP model based on elasticity curves

The current HWWP model is represented by an SC coefficient variable which ranges from 0 to 1 and a stated importance variable from 0 to 9. The range from 0 to 9 is advised to be normalized for a tight square-like model. In this way, the suggested mathematical modeling is easier to compute, understand, and visualize. Using the arguments from the previous chapter, we are motivated to make some corrections regarding the classical HWWP model which describes the relation between (normalized) stated importance and value-added (SC), in four uniform squares. The new non-uniform refined model is based on a supplementary partition with elasticity curves. They are constructed upon the equation: y = a · xb, which uses a similar idea given by price elasticity. The constant elasticity demand function is represented as $Q = a \cdot P^b$. Such an approach sections two variables (in the case of price elasticity we have price and quantity) through a diagonal or a point of unit elasticity where ED (demand) =1. All above region (ED >1) is considered as elastic and the below region (ED <1) as inelastic. Similarly, when we divide the HWWP model through the coefficients a and b, computed in such a way as to obtain seven equidistance elasticity curves concerning the added-value and importance of wants variables (the top and the right side of the unit square), we project a diagonal (curve 4) which separates an elastic and an inelastic region. In the elastic region, any small change in a quality attribute influences positively or negatively customer satisfaction, unlike in the inelastic region where a value improvement has a reduced influence on customer satisfaction.

Therefore, the HWWP model is partitioned in a non-uniform way through seven elasticity curves which are furthermore presented in Figure 1.3.2.

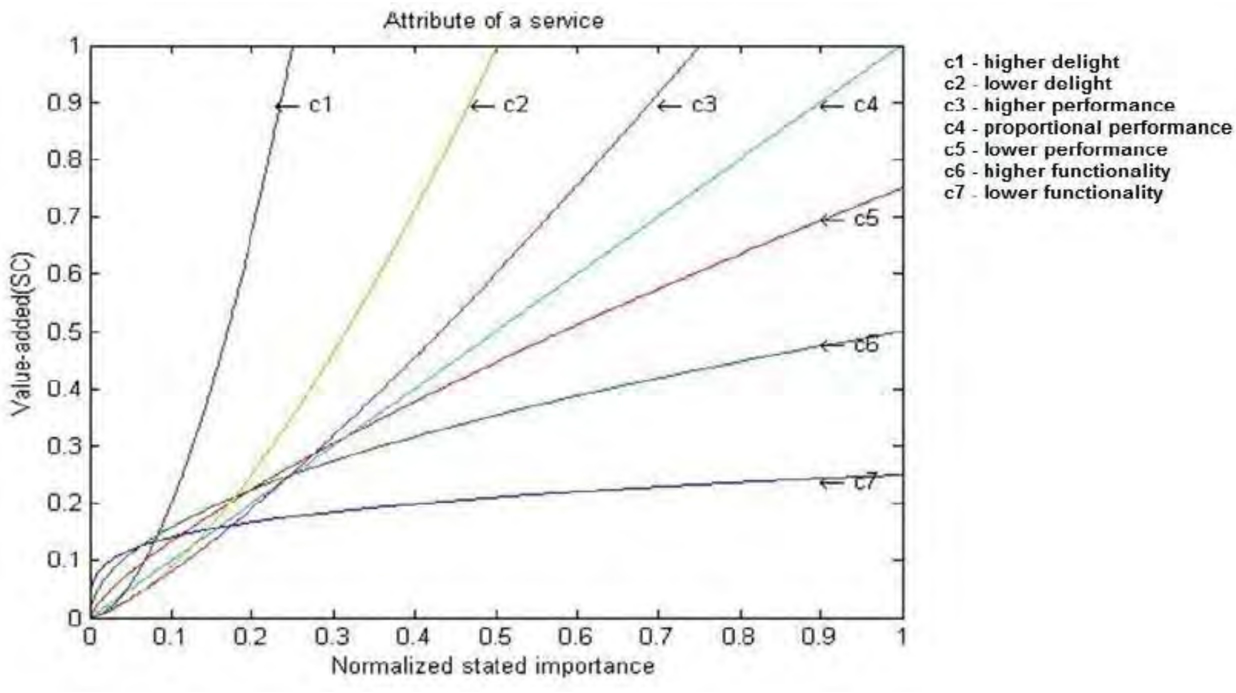


Fig. 1.3.2 The representation of the customer stated importance and value-added variables as a non-uniform model with elasticity curves

The labels of the seven elasticity curves are inspired by Yang's (2005) integrated Kano categories:

- the curve denoted c1for higher delight: $y = 11.31 \cdot x^{1.75}$ (elastic region)
- the curve denoted c2 for lower delight: $y = 2.82 \cdot x^{1.5}$ (elastic region)
- the curve denoted c3 for higher performance: $y = 1.43 \cdot x^{1.25}$ (elastic region)
- the curve denoted c4 for proportional performance: $y = x$ (regions' divider)
- the curve denoted c5 for lower performance: $y = 0.75 \cdot x^{0.75}$ (inelastic region)
- the curve denoted c6 for higher functionality: $y = 0.5 \cdot x^{0.5}$ (inelastic region)
- the curve denoted c7 for lower functionality: $y = 0.25 \cdot x^{0.25}$ (inelastic region)

The nine areas thus formed are eight limited by seven curves and one in the left-bottom side of the unit square where the crossing of the curves occurs and it is not possible to make a decision. This area is included in the HWWP "up in the air" dimension, pointing to the fact that it has a very low sensitivity and irrelevant results. The basic idea is that quality attributes in a new product or service can be associated with the closest curve according to the formula of distance. We use the minimum

Euclidian distance between a point and a curve from a plane XOY. More precisely, this distance denoted with d(P,c) is computed using the following assertions:
- first step, use the Euclidian distance, as in relation (1.3.4):

$$D\left(P(x_{0,}y_0), c(x)\right)^2 = (x - x_0)^2 + \left(a \cdot x^b - y_0\right)^2 = S(x) \qquad (1.3.4)$$

- second step, find the minimum of this distance using the mathematical analysis technique, i.e. using differential of the function S(x), as in relation (1.3.5):

$$S'(x) = 2 \cdot x + 2 \cdot a \cdot b \cdot x^{(b-1)} \cdot \left(a \cdot x^b - y_o\right) \qquad (1.3.5)$$

- third step, find the solution of the (non-linear) equation S'(x) = 0, using a Newton-Raphson procedure, choosing an initial value closed to x_0.

Our model is not limited to nine areas, a more partitioned model can be made using the same technique, but for good visualization of the graph, we have chosen this number of areas and curves. As a future research direction, the optimum number of curves can be determined with the help of specific statistical techniques, for example the informational criteria of Akaike - AIC (Akaike, 1974).

1.3.3 Discussion of the refined HWWP model

HWWP model (Potra, Izvercian, **Pugna**, & Dahlgaard, 2017) has been applied to a new personalization service for a Romanian shoe manufacturing company. In that case study, we had 14 quality attributes illustrated in a rectangular shape. As we have explained, normalized importance of wants is necessary for a square shape model and mathematical calculations. Therefore, we represent the old results in a square-shaped HWWP model in Figure 1.3.3, where the added-value variable is illustrated as Y and the importance variable as X.

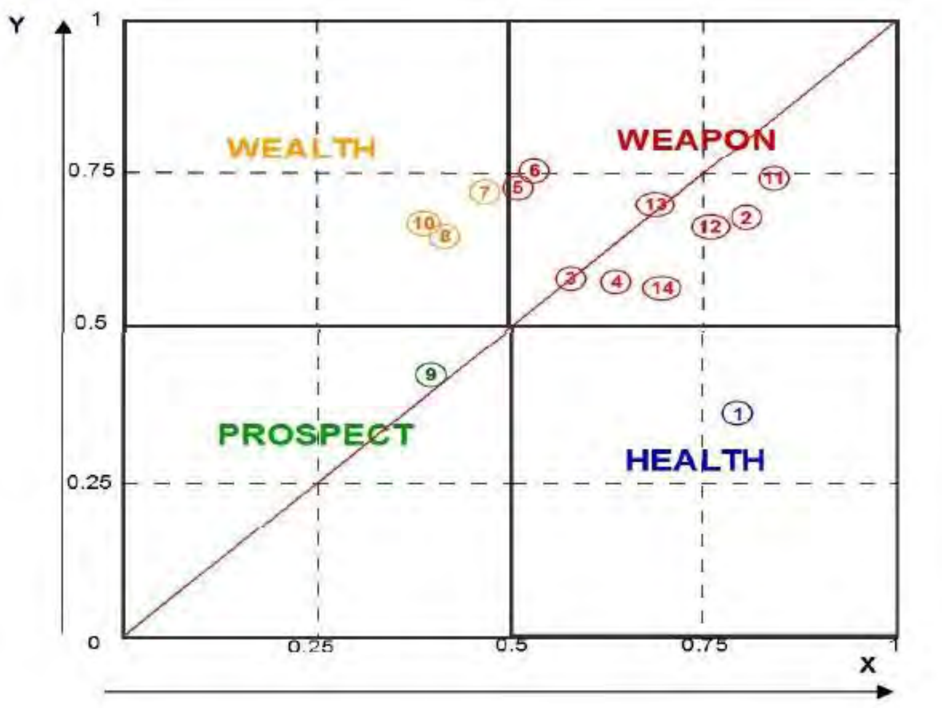


Fig. 1.3.3 The quality attributes of the contest computed in an HWWP model with normalized importance of wants (X)

If the old model was represented by Y, X from which an HWWP stage was denoted, the refined model takes into consideration the distance to the closest curve and the elasticity curve direction (Table 1.3.1) for a strategic understanding of a quality attribute's present and future value in a new product/service lifecycle.

We have applied the refined model for the old case study to see if it indeed brings explanations and corrections to the results.

The records (blue points) represent the 14 quality attributes. It's not difficult to observe the concentration of quality attributes around the point M(0.6236, 0.6286).

The model together with all points is given in figure 1.3.4. In our case, the semi-interquartile range is smaller than the amplitude (0.3050 for y coordinate and respectively, 0.2950 for x coordinate), therefore, we can sustain the concentration of the empirical distribution of the records.

The computed Gini coefficient for both coordinates of the analysis is less than 0.15, hence, we can reject the uniform hypothesis of the record (in the uniform distribution the Gini coefficient is 0.3).

For the case study, the concentration of measure concerning the half part of the unit square is less than 0.3 and this confirms a nonuniform (2-dimensional) distribution (where the concentration of measure is 0.5).

Tab. 1.3.1 The 14 attributes of a personalization service with their coordinates, traditional Kano categories, HWWP dimensions, elasticity curve distances, and directions

	Customization requirements	Y Value-added(SC)	X Stated importance	Traditional Kano category	HWWP stage	Distance to the closest curve	Elasticity curve direction
1	information clarity and concision	0.37	0.81	M	Health/ Assurance	0.67	C6 -Higher functionality
2	ease of use	0.68	0.80	O	Weapon/Shield	0.29	C5- Lower performance
3	loading time optimization	0.58	0.63	O	Weapon/ Helping hands	0.31	C4-Proportional performance
4	fast order confirmation	0.57	0.67	O	Weapon/ Helping hands	0.10	C4-Proportional performance
5	modern design	0.73	0.51	A	Weapon/ Helping hands	0.54	C3-Higher performance
6	product 3D format	0.75	0.54	A	Weapon/ Tactical device	0.31	C3-Higher performance
7	image rotation	0.72	0.48	A	Wealth/ Precious jewelry	0.75	C2-Lower delight
8	customization storage	0.63	0.43	O/A	Wealth/ Precious jewelry	0.65	C2-Lower delight
9	view of other's customized orders	0.43	0.41	I	Prospect/Potential	0.31	C4-Proportional performance
10	large number of customizable shoes	0.67	0.42	A	Wealth/ Precious jewelry	0.48	C2-Lower delight
11	customizing color	0.74	0.85	O->A	Weapon/Shield	0.59	C5-Lower performance
12	customizing leather material	0.67	0.77	O->A	Weapon/Shield	0.58	C5-Lower performance
13	customizing accessories	0.70	0.70	O->A	Weapon/ Helping hands	0	C4-Proportional performance
14	payment options	0.56	0.71	O->A	Weapon/ Helping hands	0.14	C5-Lower performance

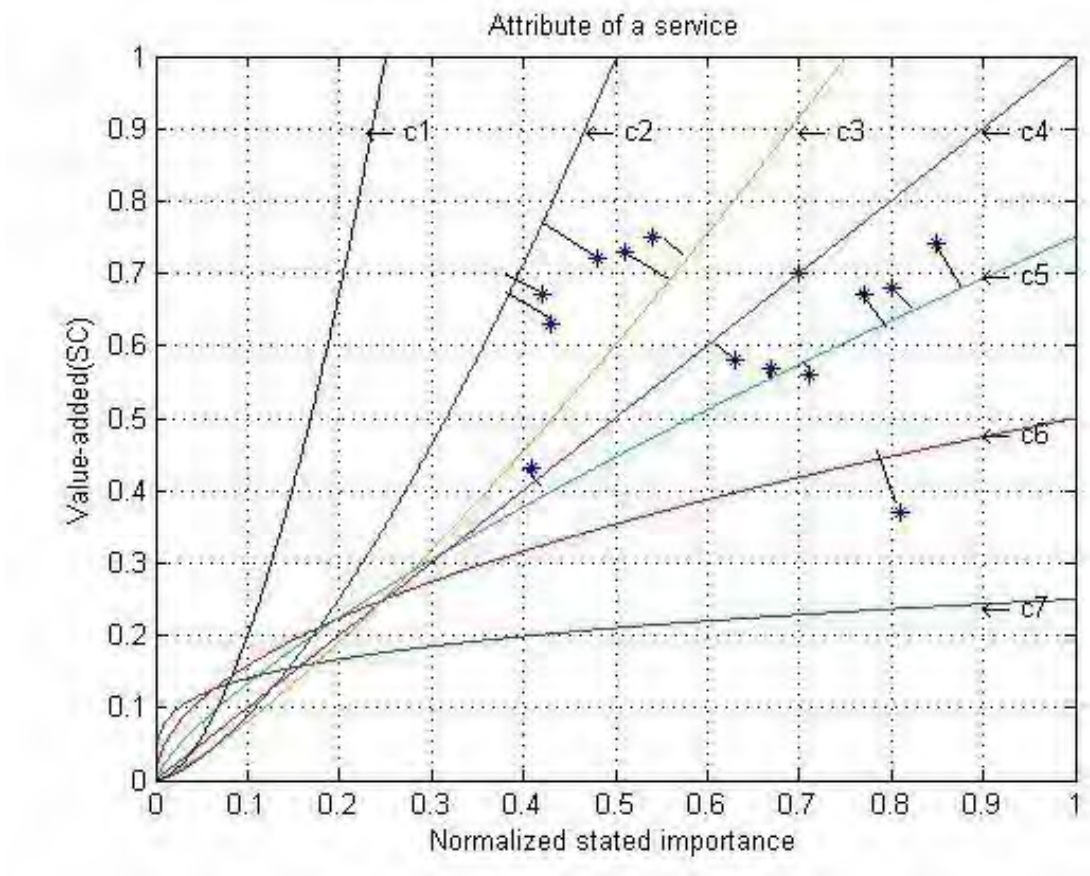


Fig. 1.3.4 The allocation of quality attributes to a specific elasticity curve in the refined HWWM model

The 14 quality attributes are modeled in the refined HWWP model, corresponding to one of the seven elasticity curves after thorough computing of the distance between the point and the closest curve. In this way, a point situated between two categories can be classified with precision for management decision support. Besides, by associating a quality attribute to an elasticity curve, the design and management team can foresee a

strategic developing path ascending the direction of the curve.

As an example, the quality attribute with the number 13 - customizing accessories from Table 1 had an initial one-dimensional and attractive Kano category, being a little bit vague for decision making. The classical HWWP model recommended a "helping hands" (weapon) dimension. The problem was that also number 14 - payment options (an ambiguous Kano category) have been considered as having a "helping hands" dimension. No major difference can be outlined at this point between them. The management team is not able at this moment to evaluate the quality attributes' value for their new product or service and envisage future strategic decisions. With the refined non-uniform HWWP quality attribute classification model we can assign the 13 point to the C4 elasticity curve. Thus, customizing accessories is a proportional performance feature that can be developed strategically as a "strategic advantage" in correlation with the direction of curve 4. Unlike point 13 (customizing accessories, which adequately developed can become a very important feature in a company), point 14 regarding payment options is associated to the curve 5 denoted as lower performance and a more inelastic region. Therefore, point 14 - payment options have a lower degree of performance than point 13, even if in the classical HWWP model they were the same. As a strategic development, point 14 can reach a "shield" dimension in correlation with the direction of the curve 5. The same discussion can occur for all 14 quality attributes of the previous case study, the new insight can facilitate decision making and strategic forecast of the potential development lifecycle.

Since the traditional Kano model has a qualitative nature and limited decision support in engineering design the HWWP (Health-Weapon-Wealth-Prospect) model emerged as an explanatory paradigm and a more useful option in decision making. The present study has normalized the importance of wants variable of the HWWP model and rejected its classical uniform partition based on three statistical techniques: the interquartile range, the Gini coefficient, and the concentration of measure. Thus, it has been demonstrated that a uniform repartition of results in square dimensions does not provide enough information for subtle decision making. In the uniform HWWP model, a quality attribute’s dynamics could be seen as a precipitous jump from one dimension to another with high financial repercussions for the firm. Instead, the non-uniform partition with the help of elasticity curves first sections the model in elastic and inelastic regions and then provides a natural strategic trajectory (the direction of the curve) for improvement. The non-uniform proposed partition has been realized with the help of seven elasticity curves inspired by the price elasticity of demand principles. The number of curves is not limited to seven, the refined HWWP model can be adapted to each situation, depending on the concentration of quality attributes. The proposed elasticity curves have been applied to Potra, Izvercian, Pugna, and Dahlgaard (2015) case study to refine the results and prove the new model’s applicability. In the discussion section, the authors have argued the fact that elasticity curves overlapping the HWWP dimensions facilitate a clearer understanding of potential customer needs and a strategic overview of the possible quality attribute’s development opportunities.

By allocating each quality attribute to an elasticity curve we can delineate a potential lifecycle path for that specific characteristic. In this way, the new product or service will be accurately designed to fit customer needs. Additionally, managers will be able to plan future development stages of each quality attribute with precision. In conclusion, the refined HWWP model based on a non-uniform partition with elasticity curves wishes to integrate the understanding and classification of customer needs as an important decision-making tool in a new product or service design. Future research will focus on adapting the refined HWWP model to take into consideration also the producer's capability to fulfill prioritized and classified customer needs.

1.4 The Greenhouse Model

Dahlgaard, **Pugna**, Potra, Negrea, and Mocan (2016) explores design requirements to take into consideration when designing and developing new products or services. The purpose is to develop a strategic approach for analyzing variations between potential customer needs in order better to understand what qualities should be further cultivated before product launch. This new approach is called 'A Greenhouse Approach for Value Cultivation'. Case study data of a new web-based customization service for a Romanian shoe manufacturing company has been re-analyzed by using questionnaire data on 166 respondents' perceptions on 14 attributes' importance and value. A nonlinear regression model was developed and used to understand the relations between importance and value. Such relations were used together with the Greenhouse Model to better understand the service attributes' potential life cycles if selected for further cultivation. The Greenhouse Model envisages new perspectives of the evaluation of customer needs to support strategic decision-making regarding further value cultivation for profound affection (= customer delight). Even if there is a need for further tests the suggested 'Greenhouse Approach for Value Cultivation' is regarded as a new and original contribution to the theory of attractive quality creation which deepens its position in the theory of attractive quality and transforms it into a practical management tool to support new product and service design.

In an attempt to understand and hence help in providing superior quality to clients, the theory of attractive quality has emerged (Kano, 2001; Kano, Seraku, Takahashi, &

Tsuji, 1984). This theory aims to understand and explain the roles different quality attributes play for customers and suggests a methodology for classification and understanding of quality at an attribute level seen from the customer's perspective. The Kano model has been widely practiced because it visually captures a nonlinear relationship between product performance and customer satisfaction for the attractive quality attribute category (Xu, Jiao, Yang, Helander, & Halimahtun, 2009). However, in new product or service developments, we do not have prior performance data and hence customer needs or wants are to be used as a proxy to ascertain and decide on which quality attributes the company should focus upon. Product and service development managers need for that purpose a reliable classification methodology to be used for understanding the impacts of newly designed product and service quality attributes. However, the Kano model is considered to have inherent weaknesses (Xu et al., 2009) and to be inefficient in identifying the rate of importance for each attribute (Yang, 2003). Therefore, as Witell, Löfgren, and Dahlgaard (2013) argue, after the 'emergence, exploitation and explosion phases' in the evolution of the theory of attractive quality a new 'explanation phase' has emerged where the aim is to further develop the field of attractive quality creation. For that purpose, Potra, Izvercian, Pugna, and Dahlgaard (2015) suggested the so-called HWWP model which is a two-variable diagram formed by the stated rate of the importance of customer wants and needs and Berger et al.'s (1993) satisfaction coefficient as a proxy for 'the value-added potential' of the product's different quality attributes. With this new methodology, the Kano categories were correlated with the customer stated rate of importance and Berger's satisfaction coefficient. TheHWWP model, however, did not always provide a clear and reliable assessment of the localization of all types of quality attributes due to its assumption of a uniform distribution representing variations between potential customer needs. Hence, the understanding of potential dynamics (life cycles) of the quality attributes may be uncertain because the transition from one dimension to another seems to be done abruptly and with no clear strategic understanding about why and how? Based on this observation, we concluded that a non-uniform partition model will be better to enhance the information analysis about consumer needs and wants to be used for new product and service developments. The present article rejects the general uniform distribution assumption and suggests instead a nonlinear regression model as the basis for developing a strategic approach for analyzing variations between potential customer needs in order better to understand what qualities should be further cultivated before product launch. The article discusses resulting value elasticity curves and argues that through the use of such curves, quality attributes can be more clearly separated and classified for a strategic understanding of their future dynamics (life cycles). The new approach is called ‘A Greenhouse Approach for Value Cultivation’. We regard the concept of value cultivation as a complement to the concepts of value creation (Santos, Rebelo, Silva, & Lopes, 2015) and value co-creation (Edvardsson & Vargo, 2015). A key concept in value cultivation is care which easily can be understood when we relate it to a gardener’s cultivation processes for the creation of the most attractive flowers (e.g. roses) in the market. Without continuous care for the individual plants during the creation process, only standard roses will be the result, but with continuous care, much more attractive roses will be the result of the gardener’s work. So value cultivation is the careful development of any product or service characteristics to optimize the value of those features. In the next sections, we will first shortly summarise the advantages and disadvantages of the Kano Model, and after that, we will present our suggestions for a new model called ‘The Greenhouse Model’ which we have found useful for initiating further value cultivation. The Greenhouse Model will be presented and tested by using case study data in subsequent sections of this article and the value elasticity curves are estimated. After that follows a reflection section on the strategic implications of using the Greenhouse Model in the final design and development of new products or services. The article will end up with a conclusion section with suggestions for further research on how to refine further the Greenhouse Model.

Customer needs should be analyzed based on interpretations of the voice of the customer (Jiao & Chen, 2006), and after understanding customer preferences a classification and prioritization of the requirements are advised. The strength of the Kano Model is its simplicity which makes it easy to understand and hence explain to others the roles different quality attributes play for customers. The classification methodology suggested for the classification of product or service attributes is also relatively simple to understand and explain. Because of its simplicity and its relevance, together with the need for such a model, the Kano Model soon became popular and spread to a variety of applications within production and later service areas (Witell, Löfgren & Dahlgaard, 2013). The Kano Model, however, was not equipped with a reliable quantitative assessment methodology, and the subjective classification of customer requirements lacks logical classification criteria, thus providing limited decision support (Xu et al., 2009). In short, Kano et al. (1984) defined customer requirements as to quality attributes and classified them into six alternative categories based on the so-called Kano Questionnaire (Table 1.4.1). Selected customers are asked to fill out such a questionnaire which has two questions, a functional question, and a dysfunctional question, for each quality attribute. Based on customers' perception of each pair of questions, the classification follows directly from the questionnaire. For example, if a selected customer has circled 1 (I like it that way) on the functional question and 4 on the dysfunctional question (I can live with it that way) then this quality attribute will be classified as an Attractive quality attribute. By using such a questionnaire quality attributes are classified into one of the following six categories:

A = Attractive quality, O = One-dimensional quality, M = Must-be quality,

I = indifferent quality, R = Reverse quality, Q = Questionable category

Surprisingly, Kano and his group did not suggest a supplementary quantitative measurement scale to help in differentiating between the various qualitative response combinations in the questionnaire. For example, it follows from the questionnaire that three response combinations lead to Attractive quality, nine combinations to Indifference quality, and three combinations to Must-be quality. We do not think that the three combinations leading to an Attractive quality classification have the same value to the customers and the same with the other too broad classification categories. Hence, we suggest in this article, a new quantitative measurement scale together with a new assessment model, the Greenhouse Model, to make the classifications more accurate and more understandable.

Löfgren and Dahlgaard (2013) posed a question for the research community on how to support managers with knowledge on the theory of attractive quality and further how to develop the Kano methodology. Several scholars have tried to build a new refined Kano Model. Berger et al. (1993), Matzler, Hinterhuber, Bailom, Sauerwein, and (1996), Newcomb and Lee (1997), Sampson and Showalter (1999), Martensen and Grönholdt (2001), Yang (2005), Xu et al. (2009), Kuo, Chen, and Deng (2012), are some of the most important suggestions. All the suggested approaches have examined different Kano deficiencies striving to refine the existing Kano methodology. All those authors understood that the Kano categories are too imprecise for managerial practice and have provided various evaluation criteria for enhancing accuracy, but they mainly used the suggested approaches for analyzing customer satisfaction/dissatisfaction and importance criteria on quality attribute classifications of existing products and services. What is needed now is a new approach which deepens its position into the theory of attractive quality and transforms it into a practical management tool to support new product and service design. Our suggested new approach is called 'A Greenhouse Approach for Value Cultivation' and the development of this approach started with the development of the Greenhouse Model explained in the following section.

Tab. 1.4.1 Respondents' use of the Kano Questionnaire and the six alternative classifications

What is your perception of the existing quality/service attribute?		Dysfunctional question: What is your perception of the quality attribute if it is not part of the product/service?				
		I Like it that way	It must be that way	I am neutral	I can live with it that way	I dislike it that way
Functional	I Like it that way	Q	A	A	A	O
	It must be that way	R	I	I	I	M
	I am neutral	R	I	I	I	M
	I can live with it that way	R	I	I	I	M
	I dislike it that way	R	R	R	R	Q

Based on literature and empirical research, the suggested Greenhouse Model was a further development of the HWWP Model (Potra et al., 2015). The model is constructed based on the following four main categories: Potential, Maintenance, Growth, and Wealth. Each of these categories can then be sub-divided into four sub-categories as can be seen in Figure 1.4.1 The background for using the name Greenhouse Model is that we have found it useful to compare the early processes in new product and service design with the processes a gardener follows when he cultivates new plants in a greenhouse. A gardener may have a lot of potential plants in his mind before he selects the seeds to be put into the soil. We can compare the potential plants and seeds with the first step in new product and service design – the idea generation phase. In this step, there will always be a lot of ideas that have to be selected and cultivated or rejected for some reason. In the end, the gardener has to choose between the alternative seeds to be put into the soil, and the same is the case with a project team responsible for developing a new product or service.

After the seeds have come up as tiny or small plants, the gardener will cultivate them further in another part of the greenhouse which we have called maintenance. All seeds need in the beginning to follow a simple cultivation process where the aim is to assure that the tiny plants will have enough space and get the right fertilizer for growing fast. After a while, the gardener will then select the plants which he expects the market will find most valuable and he will do special cultivation and care of those plants. The selected plants will be moved to a new part of the greenhouse – the growth area – which consists of plants that the gardener expects to have both high market value and also high importance because he has previous experiences with similar types of plants. The wealth category consists of plants which are quite new to the market so the gardener expects that before market launch such plants will not be regarded as highly important but he expects that after a while the selected plants will surprise, charm, and delight the customers and hence the market will regard such plants as both highly valuable and highly important. When compared with a project team's problems, challenges, and processes when moving from the idea generation process to the blueprint or prototype of a new product or service it is not too difficult to compare the project teams problems, challenges, and processes with the gardener's problems, challenges, and processes. Both the gardener and the project team need to have a deep understanding of the market, meaning customer needs and wants, and both need to develop and cultivate new or existing products or services which they expect will satisfy or exceed customer needs and wants. Both the gardener and the project team have the challenge of how to identify and satisfy latent needs. The Greenhouse Model is, as shown in figure 1.4.1, built upon the following two variables related to each attribute: (1) Importance; (2) Value added. Wherever quality attributes are first located in this diagram, the model offers invitations and opportunities for discussing strategies for future enhancement of the importance degree through promotion/customer education and increased value-added through continuous renewal.

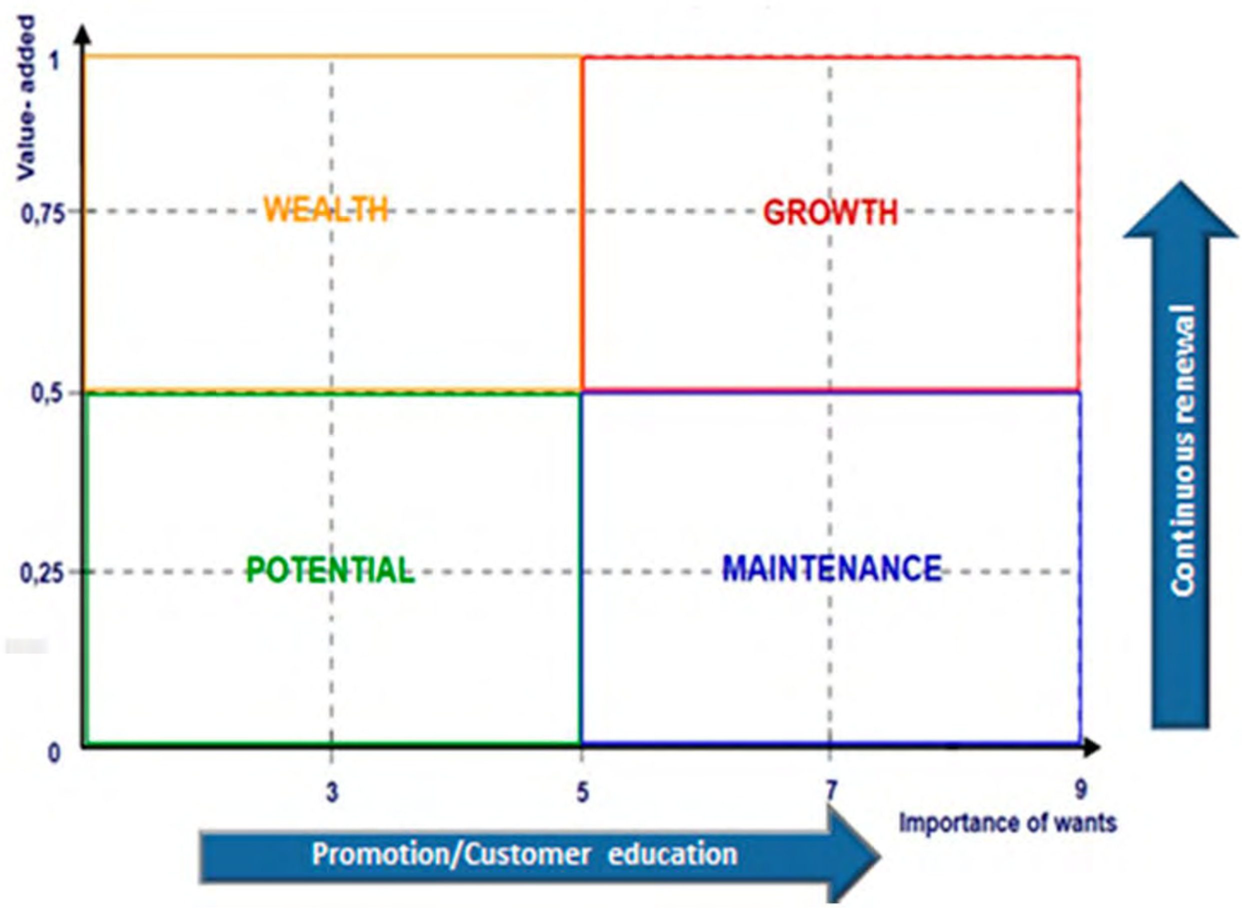


Fig. 1.4.1 The Greenhouse Model

For a better understanding of the Greenhouse Model, we have re-tested Potra et al.'s (2015) case study data of a new web-based customization service for a Romanian shoe manufacturing company to check if the results can be more accurately analyzed by using the Greenhouse Model. A Kano questionnaire was designed based on a pair of questions for each specific service characteristic. Thereby, one question from each pair had a functional form (concerning the reaction of the customer if the product had that feature), and the second question had a dysfunctional form (concerning the customer's reaction if the product did not have that feature). A standard importance questionnaire was also used with the following scale: 1 (Not at all Important) . . . 9 (Extremely Important).

Before applying these two questionnaires an optimal proportional sample size was established. People from 18 to 35 years old who had demonstrated an increased online buying behavior responded to the questionnaires, both by mail and by standard face-to-face oral interviews, totaling 166 individual valid responses.

Each quality attribute proposed for the customization service was classified into one of the Kano categories below (see also Table 1.4.1). The classification into R = Reverse category and Q = Questionable category was not included in this first data analysis.

A = Attractive quality category, O = One-dimensional category, M = Must-be quality category, and I = Indifferent quality category.

Together with the classification of each attribute into one of the above categories, we also used distribution data for each attribute showing how many of the 166 respondents had evaluated the attribute as A, O, M, or I. The distribution data were used to analyze the value-added criteria (the Y-variable of the model) based on Berger et al.'s (1993) customer satisfaction coefficient (SC) calculated as Equation (1.2.1)

The SC coefficient ranges from 0 to 1; the closer the value is to 1, the higher is the influence on customer satisfaction as well as the customers' perceived value. In our previous study, we used this coefficient to represent the value an attribute adds to a service (Potra et al., 2015). Table 1.4.2 presents for each attribute the identified Kano categories, the satisfaction coefficient (SC) as a measure of the value-added variable, the average customer-stated importance, and the main domains of the suggested Greenhouse Model. Figure 2 shows the Greenhouse Model with the 14 points of averages (Importance, Value) = (Xavg,Yavg). As can be seen from Figure 1.4.2 and Table 1.4.2, the Greenhouse Model has refined the Kano Model classifications by taking into consideration the average importance which customers have assigned to the specific quality attributes and the average value (= SC) each attribute adds to customer satisfaction. The Greenhouse Model assigned attribute six into the upper part of the Growth quadrant which indicates that the attribute is extremely valuable as a growing strategic advantage in future service market differentiations. The quality attributes 12 and 13 – customization requirements – were both classified with the Kano Model as attractive quality classifications, and the Greenhouse Model classified both of them as growth characteristics. The quality attribute 12 – customizing leather material – has higher importance as well as a higher value-added compared with quality attribute 13 (customizing accessories). This indicates that it may be a good strategic decision to invest more money and time to improve attribute 13 so that both value-added and importance are improved further and its position changes to the top position of the growth domain where attribute 12 right now is situated. As the above discussion clearly shows the Greenhouse Model offers better decision support for a new product or service designs than the Kano Model. However, the Greenhouse Model may even be further refined into a square-shaped model, which, together with a suggested new value measurement scale, can provide even better strategic information for managerial thought. The development of such a model will be discussed in the following sections.

Tab. 1.4.2 Quality categories, satisfaction coefficient, importance, and greenhouse domains

Customisation requirements		Category	Value added (SC)	Stated importance	The greenhouse domains
(1)	Information clarity and concision	O	0.62	8.44	Growth
(2)	Ease of use	O	0.59	8.06	Growth
(3)	Loading time optimisation	O	0.67	8.50	Growth
(4)	Fast order confirmation	M	0.49	8.63	Maintenance
(5)	Modern design	A	0.63	7.16	Growth
(6)	Product 3D format	A	0.80	7.28	Growth
(7)	Image rotation	A	0.71	7.68	Growth
(8)	Customisation storage	A	0.58	6.89	Growth
(9)	View of other customer orders	I	0.42	4.98	Potential
(10)	Large no of customisable shoes	A	0.65	6.76	Growth
(11)	Customising colour	O	0.76	8.73	Growth
(12)	Customising leather material	A	0.77	7.87	Growth
(13)	Customising accessories	A	0.66	6.92	Growth
(14)	Payment options	O	0.58	8.93	Growth

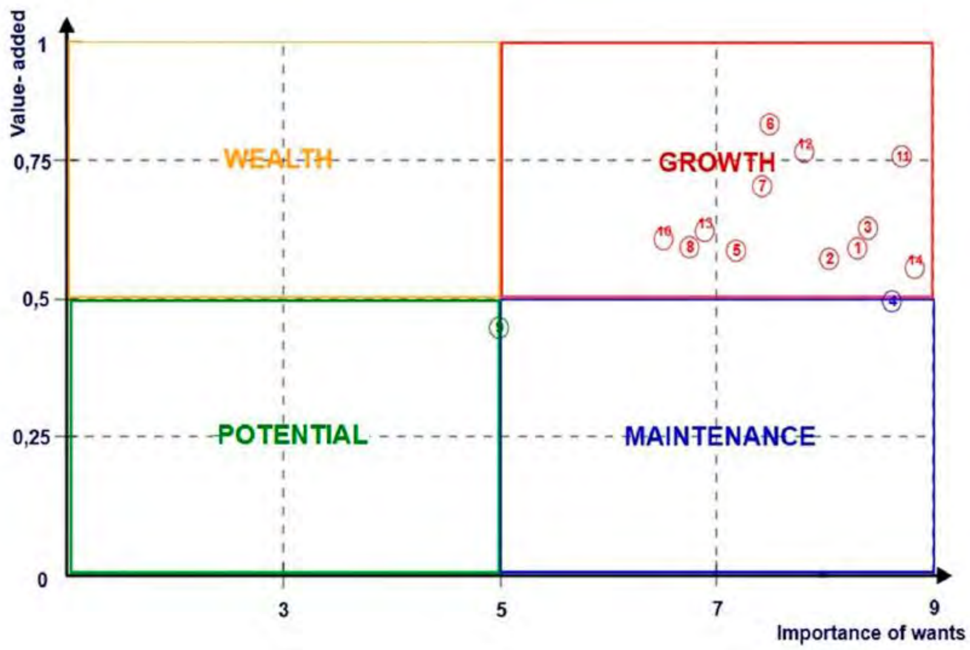


Fig. 1.4.2 The Greenhouse Model with respondents' perception of importance and Berger's satisfaction coefficient as the Value

The value-added variable computed with Berger et al.'s (1993) satisfaction coefficient (SC) provides an overall view of the averages (Importance, Value) = (Xavg,Yavg), but the details about variation within the different categories are not exploited. Also, the attractive (A) and one-dimensional (O) categories are considered to provide equal customer satisfaction when calculating the satisfaction coefficient. Furthermore, Equation (1) does not take into consideration the values of the must-be (M) and indifferent (I) categories in the numerator, indicating that customers regard M and I to have the same values.

Hence it is questionable to use Berger et al.'s (1993) satisfaction coefficient as a value-added variable. Instead, we suggest in this section to use the entire information at our disposal by giving notes and ranks to all six categories depicted from the detailed questionnaire responses.

Farquhar (1994) described adding value as a 'market value' adding distinctive benefits perceived by customers. Thus, the attractive category provides the highest benefits deserving the first rank in the added value criteria followed by the one-dimensional category.

The must-be category does not provide a significant added value (benefits) because it refers to basic needs, and customer delight occurs only when customers' basic needs and expectations are exceeded (Naumann, 1995).

The indifferent category may at a first glance be considered as providing no value, but when we think about a product such as a mobile phone, in the design stage it has several quality attributes that are assessed differently by different customers. For most customers in developed countries, a built-in camera is seen as a must-be attribute, a touch screen as one-dimensional, a 3D function as attractive, and an additional button for web navigation as indifferent.

However, this does not mean that only the first three attributes provide value (benefits) and the last provides none. It does only mean that for the time being a 3D function provides less interesting benefits and therefore for the majority of users they are indifferent (they do not care too much if they have those benefits or not).

Thus, we may consider the lowest value marks for the indifferent. For the above reasons, we suggest using the value scale suggested in Table 1.4.3, and we will use this scale together with respondents' importance perceptions to estimate potential relationships between value and importance.

As seen from Table 1.4.3, we used in this article an 11-point integer scale starting with zero given to Kano's R and Q categories and some I categories. It follows that the three A (Attractive) combinations are valued as 10, 9, and 8. The O (One-dimensional) is valued as 7. The three M (Must-be) combinations are valued as 4, 5, and 6, three out of the nine I (Indifference) combinations are valued as 1, 2, and 3, and the remaining I combinations are valued as zero together with the R and Q combinations.

The qualitative description of these values follows below. These qualitative descriptions were our first logical test when we selected the below value scale. The remaining part of this article shows also our first empirical tests of the reasonableness of this new value scale related directly to the Kano Questionnaire.

Tab. 1.4.3 Suggested Value scale related to respondents' use of the Kano Questionnaire

Quality Attribute		Dysfunctional				
		I Like it that way	It must be that way	I am neutral	I can live with it that way	I dislike it that way
Functional	I Like it that way	Q 0	A 10	A 9	A 8	O 7
	It must be that way	R 0	I 3	I 2	I 1	M 6
	I am neutral	R 0	I 0	I 0	I 0	M 5
	I can live with it that way	R 0	I 0	I 0	I 0	M 4
	I dislike it that way	R 0	R 0	R 0	R 0	Q 0

- Value 10: It must be that way if it is not there but you like it if it is there. This should be the highest positive value an attribute can get. Hence value = 10.
- Value 9: You are neutral if it is not there but you like it if it is there. This should be the second-highest positive value an attribute can get. Hence value = 9.
- Value 8: You can live with it if it is not there but you like it if it is there. This should be the third-highest positive value an attribute can get. Hence value = 8.
- Value 7: You dislike it if it is not there but you like it if it is there. This should be the fourth highest positive value an attribute can get. Hence value = 7.
- Value 6: You dislike if it is not there but it must be that way if it is there. This should be the fifth-highest positive value an attribute can get. Hence value = 6.

- Value 5: You dislike if it is not there but you are neutral if it is there. This should be the sixth-highest positive value an attribute can get. Hence value = 5.
- Value 4: You dislike it if it is not there but you can live with it if it is there. This should be the seventh-highest positive value an attribute can get. Hence value = 4.
- Value 3: It must be that way if it is not there but it must be that way if it is there. This should be the third-lowest positive value an attribute can get. Hence value = 3.
- Value 2: You are neutral if it is not there but it must be that way if it is there. This should be the second-lowest positive value an attribute can get. Hence value = 2.
- Value 1: You can live with it if it is not there but it must be that way if it is there. This should be the lowest positive value an attribute can get. Hence value = 1.

The distribution of the 166 respondents' perceptions is shown for each attribute in Table 1.4.4. It follows that for most of the attributes respondents' perceptions can be transformed to the higher values of the 11-point scale but for some attributes, the transformation led to many low-value points such as attribute 9; more than 50% of the respondents' perceptions of this attribute led to the lowest value point (= 0). For building a square-shaped model, the importance of the wants/needs has to be normalized. Table 5 shows the averages of importance and value to be used in a square-shaped model with normalized data, and Figure 1.4.3 shows the square-shaped Greenhouse Model where the averages of importance and value from Table 1.4.4 have been used.

Tab. 1.4.4 Frequency distribution of 166 respondents' perceptions related to new value scale

	Value Scale										
Service requirement (quality attributes)	10	9	8	7	6	5	4	3	2	1	0
(1) Information clarity and concision		5	19	78	44	2			2	12	3
(2) Ease of use		6	18	76	41	1			6	14	4
(3) Loading time optimisation	2	5	33	72	39				2	11	2
(4) Fast order confirmation		2	26	55	60	1			6	14	2
(5) Modern design		50	45	10	1	1			5	8	46
(6) Product 3D format		34	83	10	2				2	6	29
(7) Image rotation	1	25	43	50	18		1			12	11
(8) Customisation storage		20	51	28	16		1		10	9	31
(9) View of other customer orders		21	40	8	1	1			5	3	87
(10) Large no of customisable shoes	2	24	54	2	5	3			4	7	46
(11) Customising colour		15	35	76	26		1			10	3
(12) Customising leather material	1	18	52	56	4	1			3	8	23
(13) Customising accessories		27	55	25	9				1	6	43
(14) Payment options		8	36	51	38	1			6	15	11

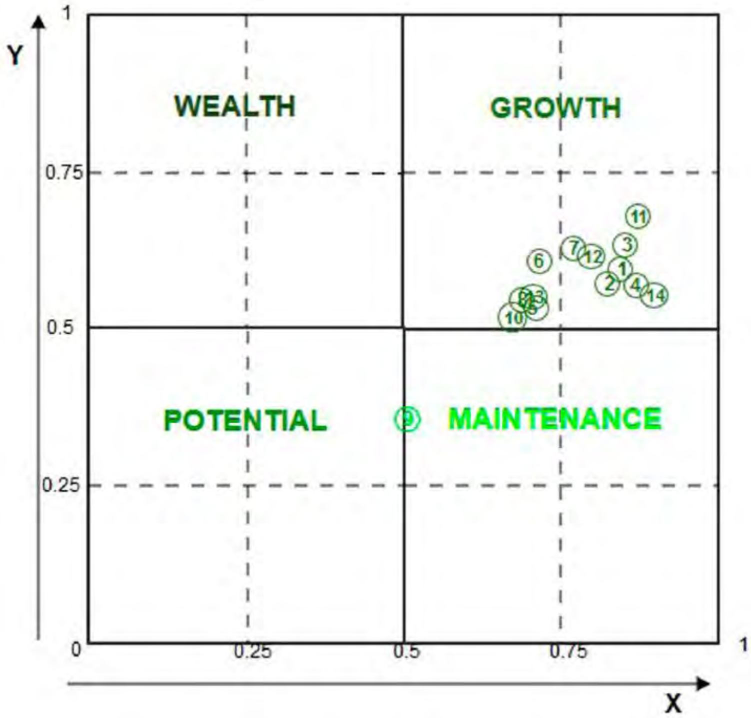


Fig. 1.4.3 The square-shaped Greenhouse Model with the averages (Xavg, Yavg) positioned

By comparing figure 1.4.3 with figure 1.4.2, we observe several significant changes which are caused by the different value scales used. For example, we see no averages positioned in the top-right square of the model while figure 1.4.2 showed that three attributes (6, 11, 12) were positioned in this highly important and highly valuable part of the growth domain. We observe that all average value measurements have been reduced compared with figure 1.4.3.

Tab. 1.4.5 Averages of importance and value with normalized scales {0;1}

Customisation requirements		Importance (X_{avg})	Value (Y_{avg})
(1)	Information clarity and concision	0.84	0.62
(2)	Ease of use	0.80	0.60
(3)	Loading time optimisation	0.85	0.65
(4)	Fast order confirmation	0.86	0.60
(5)	Modern design	0.71	0.54
(6)	Product 3D format	0.72	0.63
(7)	Image rotation	0.76	0.64
(8)	Customisation storage	0.68	0.55
(9)	View of other customer orders	0.51	0.35
(10)	Large no of customisable shoes	0.67	0.52
(11)	Customising colour	0.87	0.67
(12)	Customising leather material	0.78	0.61
(13)	Customising accessories	0.69	0.55
(14)	Payment options	0.89	0.58

1.4.1 The Greenhouse Model based on a non-uniform distribution

The second improvement we propose regards the uniform assumption of the quality attributes' variation of the importance-value data {x,y}. Our statistical tests (using the interquartile range, the Gini coefficient, and the measure of concentration) showed that for the case data the uniform assumption is unreasonable and hence the Greenhouse Model's assumptions should be refined into a nonlinear partition assumption which will increase the entropy (value of information). So, even if the strength of the first refined model – the Greenhouse Model – is its simplicity (based on the uniform distribution) we found it necessary to develop a new refined model which is based on a non-uniform partition of a unit square. For choosing a non-uniform model, we used the regression analysis on the data from the four quality attributes 8, 9, 11, and 13 and used the following nonlinear regression model:

$$\mathrm{Y} = \mathrm{a} \cdot \mathrm{X}^{\mathrm{b}} \tag{1.4.1}$$

where Y = Value of the attribute and X = Importance of the attribute.

Equation (1.4.2) is similar to the constant elasticity demand function (Chen, 2007) represented as:

$$\mathrm{Q} = \mathrm{a} \cdot \mathrm{P}^{\mathrm{b}} \tag{1.4.2}$$

where P = price, Q = demand (measured as a quantity).

Equation (1.4.3) sections the two variables {P, Q} through the diagonal or the point of unit elasticity where ED (elasticity demand) = 1. All points above this region or point (ED > 1) are considered as elastic and all the points below this region or point (ED < 1) as inelastic. Hence, the same is true for model (2) and also model (4) which will be used in the following for estimating potential relationships between customers' perceived importance (X) and value (Y).

For a = 1, the model in Equation (1.4.2) simplifies into equation (1.4.3):

$$Y = X^b \tag{1.4.3}$$

This equation depends only on the parameter b:
For b = 1.0, Y = X, meaning that value is equal to the importance and situated on the 45- degree diagonal. This means that the elasticity between importance and value is equal to 1.0.
For b < 1.0, Y > X, meaning that value is higher than importance. This means that the elasticity between importance and value is less than 1.0.
For b > 1.0 we have Y < X, meaning that value is lower than importance. This means that the elasticity between importance and value is higher than 1.0.
For b = 1 the model in Equation (1.4.2) simplifies into the following linear model (1.4.4):

$$Y = a \cdot X \tag{1.4.4}$$

This equation depends only on the parameter "a" as follows:

- For a = 1.0, Y = X, meaning that value is equal to the importance and situated on the 45 - degree diagonal. This means that the elasticity between importance and value is equal to 1.0.
- For a < 1.0, Y < X, meaning that value is lower than importance. This means that the elasticity between importance and value is less than 1.0.
- For a > 1.0 we have Y > X, meaning that value is higher than importance. This means that the elasticity between importance and value is higher than 1.0.

The relation of models (1.4.2), (1.4.3), and (1.4.4) gives the Greenhouse Model a practical managerial thought by dividing into elastic and inelastic regions where value elasticity is equal to one if the relationship between importance and value follows the diagonal, greater than one if the relation follows a curve (or a section of a curve) above the diagonal, and less than one if the relation follows a curve (or a section of a curve) below the diagonal.

- *Estimation of the model (1.4.3) – nonlinear regression models without intercept*

We used the new value scale data for the attributes 8, 9, 11, and 13 to test the hypothesis assumption that data follow the nonlinear regression model in Equation (1.4.4) with random variations.

The P-values in Table 1.4.6 strongly support this assumption. Table 6 shows the estimated regression coefficients and the coefficient of determination which are relatively high.

The estimated regression models are all situated below the diagonal which means that the variation in the data follows an elastic curve even if some data points may be regarded as outliers about the shown models (see Figures 1.4.4–1.4.6).

The value-added data equal to 0.05 shown in the diagrams are necessary approximations to zero (0) in the 11-point value scale because of the statistical software used for the estimation uses logarithm transformations. In summary, we regard the estimation results as a support for the practical use of the simple nonlinear model in Equation (1.4.4). All of the estimated models showed a relatively high degree of explanation (= determination coefficient). However, we could in some of the estimations observe some strange positions of data points with the highest values. For example in Figures 1.4.4 and 1.4.7, the highest values (9 and 8) had lower importance than the medium values (6 and 7). This observation indicates that there may be a need to fine-tune the scale for the highest as well as the medium values. As mentioned above, this fine-tuning and retesting concerning the applicability of the used nonlinear model in Equation (4) are ongoing right now and could not be finalized to be included in this study.

Tab. 1.4.6 Model (1.4.3) – nonlinear case without intercept

Attribute	Attribute name	Regression coefficients	Coefficient of determination	*P*-value
8	Customising accessories	$b = 2.14$	0.781	10^{-13}
9	View other customer orders	$b = 1.99$	0.806	10^{-13}
11	Customising colour	$b = 2.42$	0.710	10^{-13}
13	Payment options	$b = 2.42$	0.789	10^{-13}

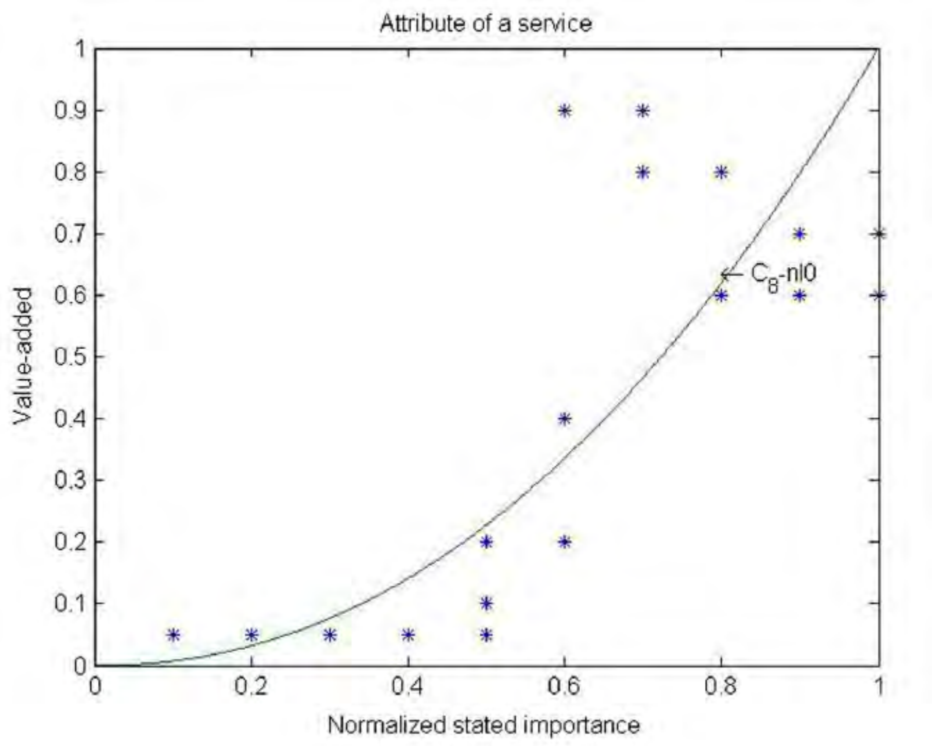


Fig. 1.4.4 Attribute 8 (customizing accessories)

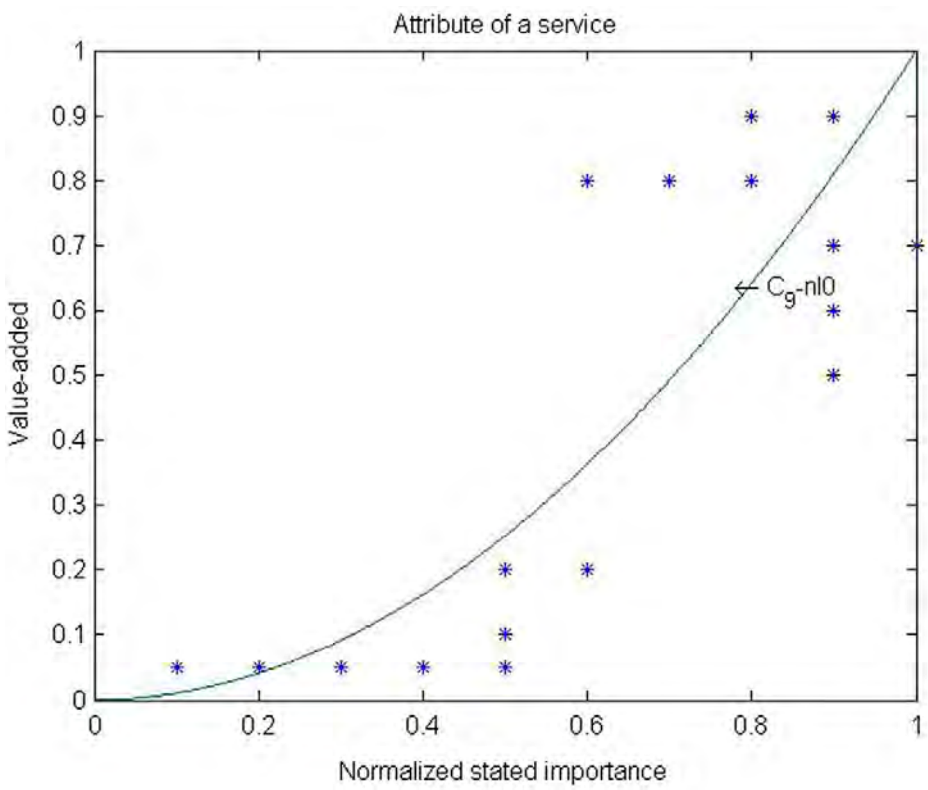


Fig. 1.4.5 Attribute 9 (view of other customer orders)

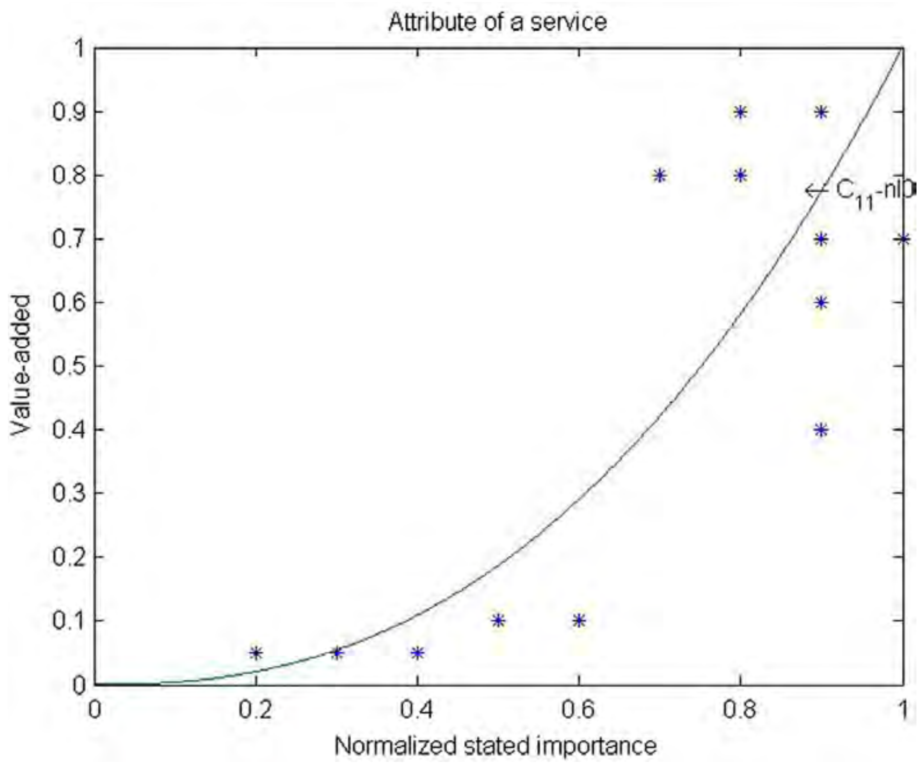


Fig. 1.4.6 Attribute 11 (customizing color)

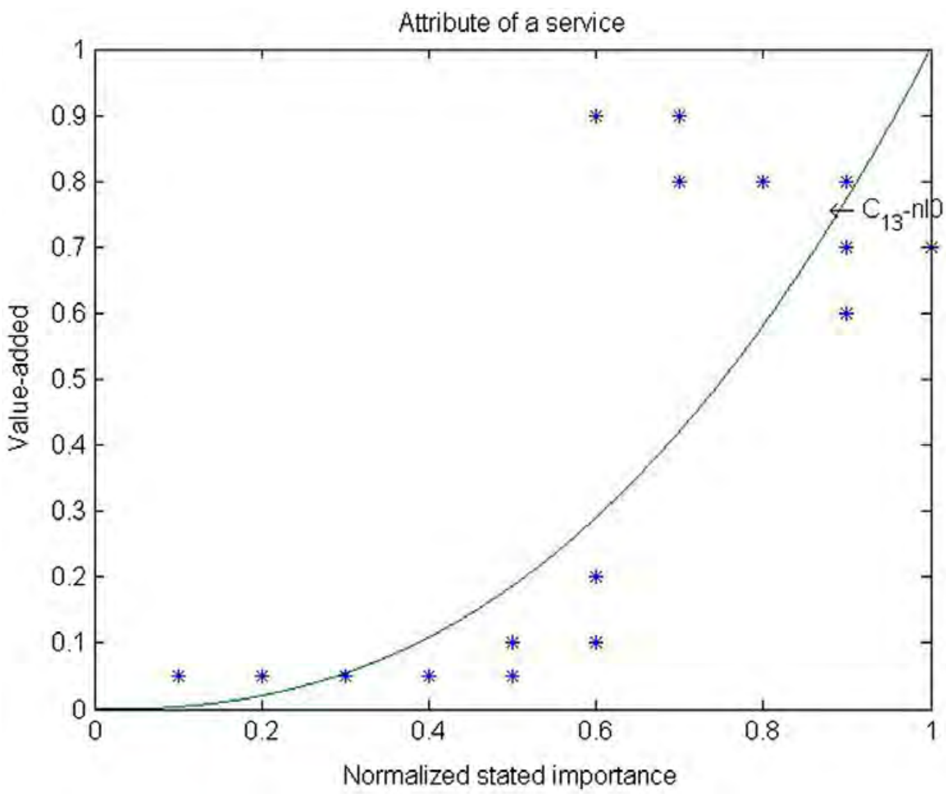


Fig. 1.4.7 Attribute 13 (payment options)

- *Strategic implications*

So what are the strategic implications and possibilities of using models like Equations (1.4.2), (1.4.4), and (1.4.5) together with the Greenhouse Model in the process of further cultivation of the selected attributes where the overall aim is to maximize the final design's capability to affect customers' perception of the value-added? Potential answers to this complex question will be discussed in the following.

In brief, improvements of a quality attribute measured with X = importance and Y = added value situated in an elastic region may have a high potential to satisfy customers. Small improvement of attributes situated in this region may have a substantial effect on customers' perception of added value. Conversely, improvements of a quality attribute situated in an inelastic region may have less potential to create substantial effects on customers' perception of added value. However, as indicated in figure 1.4.1 of the Greenhouse Model, the strategic improvement process may also comprise a selection of attributes which for some reason need to be promoted and selected customers educated. Indications of the need for such activities are (1) Outliers, meaning data points outside the normal variation around the estimated regression models, (2) Low-value data. (3). Low importance data. Attribute 9 has all three indications. From Table 1.4.3, we can see that 87 out of 166 respondents valued attribute 9 (view other customer orders) with a zero value, and we can also see from the table that 21 respondents valued the possibility of viewing examples of what other customers might previously have ordered with a value of 8 and 40 respondents valued this possibility with a value of 7. Why is this variation in respondents' value perceptions? Maybe the negative respondents did not understand how such a possibility may help them when they try to customize the product they consider to buy. Is it possible to promote this possibility or educate in some way the negative customer segment related to this attribute so that most of the negative customers can see the value for themselves and in this way improve such potential customers' perceptions of both importance and value? Is it possible to further develop the web-based customization service so that it includes possibilities for changing the negative customers' attitudes concerning this attribute? We have no answers to these questions but design specialists have to find the answers to such questions before they decide what should be done with this quality attribute during the final cultivation/improvement of the prototype and market launch of the product. The answers are crucial for the cultivation and further development of this attribute so that it can be moved from being just an attribute that potentially gives value to customers to an attribute that is regarded as a growth attribute that customers perceive as highly valuable and important. The Greenhouse Model showing the attribute averages of (X, Y) = (Importance, Value) as perceived by potential customers (as Figure 1.4.3) may be the best tool to use first when starting the strategic process of deciding on the final decisions and processes for what attributes to further cultivate and develop. Figure 3 shows clearly that attribute 9 should have special attention but also other attributes seem to have possibilities for further cultivation. For example, attribute 14 has the highest average importance of the 14 analyzed attributes (= 0.89) but the average value is relatively low (= 0.58). Why? What kinds of improvements are needed to increase customers' value perceptions so that the position of this attribute may move to the upper-right square of the weapon domain?

Because the Kano Model has a qualitative nature and hence gives limited decision support in engineering design the Greenhouse Model was developed as an explanatory paradigm and a more useful option to support strategic decision-making. The Greenhouse Model together with newly developed methods for measuring quality attributes' value effects opened for developing a new practical approach to assess and understand the potential cultivation of the value-added as well as the importance of selected quality attributes. The suggested nonlinear regression model to be used for understanding the variation of customers' perceptions of importance and value gives the possibility to estimate the relation between those two variables and to use those relations as elasticity curves. The elasticity curves section the model into elastic and inelastic regions and provide a natural trajectory for possible life cycle analysis through further value cultivations. Life cycle analysis has previously been discussed only about existing products and services. As we said in the introduction of this article, what is needed now is a new approach that deepens its position into the theory of attractive quality and transforms the theory into a practical management tool to support new product and service design. The elasticity curves, overlapping the Greenhouse Model's four main domains (Potential, Maintenance, Growth, and Wealth), facilitate a clearer understanding of potential customer needs and satisfaction. The elasticity curves together with the Greenhouse Model give a strategic overview of quality attributes' further cultivation and development opportunities so that new products or services can be more accurately designed to fit customer needs. Managers will be able to plan with more precision future cultivation and development stages of each quality attribute. In conclusion, the present research offered a Greenhouse Approach for further value cultivation based on the non-uniform partition with elasticity curves which improves the understanding and the classification of customer needs and especially the added value assessments necessary for an important decision-making tool in a new product or service design.

Based on our comprehensive analyses of the case example, we conclude that the application of the Greenhouse Model with the application of estimated elasticity curves envisages a better managerial and strategic understanding regarding classifications of quality attributes and the strategic selection and forecasting of potential effects of the potential value cultivation.

The new value measuring the 11-point scale used in the article is linked directly to the Kano Questionnaire and tries to utilize all information available instead of just classifying attributes into one of the six potential qualitative categories (A, O, M, I, R, and Q). Berger et al. (1993) suggested also using a quantitative scale by using the satisfaction coefficient (SC) which only uses 4 out of 6 classification categories in the Kano Model (A, O, M, and I categories). We used his quantification method as a start and observed that this approach did not use all information in the Kano Questionnaire. Even if the suggested value measuring scale is, to the best of our knowledge, the first to link the scale directly to the 25 combinations of the Kano Questionnaire (see Table 1.4.1), there is, as we observed when estimating the nonlinear model in Equation (1.4.4), a need for further tests to fine-tune the used 11-point scale. Furthermore, there is also a need to develop new methods for measuring the value and importance variables before and after the newly developed service has been experienced by the customers.

1.5 Generalized HWWP Model

Pugna, Potra, and Negrea (2020), proposed a strategic decision-making tool for new product and service design.

In today's business environment successful companies must differentiate their offer and provide a valuable and desired output. Quality is not enough anymore. According to Munford, Medeiros, and Partlow (2012), a valuable, even innovative output starts with information gathering and organization. The firm can use several methods to handle information and knowledge when proposing a new product or service development. But Bilgili and Unal (2011) argue that the starting point of product design resides in consumer requirements. The corporate offer must delight the customer first, to be successful. Thus, understanding customer demands determine the need to differentiate and manage them. Through time scholars and practitioners have developed and used several methods for assessing the voice of the customer. In the next section, the authors present these methods in detail with an emphasis on the Kano model which founded the theory of attractive theory and determined an explosion of research in this direction. Further, into the literature analysis, the Kano revisions are discussed and the HWWP (Health Weapon, Wealth, Prospect) model is outlined for the specific managerial situation of new products and services. The paper continues with a section called Limitations of the classical HWWP model where a recurring situation for HWWP graphical representations (in Kano representations mainly the same situation occurs) is identified - the agglomeration of quality attributes towards the upper right corner which considerably limits decision making. Thus, the linear approach (square like partition) does not offer sufficient information. In the methodology section, the present research proposes a statistical method to be used every time we have quality attribute agglomerations/clusters and an extended generalized HWWP model that explores the non-uniformity (slice like partition). In the case study section, the new approach is tested for applicability and validity, managing to delimit the strategic life cycle of each analyzed quality attribute.

The quality function deployment (QDF) process is based on the idea that the success of a product or a service largely depends on how they can meet customers' needs and expectations at the same time (Bouchereau and Rowlands, 2000). QFD was one of the leading techniques which helped managers to focus on translating customer needs into technical requirements by using the stated importance of each product or service feature (Wu and Liao, 2018). But the complexity of its charts together with the subjective analysis and the vagueness of the collected data has been its major drawbacks. Also, by ranking customer requirements only based on their importance, managers risk losing sight of other relevant variables.

Another theory that took into consideration the voice of the customer emerged in the service sector. SERVQUAL emphasized a new way of measuring service quality by taking into consideration both customers' perceptions and expectations as a future satisfaction predictor. This method ascertained a service quality's functional dimension through a special questionnaire with a Likert scale for several service quality dimensions. But Ramsaran and Fowder (2005) argue that the SERVQUAL scale needs to be tailored for a sector-specific needs and culture. Ladhari (2009) also summarises several theoretical and empirical criticisms of this scale. Also, the model cannot be applied to assessing product features. As argued by Basfirinci and Mitra (2015), the Servqual instrument needed some modifications and integration with other models for a thorough investigation.

Consumers have certain intrinsic or extrinsic requirements but want also to be surprised by an offer. This situation has led to the development of the theory of attractive quality which tries to classify the different roles quality attributes play for customers. After linear modeling of the performance-satisfaction link, where it was thought that consumer assessment increases or decreases linearly as a product attribute is improved or worsens, scholars have proven otherwise, that we can have different attributes, one which produces satisfaction and another which produces dissatisfaction (Linares and Page, 2011).

Kano et al. (1984) have demonstrated co-existing linear and non-linear attributes, being the first authors to thoroughly address the non-linear relationship between quality attribute performance and overall customer satisfaction (Lin et al. 2010). Thus, this model was thought to comprehensively analyze user demands and obtain the relevant requirements for product and service design (Liao et al., 2015). The Kano model classified each product or service feature in a specific quality category.

These Kano categories or quality dimensions influence differently customer satisfaction when met: the must-be requirement (not explicitly demanded, considered obvious and trigger dissatisfaction if not met), the one-dimensional requirement (specified and expected, the level of fulfillment determines proportionally customer satisfaction), and the attractive requirement (not expected but the level of fulfillment determines more than proportionally customer satisfaction, even delight but does not trigger dissatisfaction if not met). In addition to the main quality dimensions, Kano proposed another three with a very low level of relevancy: the indifferent, reverse, and questionable category.

Kano methodology classified each product/service attribute into one of the six categories by using a special questionnaire with a pair of questions with a functional and dysfunctional form for each product or service feature. The respondent could choose one of five different answers (I like it, it must be that way, I am neutral, I can live with it, I do not like it) for the case when the feature would be present and for its absence. All responses would be analyzed with the help of an evaluation table. Thereby, managers could better understand the roles different attributes play for customers when desiring a product or a service.

Over time the Kano method has been widely used in service quality, organizational strategy and more specific employee performance, consumer perception of product attributes, package design, education, hospitality and tourism, health products, and even new product development (Bu and Park, 2016). But the Kano methodology has also been analyzed and critiqued. Shahin and Zairi (2009) argued that the Kano questionnaire has an imprecise definition of fulfillment (it is not clear if fulfillment of an attribute refers to its existence or its performance) and does not reveal how important an attribute is in the customer’s overall judgment nor how it relates to other attributes. Bu and Park (2016) also express the fact that no one has questioned the methodological validity for the cut-off point of Kano categories. Xu *et al.* (2009) address other weaknesses and Jin et al. (2019) argue a certain degree of inefficiency of the model in identifying the degree of attribute's importance of each quality attribute.

Several scholars have tried to improve the original methodology by modifying the wording of the questions and answers (Chen and Lee, 2009), the evaluation tables (Shahin et al., 2017; Madzik, 2018), the subcategories of the original Kano categories (Shahin and Zairi, 2009), or integrating various methodologies in the Kano model like the quality function deployment (Gangurde and Patil, 2018), importance-satisfaction model, confirmatory factor analysis, improvement index model, improvement performance attribute (Kuo *et al.*, 2012) or Bandura’s triangle from the social cognitive theory (Dace et al., 2019). But the resulting model became even more rigid and resilient (Bu and Park, 2016). More recent approaches envisage combining M-Topsis, Analytical Hierarchy Process (AHP), and Kano (Avikal et al., 2014), Fuzzy AHP with Kano (Wang and Wang, 2014), or Fuzzy Kano with DAQ (directly-asked questions) model (Bu and Park, 2016). All these combinations focus on product improvements and assume a complex methodology with difficult implementation steps for practical use. Therefore they do not seem to be a valid approach in the design of new offers.

Regarding the need to assess quality attributes in relation to the importance for customers, Martensen and Grönholdt (2001) classified quality attributes emphasizing the importance of customer wants. Yang (2005) redefined Kano categories by transforming the four traditional categories into eight: highly attractive and less attractive, high value-added and low value-added, critical and necessary, and potential and care-free. He also discarded reverse and questionable categories with no strategic importance. Kuo *et al.* (2012) proposed an IPA-Kano model with three series of attribute dimensions: must-be, one-dimensional, and attractive. The Kano model and the IPA approach have been also used by Pai et al. (2018) to analyze the impact of different service quality items on customer satisfaction. Gupta and Shri (2018) employed a hybrid approach by calculating the coefficient of satisfaction with S-CR (customer requirements and customer satisfaction) relationship functions and self-stated importance questionnaire. After understanding the qualitative nature of the Kano model, Xu *et al.* (2009) suggested an analytical Kano model that introduces specific indices, classifiers, and evaluation criteria for quantification of customer satisfaction.

A wide variety of Kano related models has been suggested with the final purpose to refine the methodology for a better quality attribute classification. The majority of the work is focused on discussing customer satisfaction with a requirement (quality attribute) versus the performance of the same attribute. Thus, the relationship between the degree of sufficiency and customer satisfaction can be classified into five categories of perceived quality: attractive, one-dimensional, must-be, indifferent and reverse quality. The performance (sufficiency) factor and the perceived quality indicate an earlier customer assessment of quality attributes after consumption of a product/service.

Other Kano-based methodologies (Momani *et al.*, 2014; Meng *et al.*, 2015) are used for improvement purposes regarding the priority or importance of some quality attributes before others. But how can managers assess and even measure quality attribute performance for new offers? Yadav *et al.* (2013) admit that their proposed approach has significant limitations regarding new products that are not already introduced in the market.

Indeed, little research has been undertaken regarding new products and services which do not benefit from earlier consumption assessment. In this situation, we do not have previous performance, nor customer satisfaction (perceived value). Potra *et al.* (2017) argue that in this case, we must take into consideration the quality attribute's value-added potential (desired value).

In this line of reasoning, the HWWP model has been developed for new product and service first time right design, not taking into consideration previous performance

(Potra et al., 2017). From its online publication in 2015 till now, it has been considered a relevant refinement of the Kano method for designing new delightful offers (Wang and Huang, 2018; Galvão et al., 2018) because it exploits Kano findings in the service domain (Borgianni, 2018). The HWWP model constitutes one of the first methods to discuss the importance of indifferent quality attributes, an idea exploited by Shahin et al. (2017) when revising satisfaction and dissatisfaction indexes. It has been used to assess students' requirements in university services (Miclea et al., 2018). Based on the HWWP methodology new improvements have also been proposed: the Greenhouse model (Dahlgaard et al., 2016), a proactive approach as cited by Lawrence and Hammound (2017), and the HWWP non-linear approach (Pugna et al., 2016) with strategic purposes. Lin et al. (2017) have taken into consideration the HWWP model when researching new classification rules regarding the asymmetric relationship between quality attributes and customer satisfaction. The growing interest in the HWWP model, its pleasant visual appearance, and its ease in the application for new offers make it suited for further refinement for a thorough decision-making process.

Founded on Maslow's hierarchy of needs and introduced by two variables: the value-added potential and importance of customer wants for new attribute offerings, the HWWP model responds to managerial demand for relevant and easy to understand the value of possible new product/service attributes. It is constructed on four main domains: Health (eloquent for functional needs), Weapon (envisaging performance needs), Wealth (expressing delight needs), and Prospect (mainly research and development

needs), each with four suggestive dimensions. Wherever quality attributes are first located, the model offers future improvement strategies for enhancement of the importance degree through promotion/customer education and increased value added to the offer through continuous renewal.

Potra et al. (2017) have explored the relationship between customer satisfaction scores of the Kano model and customer's self-stated requirements importance. Mkpojiogu and Hashim (2016) also researched this relationship. They have computed Berger *et al.* (1993)'s satisfaction coefficient (SC) and the dissatisfaction coefficient (DC). After obtaining both results, they have discussed the correlation between customer satisfaction scores and self-stated requirements importance. According to their findings, SC and importance scores are significantly related but DC and importance are not significantly associated. These results support Potra et al. (2017)'s use of the satisfaction coefficient (SC) related to the importance of wants of potential clients. Because the HWWP model is built on a pre-purchase customer evaluation, we cannot measure previous performance; this is why they introduce the term added value potential, which is measured with the help of SC. They have chosen the SC for measuring added value because the value in the case of a new offer refers mainly to attractive and one-dimensional categories. SC can be computed with the help of the relation (1.2.1).

For the second variable of the HWWP model, the same authors use the self-reported customer requirements importance. The voice of potential customers is identified through a standard importance questionnaire that uses the following scale: 1 (Not at all Important)... 9 (Extremely Important). Ullah and Tamaki (2011) argue the fact that the self-stated importance is attribute dependent. Even if the self-stated importance questionnaire has weaknesses due to low discrimination, Mkpojiogu and Hashim (2016) imply that the respective flaws can be minimized by the use of higher sample sizes and by the use of trained and skilled interviewers.

1.5.1 Limitations of the classical HWWP model

The classical HWWP model better classifies and explains the importance and the value quality attributes add to new products and services. But in the graphical representation we can often see an agglomeration of points in the upper right corner of the model (see case studies from Potra et al., 2017; Dahlgaard et al., 2016; Potra and Pugna, 2015 for both HWWP and Kano models). In cases where the points are scattered, the classical HWWP model offers enough information for decision making. But when we have an agglomeration in the graph, the square like partition (a uniform partition without a transition phase) is not suited for an adequate analysis. For example, two quality attributes graphically represented in the Weapon quadrant, associated with the Shield dimension, one in the upper left and the other in the lower right are considered equal, an evaluation which is not entirely correct and can be extremely damaging and costly for decision making on the long run. By investing the same amount of time and money in both attributes, the company may loose in the long run. Therefore, the HWWP model needs to be extended. Lin et al. (2017) also examine the asymmetrical and nonlinear relationship between quality attributes and customer satisfaction. They determine the non-uniformity to better classify quality attributes. Thus, the present paper envisages providing a statistical method for prooving the non-uniformity of the classical HWWP model, immediately followed by a generalized new approach for adequate decision making information.

- *Methodology*

The methodology of the present study is represented in Figure 1.5.1, regarding the process of classifying quality attributes (customer potential requirements) for entirely new products and services.

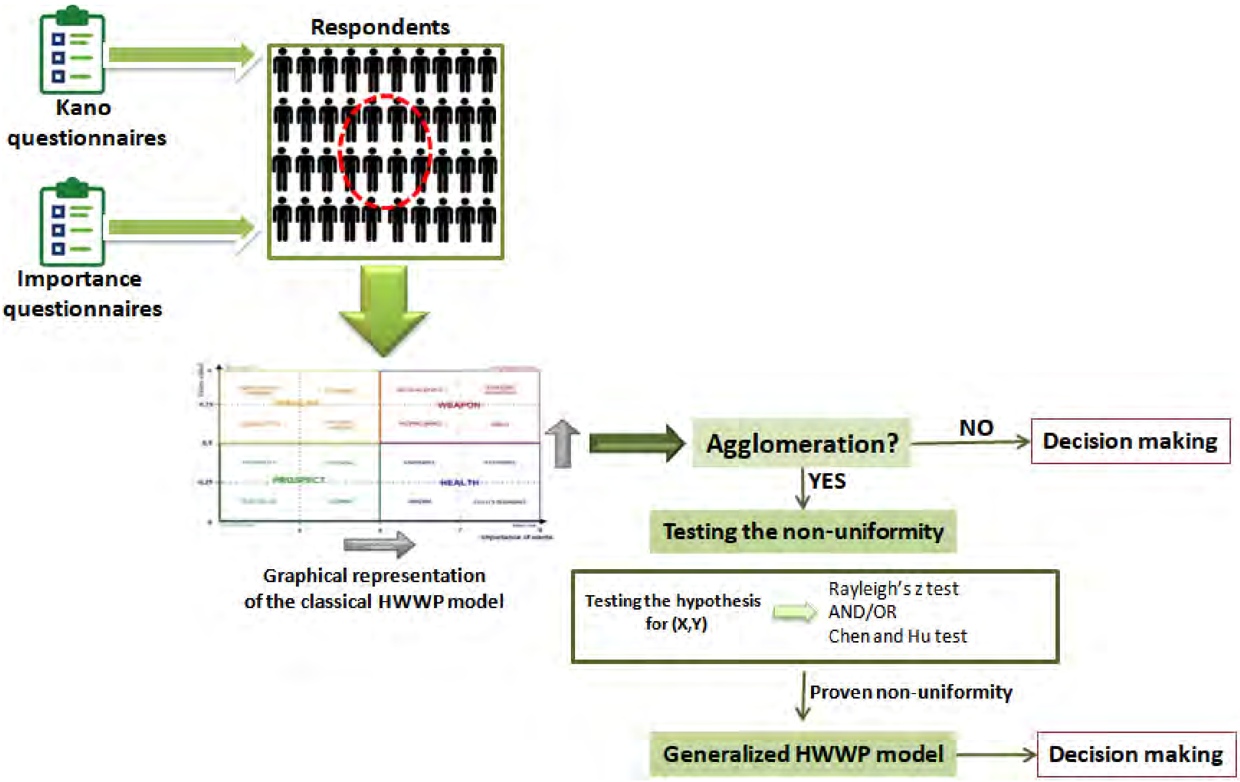


Fig. 1.5.1 The methodology proposed in the study

We start by building a Kano and an importance questionnaire. The results of these two questionnaires are computed to determine the added value and the importance variables for establishing the classical HWWP model. The quality attributes from the model are represented graphically by points. These points can be agglomerated in a corner or not. If the points are scattered and we do not have an agglomeration, we proceed with the final analysis of the current results (we have enough information for managerial decision-making) like Potra et al. (2017) already suggested. But if the points are agglomerated towards the upper right corner, we need to test the uniformity of the HWWP model. We test the hypothesis of uniformity for the vector (X,Y), where X represents the importance of wants variable and Y the value-added variable, providing a clear image of the possible non-uniform distribution. According to our knowledge, the most reliable and generally used statistical methods for testing uniformity of bidimensional vectors are Rayleigh's test and Chen and Hu test. These tests can be used but the choice of tests is not restrictive. In the case of proven non-uniformity, the present study proposes a generalized extended HWWP model for strategic thinking. The results are analyzed for final decision making.

1.5.2 Testing the uniformity of the HWWP model

The first objective of this work is to test the uniformity hypothesis of the points on the square [0, 1] x [0, 1], i.e. to test the uniformity hypothesis for the vector (X, Y). The methods of testing for goodness-of-fit to a uniform distribution have been widely investigated (see a comparison of uniformity tests in Marhuenda *et al.*, 2005). We have chosen to use one of two well known and used statistical methods: Rayleigh's z test and Chen and Hu test. We mention that the Rayleigh's z test gives some information on the orientation of the points in the case of non-uniformity distributions and this information can be used for the last step or our procedure (find a way to extract the points from swarm) and the Chen and Hu test it is a good alternative of Pearson Chi-square test for testing bivariate uniformity. Rayleigh's z test is used to analyze directional data; the existing values must first be transformed into rectangular polar coordinates. It is known that a square [-1,1] x [-1,1] is transformed in a unit circle that has a radius of r = 1 and a center in origin (0,0). In our case, the square [0, 1] x [0,1] is transformed in a circle by the radius 0.5 centred in (0.5, 0.5). Therefore, the standard (Cartesian) coordinate must to be translated from [0,1] x [0,1] in the square [-1,1] x [-1,1] . Next, the polar location is then defined as the angular measurement and its intersection with the unit circle. The cosine and sine functions are then used to place this location (based on the angle and unit distance) into a standardized Cartesian space.

$$\cos(t_i) = \frac{x_i}{r_I}, \qquad \sin(t_i) = \frac{y_i}{r_I} \tag{1.5.1}$$

and, inverse

$$t_i = \arctan\left(\frac{y_i}{x_I}\right), \qquad r_i = \sqrt{x_i^2 + y_i^2} \tag{1.5.2}$$

Thereby, we use the following equations:

$$C = \frac{1}{n}\sum_{i=1}^{n} \cos(t_i)\,, S = \frac{1}{n}\sum_{i=1}^{n} \sin(t_i),$$

$$r = \sqrt{C^2 + S^2} \;\; T = \arctan\left(\frac{S}{C}\right) \tag{1.5.3}$$

where *X* and *Y* are the rectangular coordinates of the mean angle T, and *r* is the mean vector.

The value of *r* is also a measure of angular dispersion, similar to the standard deviation with a few exceptions:

• unlike the standard deviation it ranges from 0 – 1

• a value of 0 means uniform dispersion

• a value of 1 means complete concentration in one direction.

We can use this statistical technique to test the null hypothesis according to which there is no sample mean direction:

- H0: There is no sample mean direction.
- Ha: There is a sample mean direction.

We determine the Rayleigh's z statistics using the equation (1.5.4)

$$Z = n \cdot r^2 = n \cdot (C^2 + S^2) \tag{1.5.4}$$

where n is the sample size and r is taken from the mean angle equation.

The critical values for the Rayleigh *z* test can be found in Zar (1981) or Wilkie (1983). From above, one can see that this test is for directional (circular) statistics for the unit circle (centered in the origin by the radius 1). We replace the Cartesian values with the polar values and then we translate the circle centered in (0.5, 0.5) in the origin. The hypothesis on the uniform direction is false if the points in the circle are concentrated in a circle area. Chen and Hu (2014) developed an alternative test for uniformity in a bivariate case. They propose a statistical test with the purpose to test the following hypotheses:

- ✓ H0 : The population distribution is a uniform distribution on [0,1] x [0,1].
- ✓ Ha : The population distribution is not uniform distribution on [0,1]x [0,1].

$$G_2(X_1, X_2) = \frac{(n+1)^2}{(n+1)^2 - 1} \cdot$$

$$\cdot \sum_{i=1}^{n+1} \sum_{j=1}^{n+1} \left[\left(X_{1(i)} - X_{1(i-1)} \right) \cdot \left(X_{2(j)} - X_{2(j-1)} \right) - \frac{1}{(n+1)^2} \right]^2 \qquad (1.5.5)$$

with X1(0) = X2(0) = 0 and X1(n+1) = X2(n+1) = 1.

Under H0 , let $G_{2,1-\alpha}$ be a number such that $P(G_2(X1,X2)) > G_{2,1-\alpha}$, with $0 < \alpha < 1$. Then H0 should be rejected at significance level α if the computed value of the test satisfies $G_2(X1, X2) > G_{2,1-\alpha}$. The critical values for this test can be found in (Chen and Hu, 2014). If the hypothesis of uniformity is validated, then the HWWP procedure can be used. But if this hypothesis is not sustained (i.e. some non-uniform distributions are glimpsed), then a concentration exists and a simple partition of the square [0,1] x [0,1] in more (uniform) sub-squares seems to be inadequate. Hence, the second objective of our work is to give a way to extract the points from swarms using some nonlinear median curves which yield a split of the square in more slices, like trying to build a map for better understanding the potential value of quality attributes.

1.5.3 The generalized HWWP approach

The current HWWP model is represented by an SC coefficient variable which ranges from 0 to 1 and a stated importance variable from 0 to 9. The range from 0 to

9 is advised to be normalized for a tight square-like model. In this way, the suggested mathematical modeling is easier to compute, understand, and visualize. If the statistical method (or methods) sustains the idea of agglomeration discussed earlier, we are motivated to make some corrections regarding the classical HWWP model which describes the relation between (normalized) stated importance and value-added (SC), in four uniform squares. The new non-uniform refined model is based on a supplementary partition with meridian elasticity curves. The idea has been inspired by geodesy and price elasticity. Geodesy measures the earth's orientation in space and the potential orbits for artificial satellites. In the same way, the new approach tries to map the HWWP uniform model by using geographical meridians (meridian arcs) for assessing the potential value each quality attribute will provide to the analyzed new product or service. In this way, each point (quality attribute) from the HWWP model will be given a potential elastic and inelastic orbit and orientation for future value strategic life cycle. All our proposed median arcs for the HWWP model start from the point (0,0) and reach the top and the right side of the unit square. We have chosen the parameters a and b in such a way as to build four functions (curves) which can reach four different points on the top side of the model (in the points (1,0.25), (1,0.5), (1,0.75) and respectively (1,1)) and three curves with points on the right side ((0.75,1), (0.5,1) and respectively (0.25,1)). Based on Pugna et al. (2016)'s observation regarding the overlapping of the curves in the neighborhood of the origin (0,0), we have changed the equation in such as to prevent this to happen.

These curves have an exponential shape for $b > 1$, a logarithmic form for $b<1$, and a linear one for $b=1$. These observations are similar to price elasticity discussions. The constant elasticity demand function is represented as $Q = a \cdot P^b$ (Chen, 2007). We must state the fact that we do not refer to Cheng et al. (2015)'s elasticity, understood as the market power of the firm, where the greater the elasticity, the more dominant customers are in the market (meaning less power for the firm). In our case, elasticity translates into sensitivity to customer demands. Thus, the greater the elasticity of a feature (quality attribute), the valuable it is for strategic management. Such an approach sections two variables (in the case of price elasticity we have price and quantity) through a diagonal or a point of unit elasticity where ED (demand) =1. All above region (ED >1) is considered as elastic and the below region (ED <1) as inelastic. Similarly, when we divide the HWWP model through the coefficients a and b, computed in such a way as to obtain seven equidistance meridian elasticity curves concerning the added-value and importance of wants variables (the top and the right side of the unit square), we project a diagonal (curve 4) which separates an elastic and an inelastic region. In the elastic region, any small change in a quality attribute influences positively or negatively customer satisfaction, unlike in the inelastic region where a value improvement has a reduced influence on customer satisfaction. Our partition uses the following function presented in relation (1.5.6).

$$Y = f(x) = a \cdot x^{b} \tag{1.5.6}$$

Therefore, the HWWP model is partitioned in a non-uniform way through seven elasticity curves which are furthermore presented in figure 1.5.2.

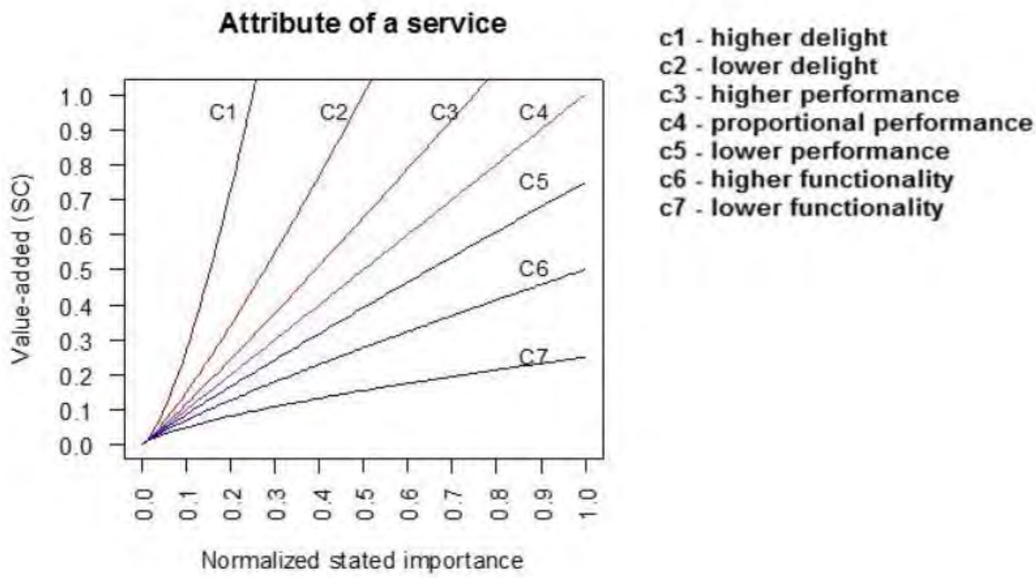


Fig. 1.5.2 The non-uniform partition of the HWWP model

We have chosen seven meridian curves because fewer would not have been able to explain/map the model and more would have made case studies confusing and very difficult to analyze, providing no more relevance. Also, the seven computed meridian curves split the HWWP model in equidistant spherical wedges which meet in some manner the demarcation points for the most relevant HWWP sub-dimensions. The labels of the seven elasticity curves are inspired by Yang (2005)'s integrated Kano categories:

- the curve denoted C1for higher delight: $C1(x) = 7.2670 \cdot x^{1.4307}$ (elastic region)
- the curve denoted C2 for lower delight: $C2(x) = 2.2613 \cdot x^{1.1772}$ (elastic region)
- the curve denoted C3 for higher performance $C3(x) = 1.3591 \cdot x^{1.0666}$ (elastic region)
- the curve denoted C4 for proportional performance: $C4(x) = x$ (regions' divider)
- the curve denoted C5 for lower performance: $C5(x) = 0.75 \cdot x^{0.9375}$ (inelastic region)
- the curve denoted C6 for higher functionality: $C6(x) = 0.5 \cdot x^{0.8495}$ (inelastic region)
- the curve denoted C7 for lower functionality: $C7(x) = 0.25 \cdot x^{0.690}$ (inelastic region)

Quality attributes in a new product or service can be associated to the closest curve according to the formula of distance. We use the minimum Euclidian distance between a point and a curve from a plane XOY. More precisely, this distance denoted with d(P,c) is computed using the following assertions:

- first step, use the Euclidian distance, as in relation (1.5.7).

$$D\left(P(x_0, y_0), c(x)\right)^2 = (x - x_0)^2 + \left(a \cdot x^b - y_0\right)^2 = S(x) \qquad (1.5.7)$$

- second step, find the minimum of this distance using the mathematical analysis technique, i.e. using differential of the function S(x), as in relation (1.5.8).

$$S'(x) = 2 \cdot x + 2 \cdot a \cdot b \cdot x^{(b-1)} \cdot \left(a \cdot x^b - y_0\right) \qquad (1.5.8)$$

- third step – find the solution of the (non-linear) equation S'(x) =0, using a Newton-Raphson procedure, choosing an initial value closed to x0.

Our model is not limited to seven curves; a more partitioned model can be made using the same technique. As a future research direction, the optimum number of curves can be determined with the help of specific statistical techniques, for example the informational criteria of Akaike (1974). If the classical model was represented by Y, X from which an HWWP stage was denoted, the refined model takes into consideration the distance to the closest curve and the elasticity curve direction for a strategic understanding of a quality attribute's present and future value in a new product/service lifecycle.

Potra et al. (2017)'s HWWP model has been applied to a marketing campaign for developing a new co-creation contest for a Romanian shoe manufacturing company. This case study has been chosen because it represents a new service idea for which we do not have prior knowledge. The Romanian public has not been used with such a co-creation creative contest, namely to design its shoe model online. The authors together with the design specialists of the company have proposed 14 potential customer requirements (quality attributes) to be evaluated for an engaging crowdsourcing experience. Because not all those requirements may be appropriate for the new service, a Kano and an importance questionnaire have been constructed and implemented on a sample size of 127 respondents with ages between 16 and 35, both male and female from the urban area, the target group for the respective service. The questionnaires have been implemented with skilled interviewers for more objective results.

Tab. 1.5.1 The 14 co-creation requirements with computed Kano categories

	Co-creation requirements	A	O	M	I	R	Q	Total	Category
1	ease in finding information	9	37	63	18	0	0	127	M
2	ease in loading artistic work	17	44	34	29	1	2	127	O
3	ease in voting/commenting competing works	22	34	41	26	1	3	127	M
4	tools & information facilitation for work improvement	36	51	27	13	0	0	127	O
5	group discussions	31	31	18	47	0	0	127	I
6	new arrivals	21	19	18	68	1	0	127	I
7	most voted works	34	45	16	30	2	0	127	O
8	corporate openness	33	51	19	21	3	0	127	O
9	attractive graphic of the contest platform	70	19	4	32	2	0	127	A
10	manufacturing of the winning shoe design	34	43	18	26	2	4	127	O
11	participant engagement	44	40	17	26	0	0	127	A
12	material reward	45	39	12	26	2	3	127	A
13	community winner appraisal	22	13	14	51	15	12	127	I
14	sales percentage for winner	24	62	21	15	0	5	127	O

The Kano categories evaluate perceived value after use. For a pre-purchase service like the co-creation contest, the categories are not conclusive enough because the respondents have not evaluated the attributes based on previous knowledge. The

HWWP model represents a better option for decision making because it provides more information (customers assign a certain degree of value and importance for each service feature). Therefore, we have computed the HWWP's two variables with a minor change, the importance of wants variable has been normalized for a square shape model and mathematical calculations. In table 1.5.2 the authors explore the Kano categories of each customer requirement, the Satisfaction Coefficient (SC)/Importance of wants variables, and the HWWP resulting dimensions.

Tab. 1.5.2 The results for the contest requirements with the Kano category, SC, Importance variables, and the HWWP dimension

	Co-creation requirements	Category	SC	Importance	HWWP dimension
1	ease in finding information	M	0.36	0.82	Health Assurance
2	ease in loading artistic work	O	0.49	0.84	Health Assurance
3	ease in voting/commenting competing works	M	0.45	0.79	Health Assurance
4	tools & information facilitation for work improvement	O	0.68	0.89	Weapon Shield
5	group discussions	I	0.48	0.49	Prospect Potential
6	new arrivals	I	0.31	0.41	Prospect Potential
7	most voted works	O	0.63	0.76	Weapon Shield
8	corporate openness	O	0.67	0.87	Weapon Shield
9	attractive graphic of the contest platform	A	0.71	0.46	Wealth Precious Jewelry
10	manufacturing of the winning shoe design	O	0.63	0.80	Weapon Strategic advantage
11	participant engagement	A	0.66	0.64	Weapon Helping Hands
12	material reward	A	0.68	0.66	Weapon Helping Hands
13	community winner appraisal	I	0.35	0.45	Prospect Potential
14	sales percentage for winner	O	0.70	0.89	Weapon Shield

The HWWP thus formed is represented in figure 1.5.3, where the added value variable is illustrated as Y and the importance variable as X. As we can easily see in some quadrants we have an agglomeration of quality attributes. What does it mean for quality attribute 5 (group discussions), 6 (new arrivals), and 13 (community winner appraisal), for example, to be situated in the Prospect dimension, a more indifferent HWWP dimension? Are these three requirements equally non-important for decision making? At this point, we do not see a major difference between them.

Fig. 1.5.3 The HWWP model (co-creation contest)

In the same way, quality attribute 9 (attractive graphic of the contest platform) is at the limit between the Wealth and Weapon dimension. The question arises, is it an attractive or more a one-dimensional feature, helping the future service to cope with competition? Decision making in this situation is very risky.

The dynamics of quality attributes in the present HWWP model is very uncertain because the transition from one dimension to another is done abruptly and with no clear strategic understanding. Also, the 14 quality attributes are mainly agglomerated around the upper right corner of the model. This observation brings us to the conclusion that a non-uniform partition model will enhance the information gathering about consumer needs for new products and services. According to Rayleigh's *z* test (Figure 1.5.4) shows our records on the polar coordinates. The hypothesis on the uniform direction is false because the points are concentrated on the first quadrant/circle area. In table 1.5.3 we have computed also the value of our data and compared it to the critical value of the test. Because the computed value is greater than the critical value, once again we reject the uniform hypothesis of the HWWP model.

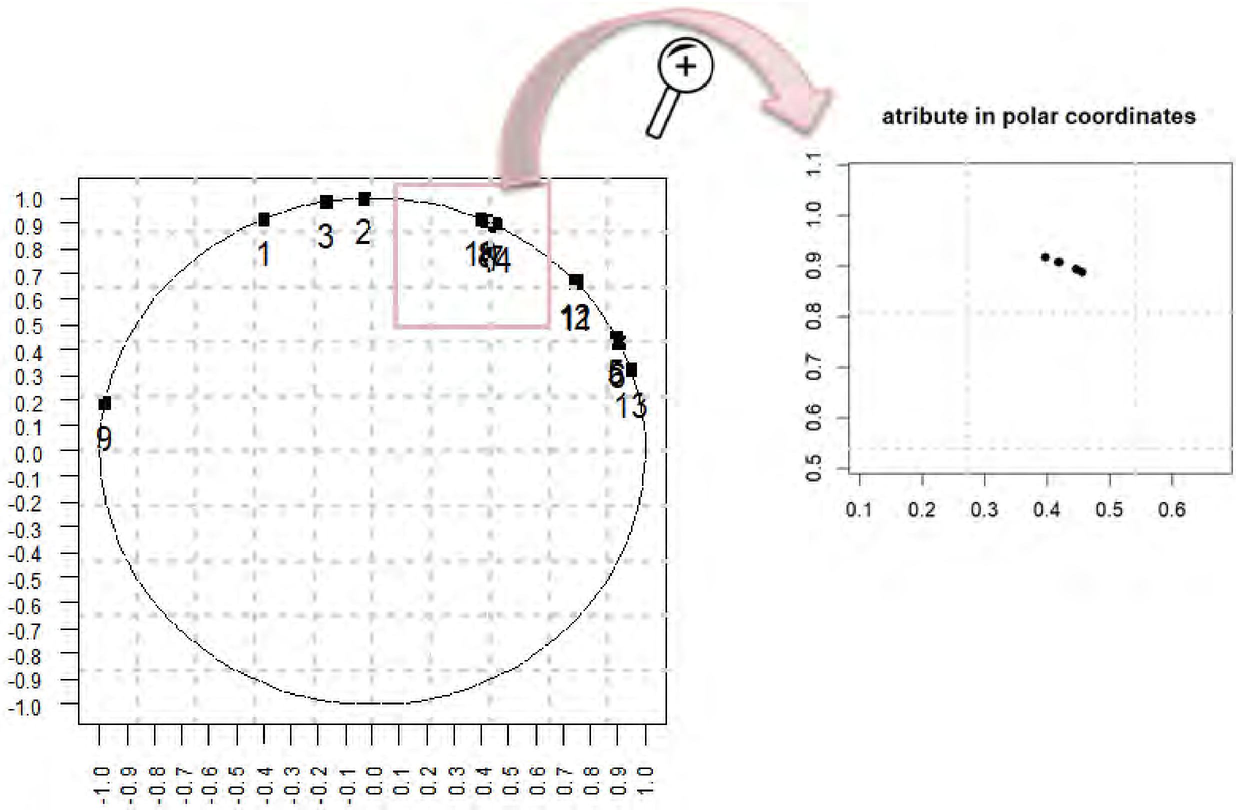


Fig. 1.5.4 Records in polar coordinates according to Rayleigh's *z* test

Tab. 1.5.3 Values for importance and added value variables using the Rayleigh test for directional statistics

Value for uniform directional (critical value)	Computed value (for our data)
2.971	8.890

Finally, we apply the Chen and Hu test, just for another validation of the non-uniformity. According to table 1.5.4, where we have computed the value of our data and compared it with the critical value of this test, our value is greater and therefore we cannot accept the uniform distribution hypothesis of the HWWP model.

Tab 1.5.4 Values for importance and added value variables using Chen and Hu test

Critical value for Chen and Hu test	Computed value (for our data)
0.00426	0.0043

Analyzing the results of the statistical methods, the classical HWWP model is not suitable for adequate decision making. The generalized HWWP described above offers a more comprehensive approach (Table 1.5.5).

Tab. 1.5.5 The 14 attributes of the new contest service

	Co-creation requirements	Category	SC	Importance	HWWP dimension	Distance to the closest curve	Elasticity curve direction
1	ease in finding information	M	0.36	0.82	Health Assurance	0.057	C6 -Higher functionality
2	ease in loading artistic work	O	0.49	0.84	Health Assurance	0.054	C6 -Higher functionality
3	ease in voting/commenting competing works	M	0.45	0.79	Health Assurance	0.037	C6 -Higher functionality
4	tools & information facilitation for work improvement	O	0.68	0.89	Weapon Shield	0.008	C5- Lower performance
5	group discussions	I	0.48	0.49	Prospect Potential	0.007	C4-Proportional performance
6	new arrivals	I	0.31	0.41	Prospect Potential	0.012	C5- Lower performance
7	most voted works	O	0.63	0.76	Weapon Shield	0.041	C5- Lower performance
8	corporate openness	O	0.67	0.87	Weapon Shield	0.091	C5- Lower performance
9	attractive graphic of the contest platform	A	0.71	0.46	Wealth Precious Jewelry	0.010	C3-Higher performance
10	manufacturing of the winning shoe design	O	0.63	0.80	Weapon Strategic advantage	0.068	C5-Lower performance
11	participant engagement	A	0.66	0.64	Weapon Helping Hands	0.079	C4-Proportional performance
12	material reward	A	0.68	0.66	Weapon Helping Hands	0.017	C4-Proportional performance
13	community winner appraisal	I	0.35	0.45	Prospect Potential	0.014	C5- Lower performance
14	sales percentage for winner	O	0.70	0.89	Weapon Shield	0.014	C5- Lower performance

We have applied the refined strategic decision-making tool for contest (co-creation) case study to see if it indeed brings explanations and corrections to the results. Figure 1.5.5 represents the 14 quality attributes in the HWWP model, but their lifecycle can be now forecast depending on the curve they are allocated to.

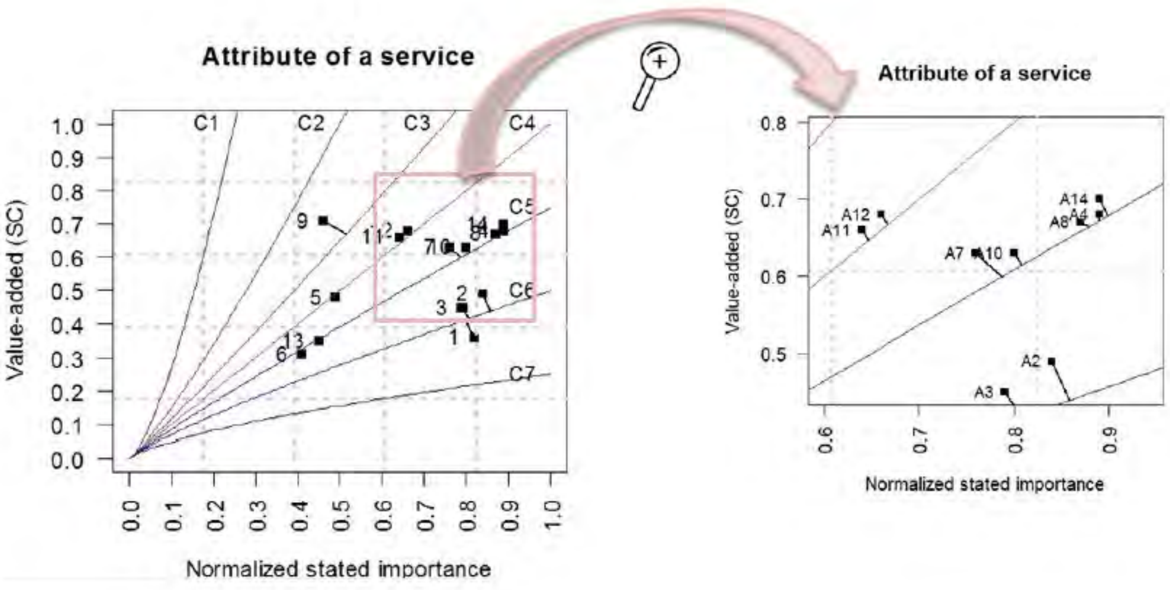


Fig. 1.5.5 The 14 quality attributes in the HWWP model

The 14 quality attributes are modeled in the refined strategic tool, corresponding to one of the seven elasticity curves after thorough computing of the distance between the point and the closest curve. In this way, a quality attribute can be classified with more precision for supporting decision making. Also, by associating a quality attribute to an elasticity curve, the design and management team can foresee a strategic developing path ascending the direction of the curve.

As an example, the quality attributes 5, 6, and 13 situated in the Prospect dimension are not equally discarded. Feature number 5 (group discussions) corresponds to curve 4, becoming a proportional service characteristic that can become a strategic advantage in correlation with the direction of its curve. Quality attributes 6 and 13 are not so valuable, because they are associated with curve 5, a lower performance direction, situated in a more inelastic region. Even if the shoe company invests a huge amount of resources in these two features, they can reach the maximum a "shield" dimension. Thus, it is not advisable to spend too much on low performance (inelastic) features because they have a reduced influence on customer future satisfaction. In the case of quality attribute 9 (attractive graphic of the contest platform), it is allocated to curve 3, a higher performance direction, situated in a more elastic region. This fact guarantees managers and design engineers that even a small investment in the graphic of the contest can influence positively customer satisfaction and help differentiate the service from the competition. The same discussion can occur for all 14 quality attributes of our case study, the new insight can facilitate decision making and strategic forecast of the potential development lifecycle.

Because the traditional Kano model has a qualitative nature and limited decision support in engineering design, the HWWP (Health-Weapon-Wealth-Prospect) model emerged in the literature as an explanatory paradigm and a more useful option in decision making. The present study has normalized the importance of wants variable of the HWWP model and rejected its classical uniform partition based on relevant statistical methods: (the) Rayleigh’s z test and/or (the) Chen and Hu test. Thus, it has been demonstrated that a uniform repartition of results in square dimensions does not provide enough information for subtle decision making. In the uniform HWWP model, a quality attribute’s dynamics could be seen as a precipitous jump from one dimension to another with high financial repercussions for the firm. Instead, the non-uniform partition with the help of meridian elasticity curves first sections the model in elastic and inelastic regions and then provides a natural strategic trajectory (the direction of the curve) for improvement. The non-uniform proposed partition has been realized with the help of seven elasticity curves inspired by the price elasticity of demand principles. The proposed curves have been applied to a new contest co-creation service for a Romanian shoe manufacturer with the purpose to prove the new strategic tool’s applicability. The authors have argued the fact that meridian elasticity curves overlapping the HWWP dimensions facilitate a clearer understanding of potential customer needs and a strategic overview of the possible quality attribute’s development opportunities. By allocating each quality attribute to a curve we can delineate a potential lifecycle path for that specific characteristic. In this way, the new product or service will be accurately designed to fit customer needs. Additionally, managers will be able to plan future development stages for each quality attribute with precision. In conclusion, the refined HWWP model based on a non-uniform partition with meridian elasticity curves wishes to integrate the understanding and classification of customer needs as an important decision-making tool in new product or service design (a pre-purchase context). Future research will focus on adapting the refined HWWP model to take into consideration also the producer’s capability to fulfil prioritized and classified customer needs.

1.6 The HWWP – DDDI model

Potra and **Pugna** (2020), proposed a new model for assessing the voice of the student in a mobile app design stage.

Society has changed drastically in the last decades. The reduction of the birth rate in European countries determined a reduction in the number of candidates for higher education services and therefore caused the emergence of a more competitive market structure (Alves & Raposo, 2007). Higher education organizations have been compelled to adapt and to monitor the quality of the educational services they offer (Gruber, Fuß, Voss & Graeser-Zikuda, 2010). Thomas and Galambos (2004) argue that students are increasingly seen as consumers of higher education services and their satisfaction is key for competitive advantage. Thus, Alves and Raposo (2007) consider as fundamental to analyze and study students' satisfaction in higher education. The same authors take into consideration also the degree of student dissatisfaction and consider it extremely important because it could have ominous consequences for both universities and students. Winsted (2000) argues that service providers will deliver satisfying service encounters if they know what their customers want. Gruber et al. (2010) transpose this idea in the higher education domain emphasizing that increasingly universities are beginning to focus more on meeting or even exceeding the needs of their students. As Joseph et al. (2005) pointed out, service quality in higher education has relied in the past too strongly on the input from academic insiders while excluding the input from the students.

Therefore, the voice of the student has to be the starting point for all higher education services. Satisfaction in higher education is influenced by the student's perception of value (Alves & Raposo, 2007). But value is no longer perceived only after use but desired before purchase. Experts and managers are not able to fully comprehend the complexity of student expectations and need adequate tools for assessing his or her voice when designing appealing and competitive services. Because students are customers for higher education offers, we will use the terms "student" and "customer" interchangeably throughout the paper. The theory of attractive quality and especially the Kano model have transformed how we evaluate quality and customer (in our case student) value. Kano et al. (1984) outlined the existence of both linear and non-linear features and as Lin et al. (2010) argue, addressed the non-linearity between quality attribute performance and customer satisfaction. As argued by Gruber et al. (2010), student satisfaction is influenced by service quality. The Kano method determined the influence of each service feature, called a quality attribute, on customer satisfaction. In this way, it enabled a preliminary prioritization of relevant features for service development and provided a new understanding of these features. Through a specially designed Kano questionnaire with two pairs of questions for each product or service attribute and an evaluation table, six quality categories are determined: attractive, one-dimensional, must-be, indifferent, reverse, and questionable. These categories are extremely helpful for managerial decision making because they entail possibilities for differentiation and priorities for development. Offers that have mainly must-be (necessary) and one-dimensional (explicitly demanded) features are perceived as average and therefore interchangeable, common. It is not wise to improve must be requirements that have a level of appropriate satisfaction but to focus on attractive and one-dimensional requirements since they have a greater influence on customer satisfaction (Gupta & Srivastava, 2011). Attractive features delight customers, whereas indifferent ones are most of the time neglected. Questionable results stand for misunderstood or mistaken responses and reverse features are rare and express the fact that the customer would like the reverse of what it was offered. With time the theory of attractive quality spread across many research areas and opened the way to new related thinking methods. The disadvantages of the Kano model like the inefficiency in identifying the rate of the importance of each quality attribute (Yang, 2003) and many others marked new improvements and the emergence of refined models.

Berger et al. (1993) offered one of the first improvements to the Kano model because they introduced two indicators, the positive and negative customer satisfaction coefficients (CSs), enhancing, as Matzler and Hinterhuber (1998) argue, the understanding regarding the influence of different customer requirements on customer satisfaction. Matzler et al. (1996) together with Zhu et al. (2010) extend the two coefficients to satisfaction index (SI) for the positive CS and dissatisfaction index (DI) for the negative CS. The formula for SI and DI defined by Berger et al. (1993) can be seen in the relations (1.6.1) and (1.6.2):

$$\mathrm{SI} = \frac{\mathrm{A+O}}{\mathrm{A+O+M+I}} \tag{1.6.1}$$

$$\mathrm{DI} = (-1) \cdot \frac{\mathrm{O+M}}{\mathrm{A+O+M+I}} \tag{1.6.2}$$

where SI represents the satisfaction index and DI the dissatisfaction index, A stands for attractive, O for one-dimensional, M for must-be, and I for the indifferent category. SI ranges from zero to one. Its influence is considered as very high when the index approaches the value of one and very low if it approaches the value of zero. On the other hand, DI ranges from zero to minus one because in relation (1.6.2) we add minus one to the computed result to emphasize the negative influence on customer satisfaction if the feature is not incorporated into the product or service. Its negative influence is considered as very high when the index approaches the value of minus one and very low if it approaches the value of zero. Park et al. (2012) summed the absolute value of SI and DI and determined the average satisfaction coefficient (ASC), in the attempt to ascertain a total performance of quality attributes. The formula for ASC defined by Park et al. (2012) is the following:

$$\mathrm{ASC} = \frac{|\mathrm{SI}|+|\mathrm{DI}|}{2} \tag{1.6.3}$$

Regarding the correlation between these three coefficients, neither Berger et al. (1993) nor Park et al. (2012) has examined a possible influence or ratio. The Kano model has been designed to focus on the extent of customer satisfaction and dissatisfaction but does not take into consideration the importance customers attach to quality attributes. As Mkpojiogu and Hashim (2016) argued, satisfaction and importance are not the same and there is an advantage to know the importance of all product requirements. Some attempts have been made in determining a relationship between customer satisfaction and self-stated importance (Zhu et al., 2010). But only Mkpojiogu and Hashim (2016) presented research specifically focused on finding the relationship between customer satisfaction scores of the Kano model and self-reported importance. In their opinion, SI, ASC, and Importance are significantly related. Also, DI and ASC are strongly related. However, SI and DI and DI and Importance are not significantly associated in two tail relationship. The relationship between Di and importance is only one-directional. This discussion will be reassumed in the next chapter of the present paper. The amount of research in the area of the theory of attractive theory shows a growing interest in assessing the relevance of quality attributes. But the majority of models and discussions are focused mainly on refining the Kano method for improving existing products and even services. As argued by Pugna et al. [16], little research has been undertaken regarding new products or services. Thus, the Kano methodology has to be explored in the case of new offers' design. The most recent attempt to refine the Kano method envisaging "the first time right design" have been Potra et al. (2017)'s HWWP (Health Weapon Wealth Prospect) model, that considers the two variables: Berger et al. (1993)'s positive SC (satisfaction index SI) and self-stated importance with the final goal to provide a tool for managerial decision making before the design stage of new products and services. In the next chapter, the two approaches are furthermore analyzed.

The HWWP (Health Weapon Wealth Prospect) model has been developed by Potra et al. (2017) as a refined IPA-Kano methodology for new products or services. It has been grounded upon Kano et al. (1984)'s categories, Berger et al. (1993)'s customer satisfaction coefficient, Yang (2005)'s quality elements, and Kuo et al. (2012)'s health, war, and treasure series. The main four Kano categories, namely attractive, one-dimensional, must-be, and indifferent features, have been incorporated into the positive CS coefficient (or SI), determining a variable of the model named "added-value" or potential value-added. The second variable is represented by the self-stated importance regarding each quality attribute which is determined with the help of a 3-5-9 level Likert scale starting from one "not at all important" and finishing with nine "extremely important". With this new model, the Kano categories have been correlated with the customer stated rate of importance and Berger's satisfaction coefficient. This two-variable diagram displays a visual guide for further decision making because it is divided into four domains with suggestive names: Health, Weapon, Wealth, and Prospect. Each domain is influenced by a certain added value and importance level and is presented as a possible corporate strategy. The main drawback of the HWWP model is the fact that it takes into consideration only the positive customer satisfaction (CS) coefficient, also known as the satisfaction index (SI), neglecting the dissatisfaction index (DI). Sauerwein et al. (1996) argued that scholars need to take into account at the same time the positive and negative CS coefficient and presented a method in which we intersect results for SI and DI. But the concept of importance is not included or it is computed and represented graphically as a variable that only affects the size of the points associated with quality attributes on the graphic.

Mkpojiogu and Hashim (2016) emphasized in their article that importance correlates well with all variables SI, DI, and even Park et al. (2012)'s ASC in a one-tail relationship. The same is true in the two tail relationships, except in the case of the correlation between SI and DI, DI, and importance. The most relevant implication of their results is the fact that there is a relationship between SI and DI, SI, and importance, and between DI and importance. This means a new model could be determined by SI, DI, and importance, not only by SI and importance as we see in the current HWWP methodology.

The present study proposes the refinement of the HWWP methodology, namely the introduction of a third variable - the dissatisfaction index alongside with satisfaction index and importance. If the positive satisfaction coefficient has been renamed as potential added value for the HWWP model because in the case of new products and services customer satisfaction a priori determines an added value to the offer, the negative satisfaction coefficient can be termed as potential value loss. Customer dissatisfaction determines a loss in value for an organization and it is very relevant, thus needs to be taken into consideration before the design process. Depending on the level of value that an organization loses if a specific quality attribute is not fulfilled, we harm the offer's future success. When customer dissatisfaction is very high it can affect basic needs determining *disease*, a "breakdown of the homeostatic control mechanisms" or "a deviation from the normal structural and functional state of an organism", as defined by Encyclopedia Britannica online. Or it can compromise the performance needs causing defeat. According to the Cambridge dictionary, the noun *defeat* is defined as "the fact of losing against someone in a fight or competition, or when someone or something is made to fail". Value loss that affects belonging and esteem needs triggers a *disadvantage* on the market. A negative influence on self-awareness needs does not cause visible harm, but more *inertia*. As Zeelenberg and Pieters (2004) argue, inertia is one of the four behavioral responses to failed service encounters and customer dissatisfaction alongside switch, complaint and word-of-mouth. In Figure 2 the new model based on potential added value, potential value loss, and importance variables is presented. The potential added value variable is computed using the eq.1 for SI and ranges from zero to one. The added value is considered as very high if the variable approaches one. The potential value loss is computed using relation (1.6.2) for DI and ranges from zero to minus one. The value loss is considered as very high if the variable approaches minus one and very low if it approaches zero. The importance variable is determined by a self-stated questionnaire with a 10 point Likert scale where 0 means not at all important and 10 extremely important. The scale can be easily computed to have normalized results ranging from 0 to 1. The potential added value and importance variables determine the four main HWWP dimensions: health, weapon, wealth, and prospect. The potential value loss and importance variables entail the other four main domains: disease, defeat, disadvantage, and inertia. Each domain is formed by the other four sub-domains which better explain the respective areas.

Thus, the *disease domain* (potential value loss 0 – 0.5; importance 0.5 – 1) consists of incubation, prodrome, chronic disease, and acute disease sub-domains, inspired by the phases of infectious disease. Incubation has low potential value loss and medium importance, there are no symptoms but harm increases inside the body. The prodrome phase with a little higher value loss and medium importance is represented by mild and generalized symptoms. The chronic disease has low-value loss but very high importance; its effects are not severe but long-lasting. And finally, the acute disease with medium value loss and very high importance represents severe pain or damage in the body. The *defeat domain* (potential value loss 0.5 – 1; importance 0.5 – 1) consists of disability, tactical failure, strategic failure, capitulation sub-domains. Disability with medium value loss and medium importance has links to the disease and disadvantage domains because it represents in the same time a condition (very often medical) "that impairs or limits a person’s ability to engage in certain tasks or actions" but can be also "a disqualification or restriction", as defined by Merriam-Webster online dictionary.

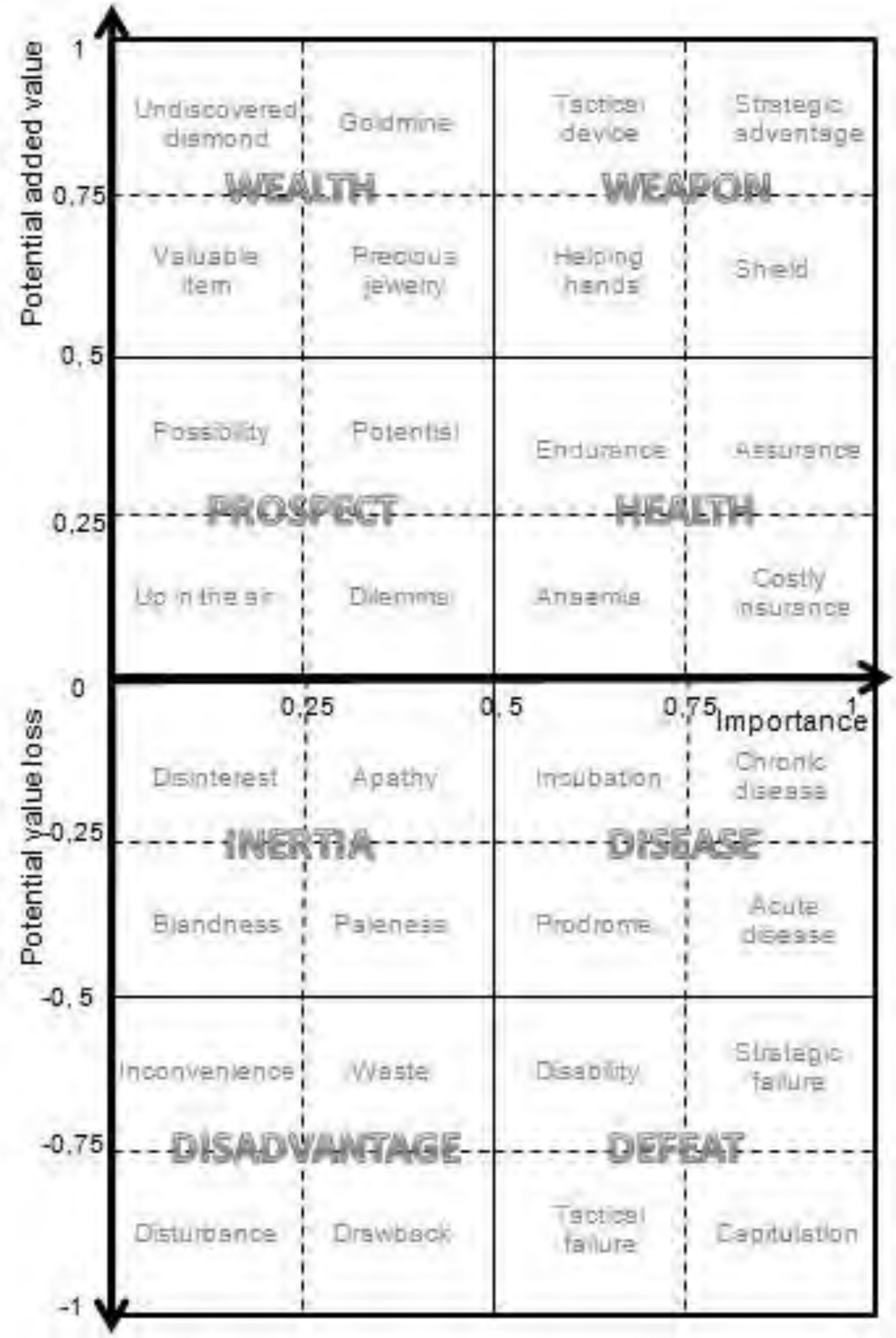


Fig. 1.6.1 The new integrated HWWP – DDDI model

The tactical failure with high potential value loss and medium importance is a small scale failure. A warrior can return in battle but the loss is significant. The strategic failure is a large scale failure due to the high importance it envisages, even if the value loss is medium to high. From such a failure, victory is just a dream.

The final capitulation with high-value loss and importance represents the final defeat. If the specific quality attribute is not fulfilled, dissatisfied customers switch to another offer and the product or service is not able to survive on the marketplace.

The *disadvantage domain* (potential value loss 0.5 – 1; importance 0 – 0.5) consists of inconvenience, disturbance, waste, and drawback sub-domains.

The inconvenience with medium-high potential value loss and very low importance is more a delay or a loss of comfort or a not so important problem that can be often overlooked.

Disturbance has a very high-value loss but still low importance. In this case, the dissatisfaction interrupts and can cause worries.

Waste represents a state when value loss is high but the importance is medium, determining a bad or wrong use of resources.

The sub-domain can be also linked with the term "wastes" which is defined by the Cambridge dictionary as "large areas of land that are not used to grow crops and have few living animals or plants". In this line of this reasoning, a quality attribute not fulfilled can cause waste, a potential not exploited. And drawback with very high-value loss and medium importance describes an objectionable feature, a problem, and a real disadvantage that has to be addressed.

The *inertia domain* (potential value loss 0 – 0.5; importance 0 – 0.5) consists of disinterest, blandness, apathy, and paleness.

Disinterest has the lowest values for both variables, becoming an area where we can disregard the dissatisfaction.

Blandness with medium value loss and very low importance is the tendency to not change what is happening also due to the low importance of the respective loss.

Apathy has medium importance and a low-value loss, and as the name says it already, it represents the situation in which someone is unwilling to take action especially over something important.

And paleness with somewhat medium value loss and importance links the main domains of disease and disadvantage. A pallid person looks unhealthy and is not attractive, showing no enthusiasm or excitement. Besides the SI, DI, and importance variables, the ASC can be computed for further ranking purposes. The pragmatic use of the new model will be furthermore analyzed with the help of a case study from the higher education domain.

For the case study, Miclea et al. (2018)'s proposition of an online application for Romanian university students has been selected. The new application is still in the design stage due to its complexity of features and the tough decision-making process. This application has been considered of great interest because with the proliferation of information technologies, online and e-learning environments, institutions of higher learning need to implement academic resources that promote student success and increase student persistence (Roberts & Styron, 2010). Ottenbreit-Leftwich et al. (2010) found that students are motivated by technology because it can increase their engagement, improve their comprehension, and promote high-level thinking. All these benefits are essential in today's competitive environment for higher education institutions. The 15 features proposed in Miclea et al. (2018)'s research have been slightly modified and are listed in table 1.6.1.

Tab. 1.6.1 The new application's proposed quality attributes

	Quality attribute/ Student requirement	***Requirement details***
1	customizable personal profile	students can personalize their profile in the university app: name, faculty, specialization, picture, filters
2	university library updates	search available resources, return warning
3	unique code for discounts	a unique code for each student to be scanned directly on the smart phone for discounts in libraries, restaurants
4	online attendance	synchronous student attendance visualization on seminaries and labs
5	classroom search engine	search engine for university buildings or new classrooms with visualization option and description
6	online classes timetable	phone screen widget regarding the timetable: classes, classroom shifts, mementos for exams
7	similar English courses	Online courses and resources (in English) from different universities similar to current faculty courses
8	messenger/discussions	discussions within the app with other colleagues, contact for student representatives or professors
9	feedback button	complaints, reporting irregularities
10	online events registration	registration directly on the app for attending university related events like speeches, university days, student contests
11	online news	news from the secretary department, notice board according to personalized filters
12	online tax/penalties payment	online payment option for student home and tuition
13	sport utilities information and online booking	visualization of sport utilities and booking options for a specific hour on the football/basketball field
14	online request for secretariat documents	requests for specific secretary documents directly from the app
15	system operation	the application must operate on all mobile systems (Android, iOs)

The 15 features have been selected and refined from 25 requirements expressed by students through focus groups. The selection supposes that all attributes have a high degree of importance and relevance. This happens also in practice where only the most interesting and advisable features are further researched for possible market success.

The new HWWP – DDDI model addressed observations derived from Miclea et al. (2018)'s HWWP approach. They discussed the very high importance rating and the congestion of points in the weapon dimension.

By computing both SI (potential added value) and DI (potential value loss) and linking them with importance variable, the graphical points had a two-dimension analysis (if fulfilled and if not fulfilled) and thus, all quality attributes could be adequately assessed. Ultimately ASC provided an average result between them for the most relevant features.

The self-stated importance questionnaire had responses ranging from zero importance to 10 extremely high importance. Besides this, the respondents have been a priori explained the Kano methodology and the importance degree. For the present study, 40 responses have been collected. Two skilled interviewers have helped the respondents to fill the questionnaires by answering all of their questions and explaining each feature in detail. For a thorough response to the 15 pairs of questions from the Kano questionnaire and the 15 questions from the importance questionnaire, a respondent needed at least 20 minutes.

The sample size has been heterogeneous, formed by students of the respective Management faculty from the 3rd Bachelor year, with different specializations in mechanics, electronics, chemistry, and constructions. The results collected from the Kano and self-stated importance questionnaires have been computed and are presented in Table 1.6.2. The Kano category has been determined by the classical Kano evaluation sheet according to the frequency of answers.

The potential added value has been calculated according to eq.1 of SI, potential value loss according to relation (1.6.2) of DI, and ASC according to relation (1.6.3). The importance variable has been obtained through the computation of the normalized arithmetic mean of self-stated responses.

Tab. 1.6.2 Results of the Kano questionnaire, SI, DI, importance questionnaire and ASC

Quality attributes	Kano category	Added value	Value loss	Importance	ASC
1. Profile	A	0,63	-0,31	0,49	0,47
2. Library	O	0,78	-0,43	0,61	0,6
3. Student code	O	0,7	-0,57	0,65	0,64
4. Online presence	A	0,76	-0,07	0,48	0,42
5. Classroom search	O	0,73	-0,55	0,61	0,64
6. Online itinerary	M	0,4	-0,77	0,61	0,59
7. Similar English courses	I	0,41	-0,15	0,41	0,28
8. Discussion forum	A	0,73	-0,39	0,53	0,56
9. Feedback button	I	0,37	-0,4	0,48	0,39
10. Event registration	A	0,67	-0,4	0,54	0,54
11. news online	O	0,6	-0,55	0,59	0,58
12. Online payment	O	0,67	-0,6	0,73	0,64
13. sport utilities	O	0,65	-0,55	0,53	0,6
14. secretary docs	A	0,75	-0,35	0,57	0,55
15. system operation	O	0,55	-0,85	0,82	0,7

The potential added value; value loss and importance variables for all 15 quality attributes have been graphically represented through the HWWP-DDDI proposed model in figure 1.6.2.

It is easily observed that the DDDI model does not mirror the HWWP results. On the contrary, the two-phase model explains and delimits very close situated quality attributes in the classical HWWP model. In this way, all the amount of collected information is used.

For example, attribute number 15 – system operation is situated in the weapon domain with the shield sub-domain. From 40 responses, 19 have been situated as one-dimensional, 15 as must-be, 3 as attractive, and 3 as indifferent. When computing only the satisfaction index for the potential added value variable, the impact of must-be responses has been minimized. Even if the quality attribute is situated in the lower part of the shield dimension towards the health domain, its relevance is much clearer in the DDDI model where it jumps to the worst Capitulation sub-domain in the Defeat dimension. From the two indifferent quality attributes, namely 7 – similar English courses and 9 – feedback button, both situated in the potential section of the HWWP model, the quality attribute 9 has a more negative impact than 7 in the DDDI model. Thus, 9 would be good to invest in feature, its absence from the final service representing almost a disadvantage. Finally, for more relevance, ASC is computed.

After quality 15 which has the highest average value, follow quality attributes 3, 5 and 12, and so on.

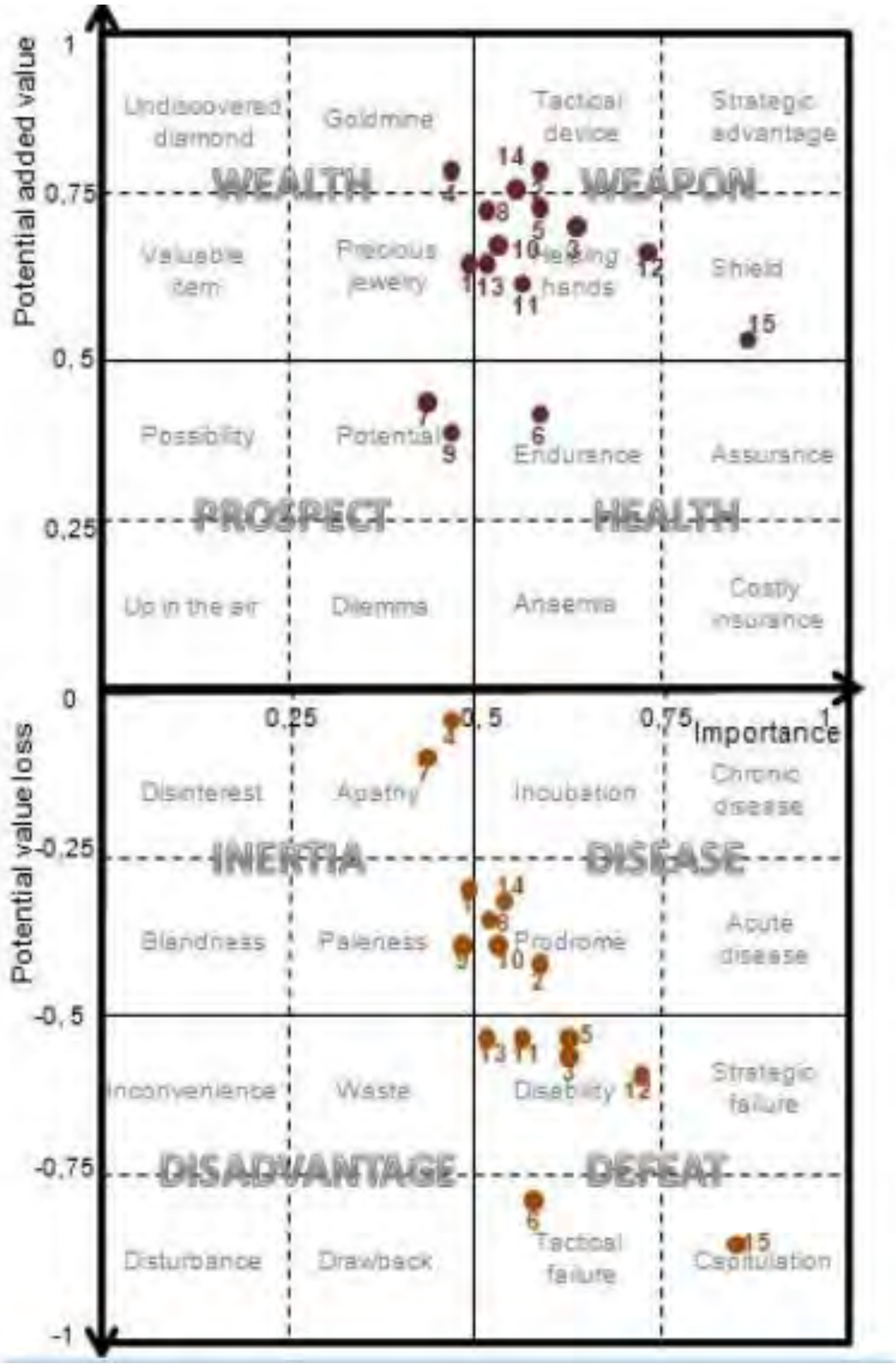


Fig. 1.6.2 The 15 student's requirements integrated into the HWWP-DDDI model

In the last decades, the voice of the student has been rarely taken into consideration. Today's competitive market structure determines a shift in higher education organizational focus towards the needs and wants of its main actor/consumer. Student satisfaction is increasingly associated with institutional success. The antecedent of student satisfaction is service quality. Thus, service quality needs further attention, especially in new offers by assessing as accurately as possible the features that attract students or that are requested by them. For an accurate assessment of the voice of each student, the theory of attractive quality is presented. The Kano model is the most renowned tool to improve existing services, therefore a refinement model named the HWWP model has been developed for the design of new offers. The major limitation of the HWWP model is the fact that it has not taken into consideration the entire amount of information collected from the Kano questionnaires. By computing the negative satisfaction coefficient and correlating it with self-stated importance, the present paper adds another measure to the classical HWWP model. The DDDI model comprises also four suggestive domains that relate to the HWWP ones and offers additional classification criteria for closely related quality attributes. The average satisfaction coefficient induces a general ranking and completes the new model analysis. As a conclusion, the new HWWP-DDDI model is easy to understand and convenient in computation and analysis, offering new perspectives regarding relevant quality attributes assessment. The new model is validated in a case study from the higher education domain, namely in the design of a new application for student use for a Romanian university. Future research directions envisage a higher sample size for generalization purposes and the examination of the ASC coefficient as an overall indicator for relevance classification.

2. Six Sigma Methodology

2.1. Introduction

There are a couple of powerful statements which are defining the future of Quality Engineering and Management, namely, "We are headed into the next century which will focus on quality… we are leaving one that has been focused on productivity" (Joseph M. Juran) and "If I had to reduce my message to management to just a few words, I'd say it all has to do with reducing variation" (w. Edwards Deming).

Six Sigma is a defined and disciplined business methodology to increase customer satisfaction and profitability by streamlining operations, improving quality, and eliminating defects in every organization-wide process. An overview of Six Sigma and DMAIC Methodology is presented in figure 2.1.1(International Six Sigma Institute™, http://www.sixsigma-institute.org).

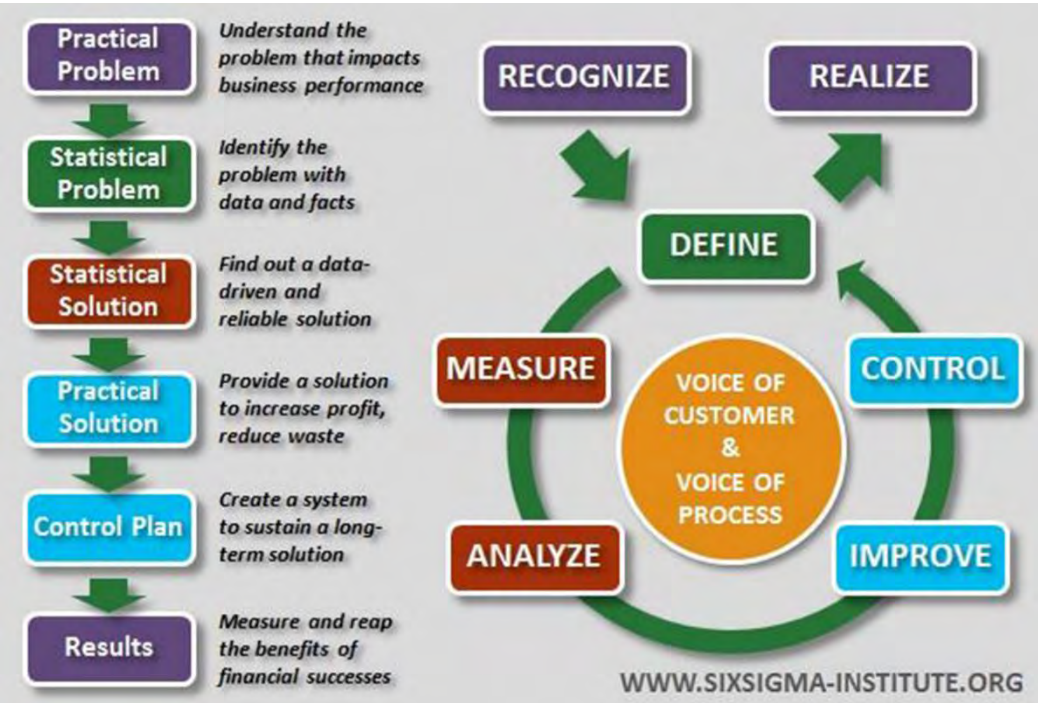


Fig. 2.1.1 Six Sigma and DMAIC Methodology overview (International Six Sigma Institute™)

It is considered that the Six Sigma methodology is the best way for improving quality / reducing waste by helping organizations produce products and services better, faster, and cheaper (Pyzdek & Keller 2010). Tomkins (1997) defines Six Sigma to be "a program aimed at the near-elimination of defects from every product, process and transaction". Harry (1998) defines Six Sigma to be "a strategic initiative to boost profitability, increase market share, and improve customer satisfaction through statistical tools that can lead to breakthrough quantum gains in quality". Park, Lee & Chung (1999) believe that Six Sigma is a "new strategic paradigm of management innovation for company survival in this 21st century, which implies three things: statistical measurement, management strategy, and quality culture". Pyzdek and Keller (2010) believe that Six Sigma is a "rigorous, focused, and highly effective implementation of proven quality principles and techniques. .. Six Sigma aims for virtually error-free business".

According to International Six Sigma Institute™ (http://www.sixsigma-institute.org) (Figure 2.1.2), Six Sigma is a " Business Strategy", a "Vision" a "Benchmark", a "Goal" A "Statistical Measure" and a "Robust Methodology".

Fig. 2.1.2 What is Six Sigma? (International Six Sigma Institute™)

2.1.1 Six Sigma Process Excellence Disciplines

According to the International Six Sigma Institute™ (http://www.sixsigma-institute.org) (Figure 2.1.3), there are 3 Six Sigma Process Excellence Disciplines.

Fig. 2.1.3 Six Sigma Process Excellence Disciplines(International Six Sigma Institute™)

➢ *Process Excellence/Process Documentation*

Process Excellence and Process Documentation helps the project team to define, measure, and control the business processes. Six Sigma and Lean tools are used for both Process Excellence and Process Documentation. Process Excellence and Process Documentation ensures standardization across different processes in the same organization/department, allows business continuity in case of non-availability of Key Subject Matter Experts (SME's), helps to understand the current state of the process, and also to measure the performance of the future state of the project.

➢ *Process Improvement (DMAIC)*

Process Improvement is an effort to identify high priority problems in business processes and to train teams to tackle those problems, the methodology used is called Define-Measure – Analyze – Improve - Control (DMAIC). In the Define phase, the project is defined. In the Measure phase, data is collected, the Measurement System is validated and current performance is identified. In the Analyze phase, root causes are identified. In Improve, solutions are created and implemented In the Control phase, new performance is sustained.

Lean tools such as Value Stream Map (VSM), Pull, and Kaizen are leveraged too.

➢ *Process Improvement (Lean):*

“Lean" is the set of management practices based on the Toyota Production System (TPS). This methodology is deployed in selected processes to identify and eliminate Non-value added activities and hence increase operational efficiency. Lean is quick and avoids rigorous data analysis. There are two critical factors of Lean – Value Added and Non-Value Added. Value is what the customer cares for. It is doing the right thing the first time. Similarly, we should focus on removing non-value-added activities from the process.

➢ *Sigma Score*

From the Six Sigma point of view, the question is how many standard deviations fit between the mean and a specified limit SL. For example, figure 2.1.4 shows that 4 standard deviations fit between mean and SL. The exact number can always be calculated with the relation (2.1.1):

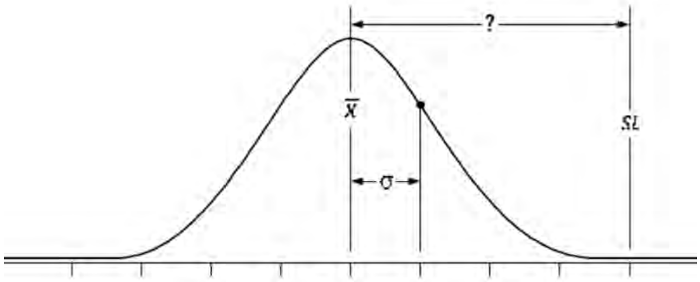


Fig. 2.1.4 Six Sigma Standard Normal Distribution

$$Z = \frac{|LS - \bar{x}|}{\sigma} \tag{2.1.1}$$

The calculation of Z shows exactly how many standard deviations fit between the mean and the specified limit of any process or characteristic. In Six Sigma this value is called the Sigma Score of the process or characteristic. In Statistics, this value is called a Z Score or a Normal Score. Whether it is called Z Score, Z Value, Sigma Score, Sigma Value, or simply Sigma, it expresses how many standard deviations fit between the mean and the specified limit and should not be confused with the standard deviation represented by the Greek letter σ. The Sigma Score (Z) is used only for normally distributed characteristics. A small Sigma Score (Z) means that a significant part of the distribution queue extends beyond the specified limit and therefore the higher the Sigma Score (Z) the fewer defects. The Sigma Score (Z) can be changed in 3 ways:

- ✓ The position of the average changes with the specified limit;
- ✓ The width of the distribution, defined by the standard deviation, changes;
- ✓ The position of the specified limit changes.

- ➢ *Short - term and long - term Sigma Score (Z)*

The calculation of the Sigma Score (Z) is based on the mean and standard deviation, but it must be detected between what kind of standard deviation is used, ie the short - term standard deviation σ_{ST} or long - term σ_{LT}.

If the short-term standard deviation σ_{ST} is used, then the calculated Sigma Score (Z) is a short - term one, as follows:

$$Z_{ST} = \frac{|LS - \bar{x}|}{\sigma_{ST}}$$

The performance of short-term variation, as quantified by the short-term Sigma Score (Z_{ST}), is the best performance variation that can be expected from the current process configuration. It is an idealistic measure of capability and is easiest to evaluate by a relatively small sample collected from the process or on a characteristic. However, if the standard long-term deviation σ_{LT} is available, then the calculated Sigma Score (Z) is a long-term one, as follows:

$$Z_{LT} = \frac{|LS - \bar{x}|}{\sigma_{LT}}$$

In reality, a process or characteristic does not ideally behave as short - term but performance degrades over time.

- ➢ *Connecting short-term capability with long-term performance*

Figure 2.1.5 presents a characteristic Standard Normal Distribution in the short term and extension in the long term (which creates defects).

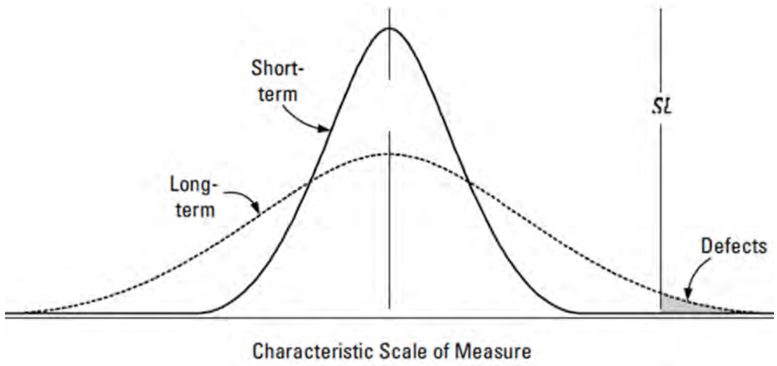


Fig. 2.1.5 Six Sigma Standard Normal Distribution (short – term and long – term)

From a mathematical point of view, it is possible to simulate the effect of this degradation by artificially moving the short - term distribution closer to the specified limit until the number of defects for short-term distribution is the same as for long-term distribution, as seen in figure 2.1.6.

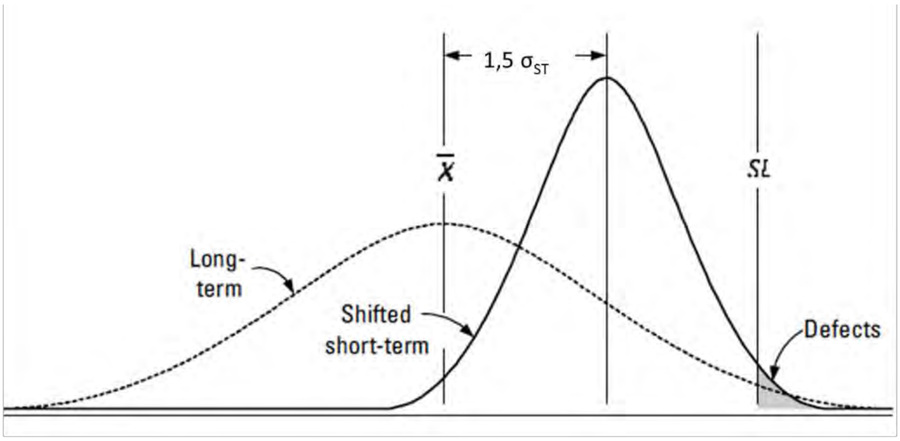


Fig. 2.1.6 Six Sigma Normal Distribution (shifted short – term and long – term)

Because Z_{ST} is the number of short-term standard deviations between the center of variation and the specification, the Sigma Score (Z) of the shifted distribution is as follows:

$$Z_{\text{shifted}} = Z_{\text{ST}} - 1.5$$

But the shifted distribution being equivalent to the long-term one in terms of defects, the previous relationship can be rewritten according to the relation:

$$Z_{\text{LT}} = Z_{\text{ST}} - 1.5$$

In practice, the short-term variability of a process or characteristics is measured and the short-term Sigma Score Z_{ST} is calculated. It then translates to long-term failure rate performance using the shift of 1.5 short-term standard deviations. This long-term Sigma Score Z_{LT} is communicated in terms of DPMO (Defects Per Million Opportunities).

Linking the short-term Sigma Score Z_{ST} to the long-term DPMO can be done by using the table 2.1.1 in two ways. Determine short-term Z_{ST} for any process or characteristic and then translate into long-term DPMO or initially determine DPMO and then translate backward to obtain short-term Z_{ST}.

Tab. 2.1.1 Connection between short-term Sigma Score Z_{ST} and the long-term DPMO

Z_{ST}	DPMO
0.0	933,193
0.5	841,345
1,0	691,462
1.5	500,000
2.0	308,538
2.5	158.655
3.0	66,807
3.5	27,750
4.0	6,210
4.5	1,350
5.0	233
5.5	32
6.0	3.4

For example, a long-term DPMO of 6,210 is the result of a short-term Sigma Score Z_{ST} of 4.0. A long-term DPMO of 32 is the result of a process with short-term Sigma Score Z_{ST} of 5.5. When asked, for example, "How much is the sigma of the process?" and you answer for example “2 sigmas” or “3 sigmas”, in fact, the correct question is “What is the short-term Sigma Score Z_{ST} corresponding to the long term DPMO”.

- *Relationship between Cp, Cpk and Sigma Score*

In general, the connection between Cpk and Sigma Score is according to the relation (2.1.2).

$$\text{Sigma Score} = 3 \cdot \mathrm{C_{PK}} + 1.5 = 3 \cdot (\mathrm{C_{PK}} + 0.5) \qquad (2.1.2)$$

It can then be considered that in the long - term, the link between Cp and Cpk is according to the relation (2.1.3) and presented in table 2.1.2. In tables 2.1.3 and 2.1.4 are presented Sigma Score and different indicators, both for short-term and long-term.

$$C_{PK} = C_P - 0.5 \tag{2.1.3}$$

Tab. 2.1.2 Connection between C_P and C_{PK}

Cp	Cpk = Ppk (a shift of 1.5σ is allowed)	Sigma Score
0.50	0.00	1.5
0.67	0.17	2.0
0.83	0.33	2.5
1.00	0.50	3.0
1.17	0.67	3.5
1.33	0.83	4.0
1.50	1.00	4.5
1.67	1.17	5.0
1.83	1.33	5.5
2.00	1.50	6.0

Tab. 2.1.3 Sigma Score and Yield, Out of Spec., C_{PK}, and DPMO (short-term)

Short - term				
Sigma Score	**Yield %**	**% out of spec.**	**Cp**	**DPMO**
2	95.4500000%	4.5500000%	0.67	45,500
3	99.7301000%	0.2699000%	1.00	2,700
4	99.9937000%	0.0063000%	1.33	63
5	99.9999426%	0.0000574%	1.67	0.574
6	99.9999998%	0.0000002%	2.00	0.002

Tab. 2.1.4 Sigma Score and Yield, Out of Spec., $C_{PK} = P_{PK}$ and DPMO (long-term)

Long - term (1.5σ shift)				
Sigma Score	**Yield %**	**% out of spec.**	**Cpk = Ppk**	**DPMO**
0.5	69.12300%	30.87700%	0.17	308,538
1.5	93.31900%	6.68100%	0.50	66,807
2.5	99.37910%	0.62090%	0.83	6,210
3.5	99.97680%	0.02320%	1.17	233
4.5	99.99966%	0.00034%	1.50	3.4

2.1.2 DMAIC tools

DMAIC methodology has its origin in "Deming's wheel", namely Plan – Do – Check – Act (PDCA) cycle, as presented in figure 2.1.7.

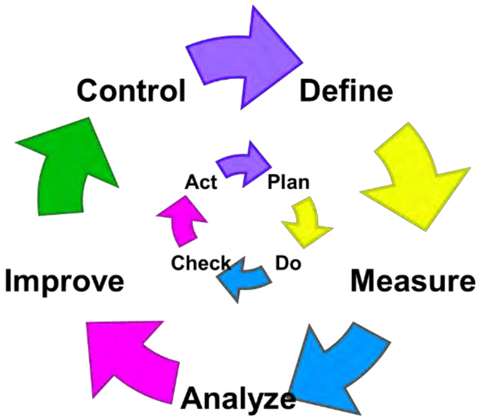


Fig. 2.1.7 PDCA and DMAIC cycles

Some of the most used tools (both statistical and management) within the DMAIC methodology are presented in figure 2.1.8 and 2.1.9. (a presentation by Frank L. Chelko from The Pennsylvania State University on October 9, 2006, entitled "Six Sigma Overview").

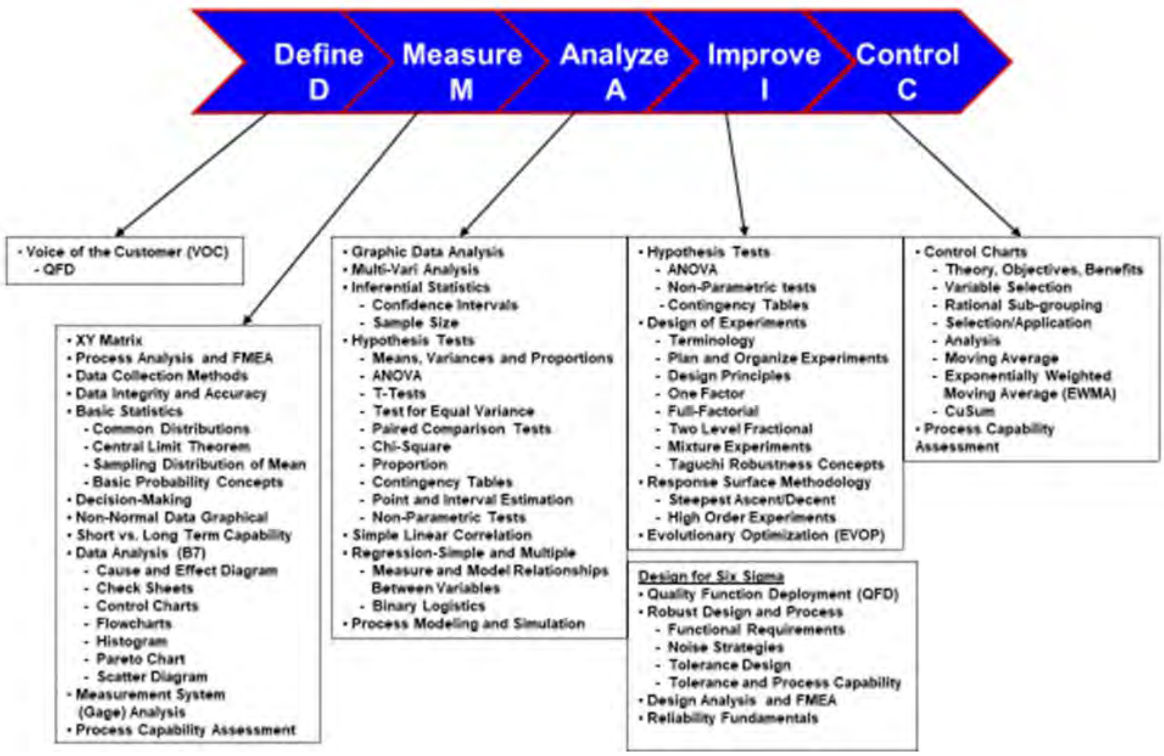


Fig. 2.1.8 Six Sigma DMAIC Process and Statistical Tools

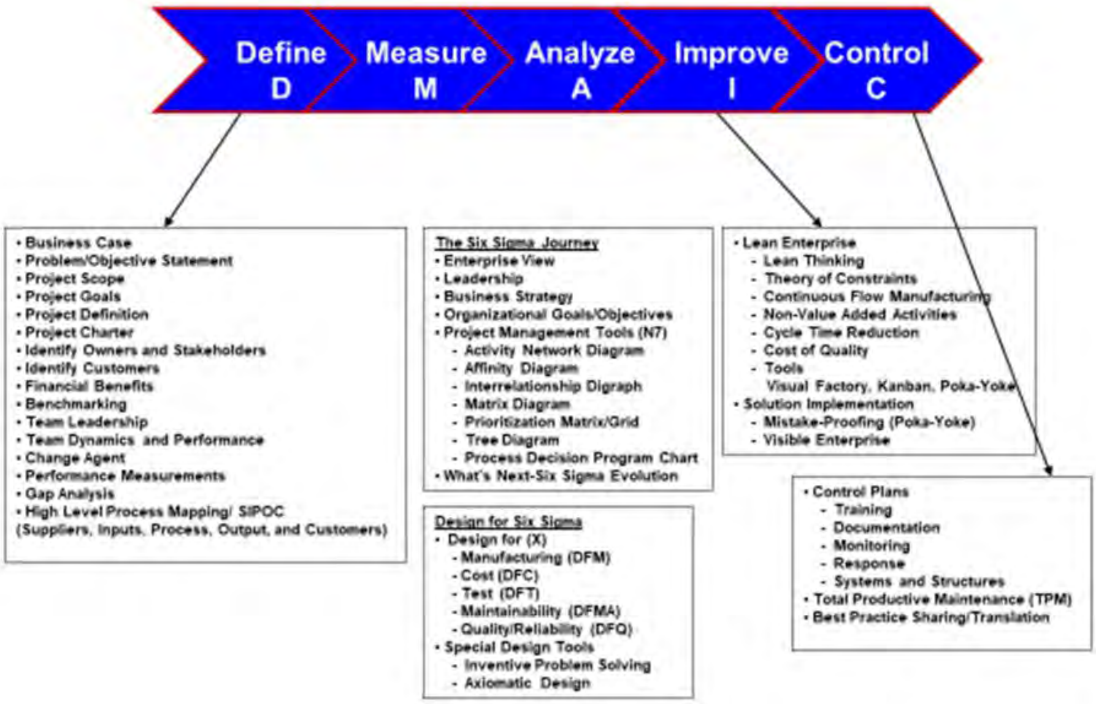


Fig. 2.1.9 Six Sigma DMAIC Process and Management Tools

In a series of interviews from IBM Institute for Business Value, former and actual professionals in Six Sigma deployment made some interesting remarks as follows. Dave Cote, President, and CEO, Honeywell International: *"At the end of the day, Six Sigma is much less of a technical program, although it has a lot of technical tools than it is a leadership and cultural change program".* ; Stephen J. Senkowski, President and CEO,

Armstrong Building Products: *"We are doing Six Sigma as part of our process improvement initiative. I see Six Sigma, indeed, as the natural next step in how we get process improvement done. Six Sigma is a more high-powered set of tools than our previous methods, plus its basic philosophy forces people like myself, the leaders of the business, to think beyond our existing management techniques and perhaps our existing management philosophy".* ; Robert W. Galvin, Chairman Emeritus of Motorola, Inc.: *"We quickly learned if we could control variation, we could get all the parts and processes to work and get to a result of 3.4 defects per million opportunities, or a Six Sigma level. Our people coined the term and it stuck. It was shorthand for people to understand that if you can control the variation, you can achieve remarkable results".*

➢ *Future of Six Sigma*

George Byrne, Dave Lubowe, and Amy Blitz in the article *Driving operational innovation using Lean Six Sigma* published by IBM Institute for Business Value consider that the Six Sigma is evolving into the Lean Six Sigma Approach: "*As its name suggests, Lean Six Sigma is a combination of Lean methods and Six Sigma approaches. It is also sometimes referred to as Six Sigma Lean. And at some of the companies we studied, leaders still label their initiatives like Six Sigma or 6 Sigma even though, from our perspective, they have moved beyond Six Sigma's original definition and scope by incorporating Lean features as well*".

They consider that "*Lean Six Sigma, incorporate and deploys, the key methods, tools and techniques of its predecessors*" (Figure 2.1.10) and "*Lean Six Sigma builds on the practical lessons from previous eras of operational improvements*". (Figure 2.1.11).

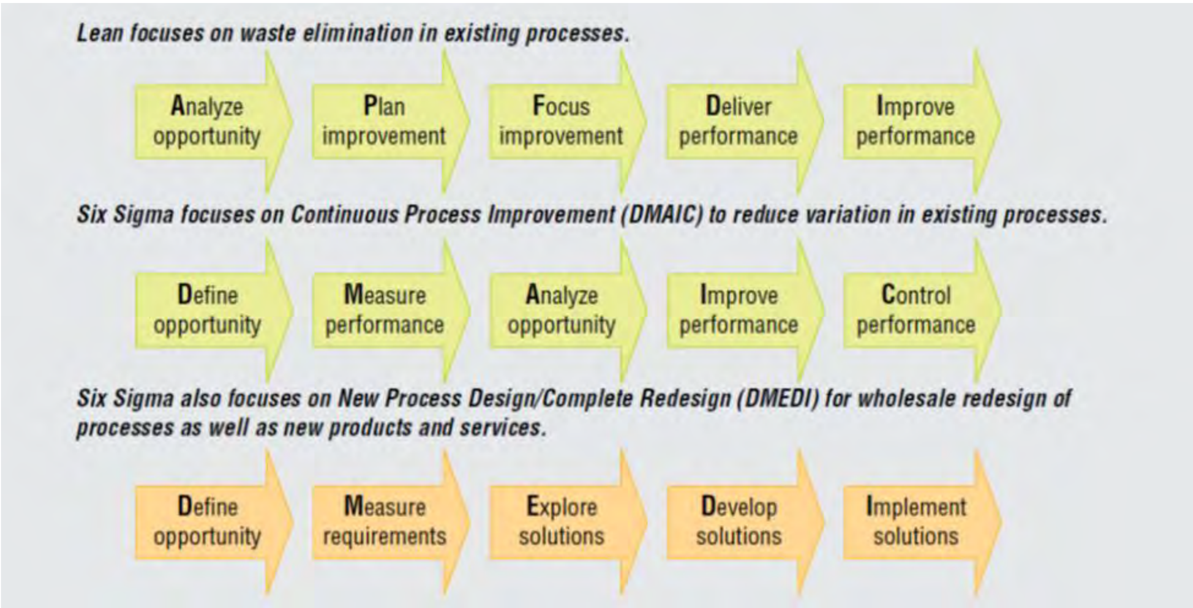


Fig. 2.1.10 Lean Six Sigma predecessors

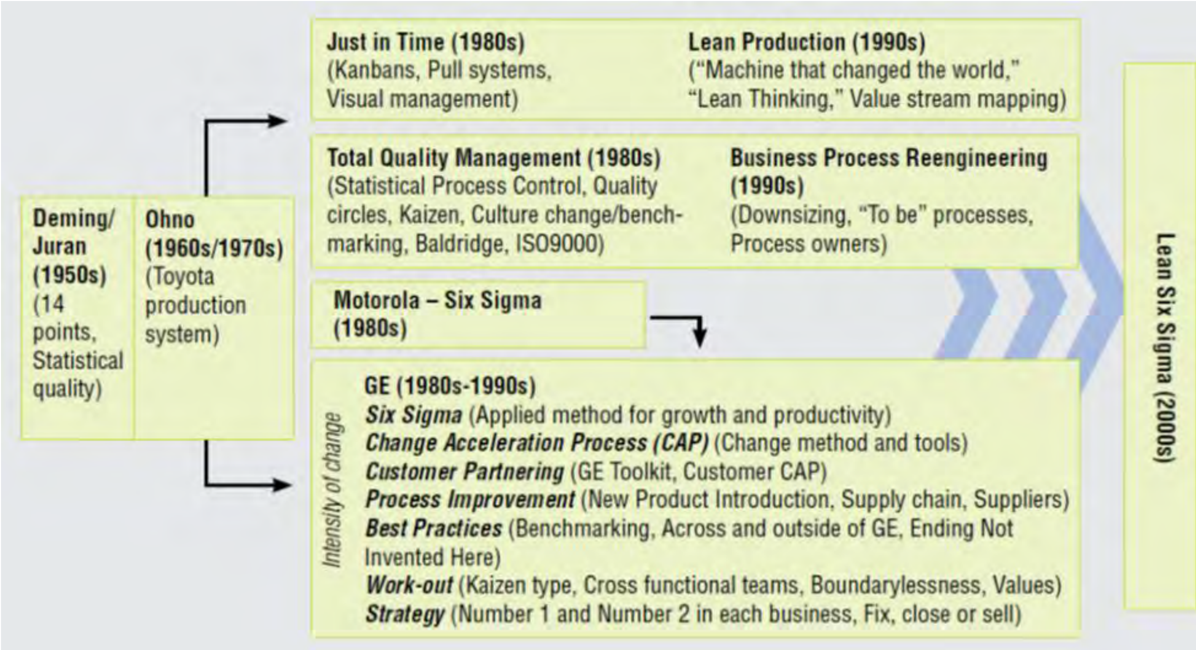


Fig. 2.1.11 Lean Six Sigma and previous Operational Improvement eras (IBM Global Business Services analysis)

2.2 Six Sigma in the Automotive Industry

The exigencies of the permanently evolving markets require continuous adaptation of the company offers. The development and continuous improvement of the quality and environment management systems would be to anticipate these developments and therefore fully satisfy the needs and expectations of each partner (customers, staff, and other stakeholders) and also maintain a competitive advantage. One of the possibilities of gaining operational excellence is implementing different quality improvement initiatives like Total Quality Management, ISO certification, Agile & Lean manufacturing, etc. Real-life demonstrated that these initiatives are neither time-efficient nor profitable in terms of quality. Therefore introducing and implementing the Six Sigma methodology was proven to provide breakthrough quality improvements in a reasonable short time. Creative solutions for improving an assembly process in an automotive company in Romania by using Statistical Thinking and DMAIC Six Sigma methodology are presented by Pugna, Negrea, and Miclea (2015) and Pugna, Potra, Negrea, and Miclea (2019)

The desire to achieve business excellence in the Automotive Industry assumes the management commitment to develop and deliver perfect solutions, products, or services, to promote the "Zero Defects" and first-time right production philosophy, the integration of environmental protection in all its activities (design and production), as well as training, motivating and involving all staff in the effort towards excellence. Usually, for an Automotive Company, a policy is conducted mainly along the following lines: increase the quality of staff, steady decrease in non-quality costs, react better to meet customers requirements and to solve problems, regulatory compliance for the environment, optimizing natural resource consumption, better waste management, prevent any type of pollution, chronic or accidental.

2.2.1 Improving Upper Wire Horn Assembly Process

A. Define Phase

The analysis was focused on the production line providing a semi-finished product in the "Horn Assembly" product, i.e. “Upper wire horn assembly”. On the production line, for this semi-product, are performed the following operations:

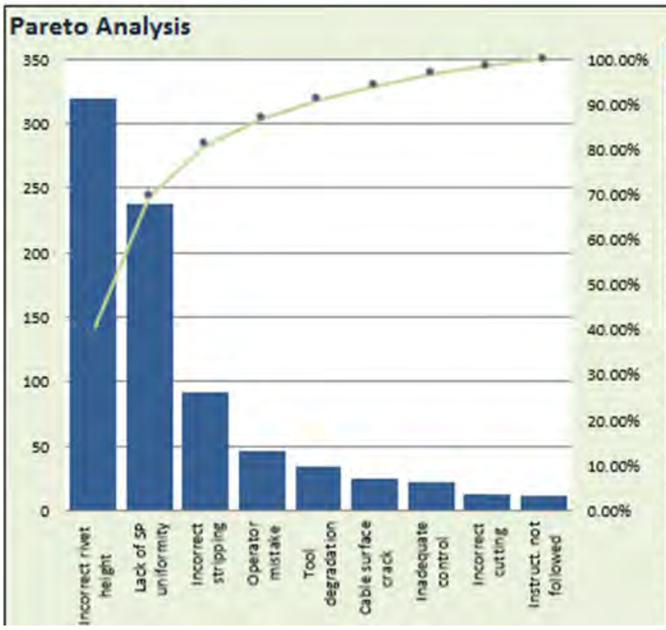
- Cutting and stripping cables
- Cables stripping and crimping terminal on the stripped cables
- Crimping terminal cables stripped from previous operations
- Riveting rivet

It was performed a SIPOC analysis and then a Flow Chart was drawn for the process.

Pareto analysis was performed on 10,000 semi-finished products from which 801 were defective, revealing the the incorrect height of the rivet (319 defects) as the major defect (Fig. 2.2.1.1).

B. Measure Phase

It has been decided to concentrate improvement efforts on the riveting process which causes the highest number of defects. This process is done manually by inserting the horn upper plate and the cables in a holding device than applying a riveting force using a special hand-operated tool. (Fig. 2.2.1.2). The measured characteristic (CTQ - Critical To Quality) is the “Rivet Height” which is very important for the next operation in the final assembly of the finished product “Horn Assembly”. According to the technical drawing (Fig. 2.2.1.3), the rivet height (assembled) dimension is 10.3 ± 0.035 mm. It has been decided to measure 20 samples of 5 semi-finished products each, during an 8-hour shift.



total: 801

Category	Frequency/Quantity	Cumulative %
Incorrect rivet height	319	39.83%
Lack of SP uniformity	238	69.54%
Incorrect stripping	92	81.02%
Operator mistake	46	86.77%
Tool degradation	34	91.01%
Cable surface crack	25	94.13%
Inadequate control	22	96.88%
Incorrect cutting	13	98.50%
Instruct. not followed	12	100.00%

Fig. 2.2.1.1 Pareto Analysis for Upper Wire Horn Assembly

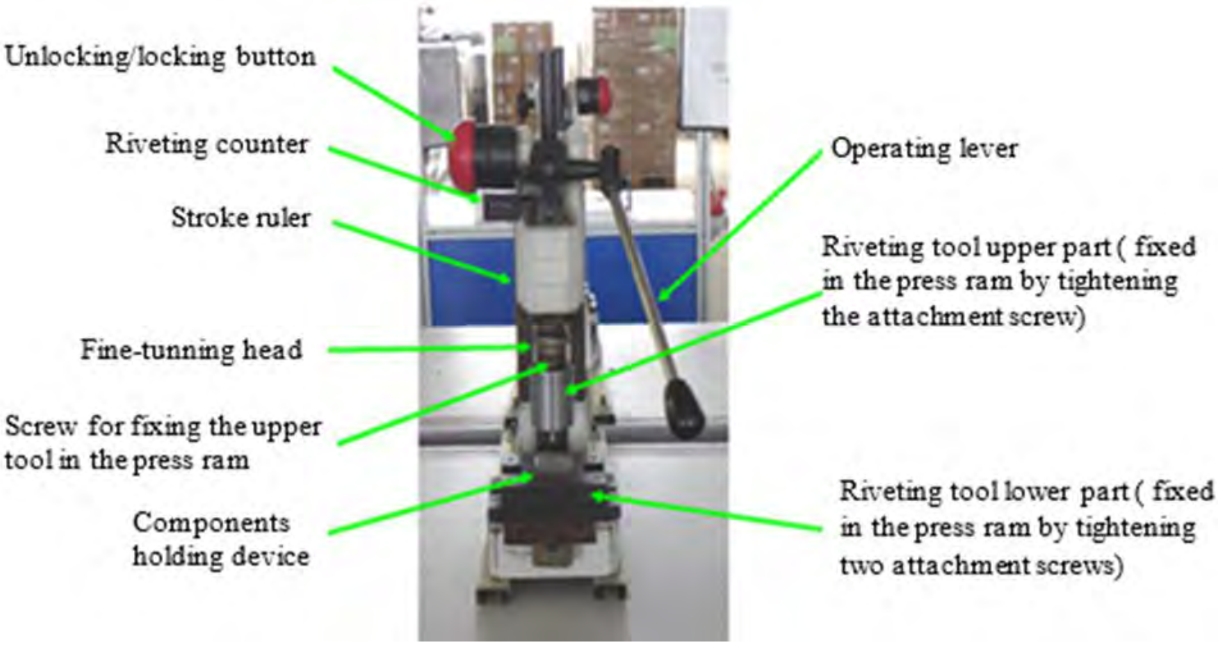


Fig. 2.2.1.2 Hand Operated Riveting Tool

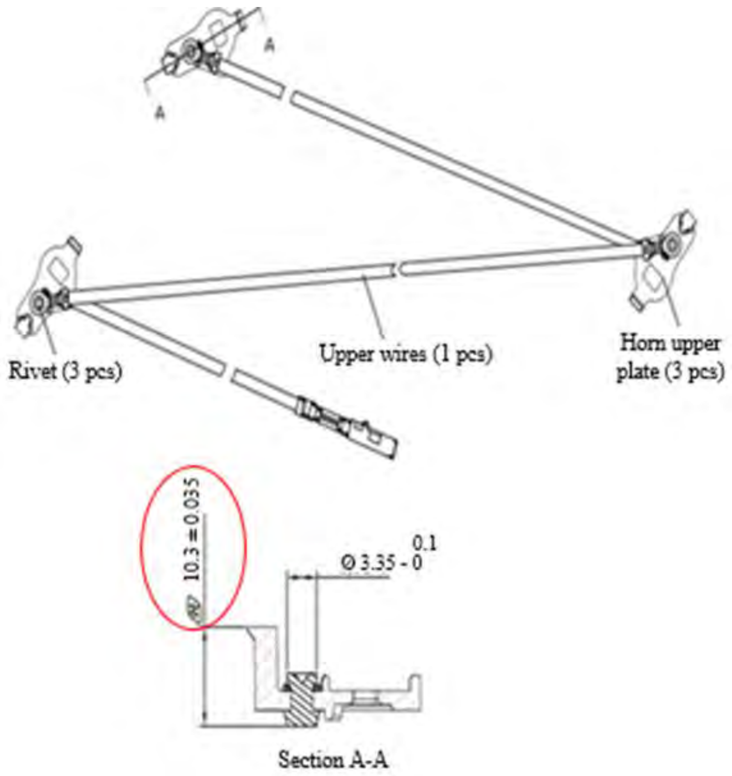


Fig. 2.2.1.3 Assembled Rivet on Upper Wire Horn Assembly

There were performed tests to detect the random character of the sample data, tests to detect and remove outliers, has been assessed whether the data obtained through measurement came from a normal distribution (Table 2.2.1.`) and also were assessed indicators of process capability (Fig. 2.2.1.4).

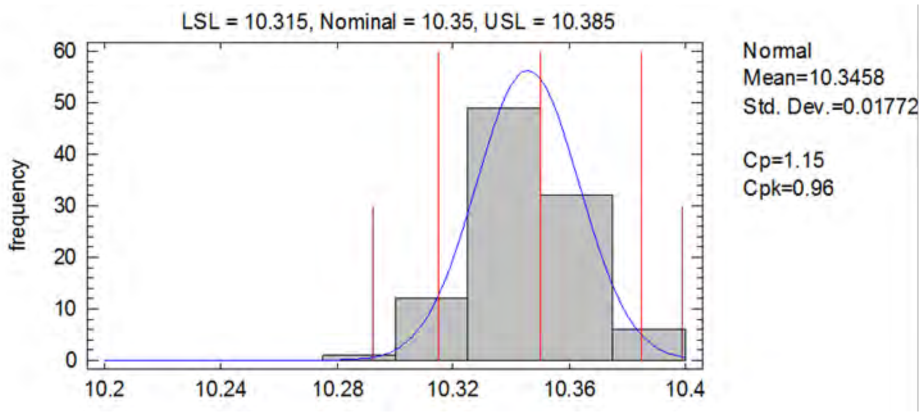


Fig. 2.2.1.4 Process capability for Rivet Height

Table 2.2.1.1 shows the results of the chi-square test, which divides the amplitude data 24 and compares the number of observations of equiprobable classes of each class of the expected number, Shapiro-Wilk test which is based on a comparison of normal distribution quintiles of the data and Kolmogorov-Smirnov test, which calculates the maximum distance between data probability function and probability function of a normal distribution, to determine whether the data can be modeled by a normal distribution. Since the p-value of the three tests is ≥ 0.05, we can not reject the idea that the data come from a normal distribution with a probability of 95%

Tab. 2.2.1.1 Statistical tests for normality

Test for normality	Test statistics	P - value	Distribution
Chi-square	30.08	0.0903922	Normal (p ≥ 0.05)
Kolmogorov-Smirnov	0.0552206	0.9205840	Normal (p ≥ 0.05)
Shapiro-Wilk	0.975131	0.2978780	Normal (p ≥ 0.05)

To assess if the process is in control or not, the 100 measurements were plotted on an Xbar & R charts, revealing that regarding the R chart the process was in control (Fig. 2.2.1.5) but regarding the Xbar chart the process was not in control (Fig. 2.2.1.6).

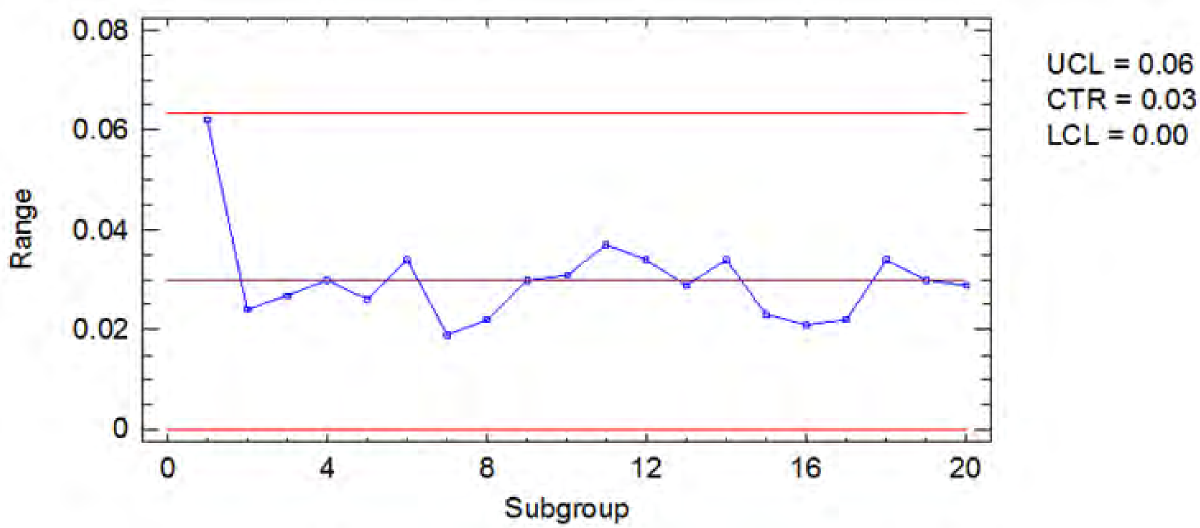


Fig. 2.2.1.5 R chart for Rivet Height

One can see that there are not only points which exceed the control limits, but also there is a clear tendency of increasing the rivet height as the time passes, definitely showing that there is a systematic problem which causes this situation. For Cpk = 0.96 resulting in Sigma Level short-term ≈ 2.9 respectively Sigma Level long-term ≈ 1.4 and therefore DPMO ≈ 81,000.

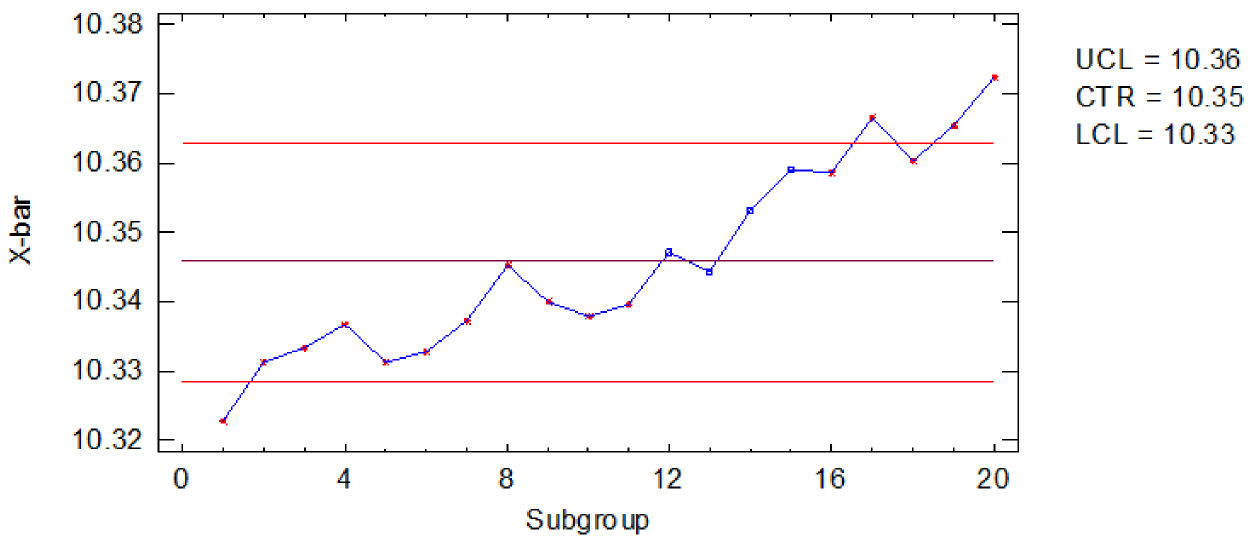


Fig. 2.2.1.6 Xbar chart for Rivet Height

After Measure Phase the following conclusions were drawn:

- ✓ Amplitude values are within control limits and therefore the riveting process is stable as precision.
- ✓ Average values exceed control limits and therefore the riveting process is unstable as adjustment (usually, adjustment instability may have as sources, failure to periodically check machine-tools, tool wear, improper machine adjustment to work dimension, and inhomogeneous semi-finished products).
- ✓ There is an abnormality in the riveting process meaning there is a constant tendency of displacement to increasingly higher values of rivet height.
- ✓ The riveting process is not capable on the short and long term.

C. Analyze Phase

Taking into account the conclusions drawn from Measure Phase it has been decided to address the following issues:

- ➢ The constant tendency of displacement to increasingly higher values of rivet height must thoroughly be analyzed.
- ➢ The riveting process must be brought into control.
- ➢ The riveting process capability must be substantially improved in the long term.

In the first instance, to analyze these issues, an Ishikawa diagram has been utilized. Ishikawa diagram or "Cause - Effect" diagram is a tool for analyzing and plotting the relationship between a given effect (e.g., variations of quality characteristics) and its possible causes. By performing his analysis in conjunction with a “5 Whys – RCFA” analysis it has been determined that the root cause off rivet height noncompliance is the use of improper riveting force during work deployment due to the operator`s fatigue, as the eight as the eight-hour shift takes place (Fig. 2.2.1.7).

It has been determined that at the beginning of the eight-hour shift the operator tends to apply a greater downforce than needed and as the shift deploys the downforce diminishes due to operator fatigue, which explains why there is a tendency of increasingly higher values of rivet height. Also, it has been performed an FMEA analysis. FMEA a considered a rational analysis technique for product reliability, process or machine (used in the process) by inventorying their possible modes of failure, of causes that could induce these failures, of failures effects on users, and as a result, a quantitative evaluation of damage probability to product/process / equipment functions.

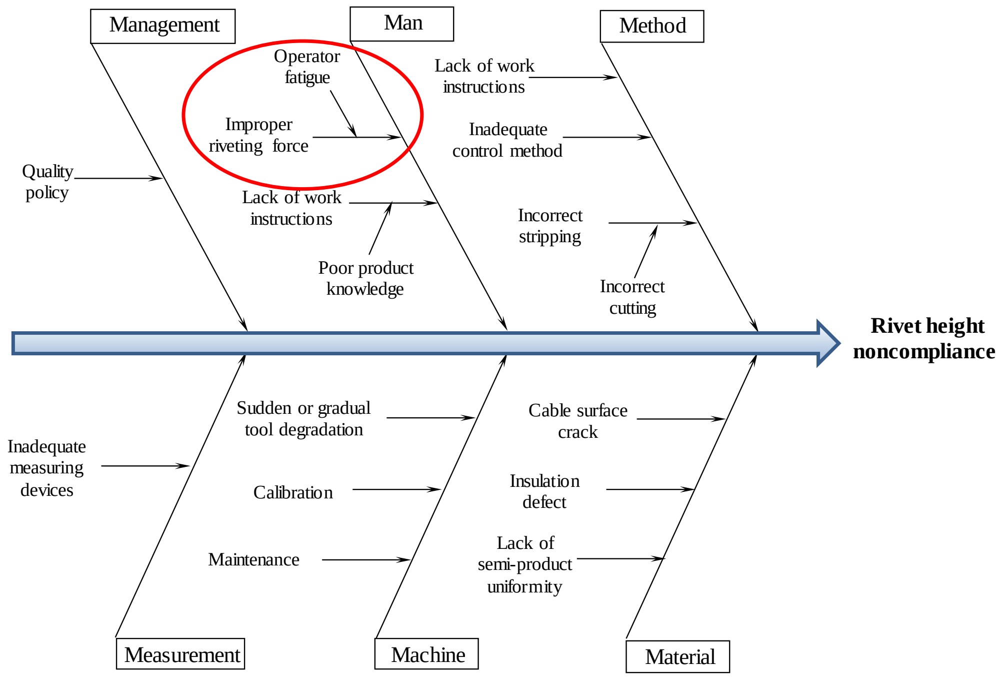


Fig. 2.2.1.7 Ishikawa diagram for Rivet Height noncompliance

It has been determined that at the beginning of the eight-hour shift the operator tends to apply a greater downforce than needed and as the shift deploys the downforce diminishes due to operator fatigue, which explains why there is a tendency of increasingly higher values of rivet height. Also, it has been performed an FMEA analysis. FMEA a considered a rational analysis technique for product reliability, process or machine (used in the process) by inventorying their possible modes of failure, of causes that could induce these failures, of failures effects on users, and as a result, a quantitative evaluation of damage probability to product/process / equipment functions. It has been determined (Fig. 2.2.1.8) that the function affected is the contact from upper wire horn assembly and the rest of the car electrical system. The potential failure mode was detected as the inadequate riveting force (resulted also from Ishikawa analysis) having as a potential failure the inability to couple to other horn subassemblies. Definitely the current control, that is operator training, is ineffective. By taking into account the severity, occurrence, and detection, an RPN of 162 was calculated. The recommended action by the Six Sigma FMEA team was to install a device to properly control the riveting force. Also, it has been recommended that the riveting hand-tool design be improved, even if the necessary downforce is not high. The Six Sigma team decide to tackle also the issue regarding the lack of semi-finished product inconsistency (generating 30.29% of total defects). It has been decided to use AHP (Analytic Hierarchy Process) to choose from 5 different suppliers of cables based on some important criteria.

D. Improve Phase

Based on the recommendations from Analyze Phase, there were implemented the following changes:

- ✓ Hand-tool design for riveting was improved by including a softer release spring.
- ✓ A Poka-Yoke device was installed.
- ✓ A supplier of cables was selected using AHP.

FMEA Template for AIAG and Six Sigma																
Prepared By:									FMEA No/Rev: 0000/01							
Date: 00/00/00									Process/Component:							
												Action Results				
Item	Function	Potential Failure Mode	Potential Effects or Failure	Svrty	Potential Causes of Failure	Ocrnc	Current Controls for Prevention/Detection	Dtctn	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Svrty	Ocrnc	Dtctn	RPN
1	Contact between the horn cables and the car electrical system	Inadequate riveting force	Unable to couple to other horn subassemblies	9	One can not control downforce	6	Operator training	3	162	Installing a device to control the riveting downforce	Process Engineering					

Fig. 2.2.1.8 FMEA for Rivet Height noncompliance

To improve the riveting process it has been decided to use a contact sensor with a warning (Poka-Yoke device). After analyzing four alternatives, an Allen-Bradley Rockwell Automation limiter was chosen. This version is more compact and has a small size, most suitable for the riveting hand-tool. When the operator applies the downforce, the limiter gives visual and acoustic signals when the necessary force has been reached, meaning that the proper rivet height is attained.

There were selected 5 potential cables suppliers (denoted from A to E), using 6 decision criteria, namely Experience (EXP), Financial Stability (FS), Quality Performance (QP), Human resources (HR), Technological Resources (TR), and Current workload (CW). Priorities matrix, Criteria weights, and Priority vector for the 5 potential cables suppliers are presented in table 2.2.1.2 Therefore, according to the Priority vector, supplier C was chosen.

Tab. 2.2.1.2 AHP for selecting the most suitable supplier

	EXP (0.188)	**FS (0.122)**	**QP (0.308)**	**HR (0.270)**	**TR (0.082)**	**CW (0.085)**	**Priority vector**
A	0.162	0.26	0.30	0.24	0.34	0.117	0.24
B	0.204	0.11	0.10	0.19	0.17	0.402	0.30
C	0.172	0.21	0.39	0.39	0.74	0.159	0.35
D	0.364	0.35	0.13	0.11	0.06	0.224	0.18
E	0.080	0.08	0.05	0.08	0.04	0.150	0.07

E Control Phase

After implementing the improvements presented in Improve Phase, there were measured 20 samples of 5 semifinished products each, during an 8-hour shift.

There were performed tests to detect the random character of the sample data, tests to detect and remove outliers, has been assessed whether the data obtained through measurement came from a normal distribution, and also were assessed indicators of process capability (Fig. 2.2.1.9).

To assess if the improved process is in control or not, the 100 measurements were plotted on an Xbar & R charts, revealing that regarding both Xbar & R charts the process was in control (Fig. 2.2.10 and Fig. 2.2.11). For Cpk = 1.72 resulting in Sigma

Level short-term ≈ 5.2 respectively Sigma Level long-term ≈ 3.7 and therefore DPMO ≈ 108.

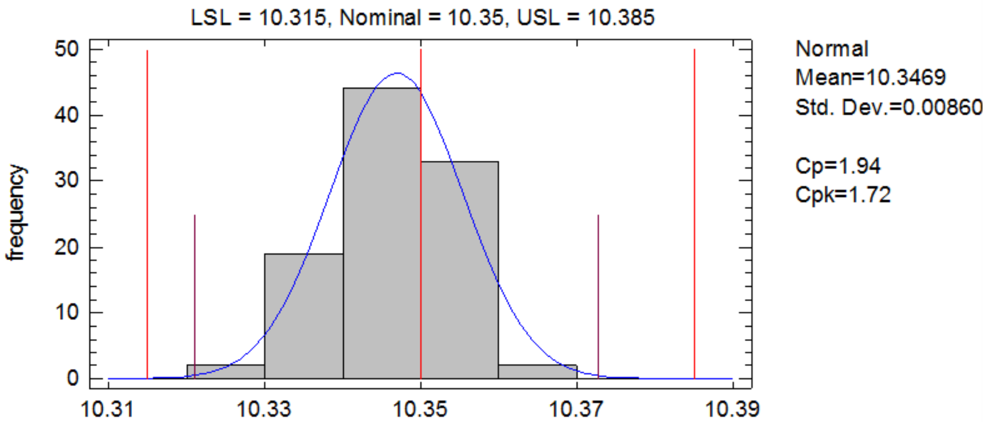


Fig. 2.2.1.9 Process capability for Rivet Height (improved process)

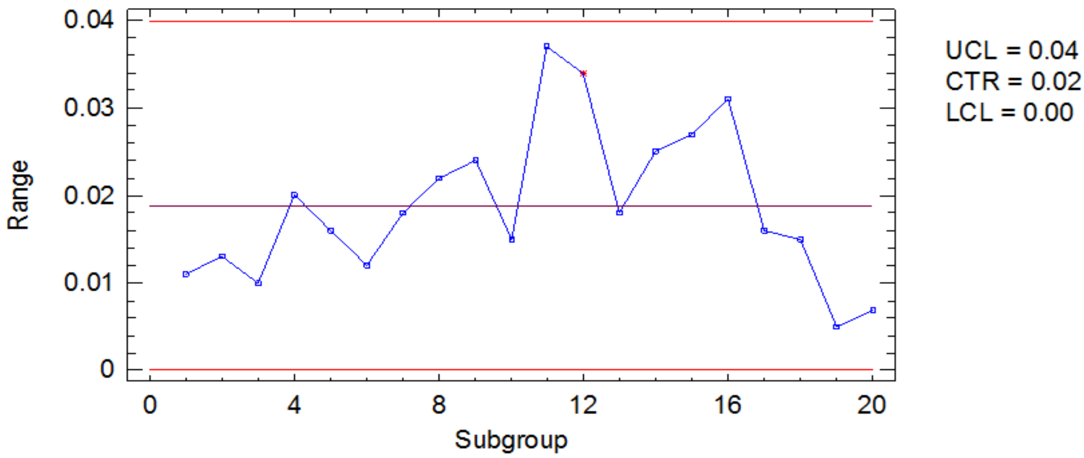


Fig. 2.2.1.10 R chart for Rivet Height (improved process)

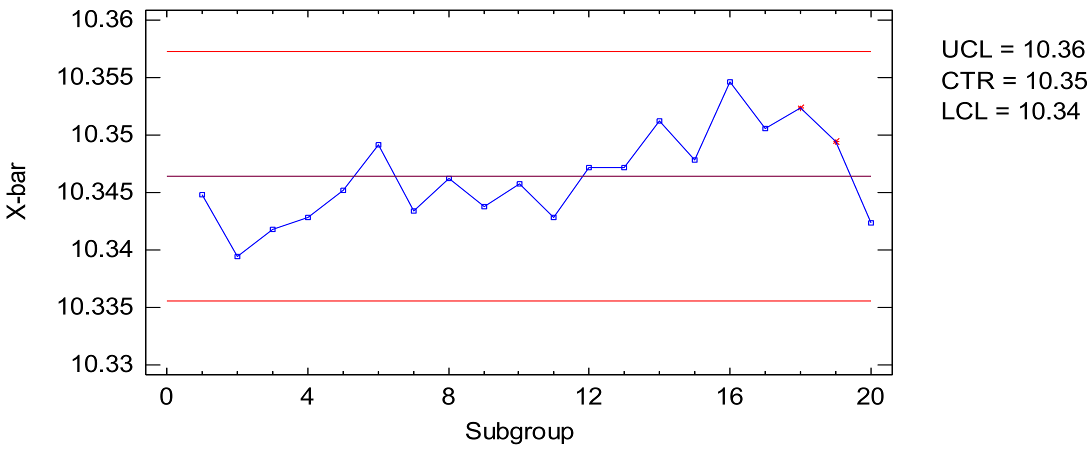


Fig. 2.2.1.11 Xbar chart for Rivet Height (improved process)

After implementing the recommended action by Six Sigma FMEA to install a device to properly control the riveting force, the updated FMEA is presented in figure 2.2.1.12, showing a much lower RPN of 32.

FMEA Template for AIAG and Six Sigma																
Prepared By:									FMEA No/Rev: 0000/01							
Date: 00/00/00									Process/Component:							
												Action Results				
Item	Function	Potential Failure Mode	Potential Effects or Failure	Svrty	Potential Causes of Failure	Ocrnc	Current Controls for Prevention/Detection	Dtctn	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Svrty	Ocrnc	Dtctn	RPN
1	Contact between the horn cables and the car electrical system	Inadequate riveting force	Unable to couple to other horn subassemblies	9	One can not control downforce	6	Operator training	3	162	Installing a device to control the riveting downforce	Process Engineering	Device installed on 01.04.2015	9	1	2	18

Fig. 2.2.1.12 Updated FMEA for Rivet Height noncompliance

By applying Statistical Thinking and DMAIC Six Sigma methodology to the riveting process the following conclusions were drawn: the riveting hand tool design was improved allowing smoother handling, a Poka-Yoke device was installed signaling acoustically and visually when the necessary downforce was attained, the riveting process was brought in-control, the riveting process capability was substantially improved on the short and long term, Cpk increased from 0.96 to 1.72, Sigma Level short-term increased from 2.9 to 5.2, Sigma Level long-term increased from 1.4 to 3.7, DPMO was reduced from 81,000 to 108, improving the riveting process led to ≈ 40% defect reduction, choosing the most suitable supplier led to ≈ 30% defect reduction. It was decided to continue the improvement process by tackling the next nonconformities from the Pareto chart and also to attempt riveting process automation, to eliminate possible human errors.

2.2.2 Improving Waste Gate Actuator Assembly Process

According to Tjahjono et al. (2010), there are four interpretations of Six Sigma in literature: a set of statistical tools, and operational management philosophy, a business culture, and an analysis methodology that uses scientific methods.

The complexity of uses and definitions determine different Six Sigma approaches for an organization: a business transformation approach, a strategic improvement, or only a problem-solving approach which focuses on persistent problems (Al-Mishari & Suliman, 2008).

Even if the transformative approach leads to achieving higher Six Sigma levels, all three are very beneficial for a company. Gowen et al. (2008), state that the most important benefit of implementing Six Sigma in a business is the competitive advantage it offers. Kumar et al. (2006), expresses that it has been demonstrated in several studies that the defect rate per unit is reduced after Six Sigma implementation in manufacturing systems.

Besides, Oke (2007), emphasizes that the adoption of Six Sigma has improved both the efficiency of the analyzed line and product capability.

The Council for Six Sigma Certification (2018), explains that in Six Sigma approaches all strategies, ideas and other corporate changes go through rigorous analysis and data testing before implementation. If any change in the company is not based on measurement and metrics, it can experience unwanted consequences like wrong spent money and a negative impact on customer perceptions.

For the case study, we have chosen to analyze the manufacturing system of an automotive company situated in the Eastern part of Europe.

More specifically, the scope of the present paper has been to apply the Six Sigma methodology to redesign the production system of their WGA (Waste Gate Actuator) product.

The WGA consists of a spring and a sealed chamber and is essential in a turbocharged engine system. Its main function is to control the wastegate valve to prevent the boost pressure in a turbocharger from exceeding critical pressure.

The line flow of the WGA production system consists of eight (semi-automated or automated) stations. A high rate of scrap resulting from the semi-automated station 2, where the PCB screwing is performed has been observed.

This problem can become a DMAIC project if it is weighted adequately after the project viability model. This 15-point viability model has been applied with success by numerous scholars (George, Rowlands, Price, & Maxey, 2005) and it removes the subjective selection of a Six Sigma project.

Based on the 15 criteria explained by The Council of Six Sigma Certification (2018), a matrix has been created with a numerical weight to each criterion on a scale from 1 to 5, with 1 being not important and 5 being very important. In the following, the team in charge of the project provided answers for each of the 15 questions by marking a 1 in the box corresponding to their choice on the grid.

The answers range from no, mostly no, possibly, mostly yes and yes variants. Once the matrix has been completed for the present project, several calculations have been realized.

Each weight has been divided by 3 and each of the 1s listed in the grid as answers has been converted to a weighted value by multiplying them with the converted weight computed in the first step.

The numbers in each of the five columns have been summed. These scores have been multiplied with the numbers at the top of the columns (for the answer “no” we have 1, for “mostly no” we have 2, for “possibly” we have number 3, for “mostly yes” the corresponding number is 4 and for “yes” is 5) and then summed up.

The last sum has been divided by the sum of the weighted totals in the third step and the obtained number represents the score of the present project, namely 3.7, (see Table 1) a score above the 3.0 score value that defines the DMAIC project viability.

Thus, the defined problem at station 2 represents a viable DMAIC project. In the following, the DMAIC model is used to rigorously analyze the cause of the identified problem and to test the capability of the process before and after the improvement.

Tab. 2.2.2.1 The project viability matrix

Criteria	Weight	No (1)	Mostly no (2)	Possibly (3)	Mostly yes (4)	Yes (5)
Is there a sponsor?	4					1.7
Do project goals align with corporate goals?	3				1	
Is data available?	5				1.7	
Are defects well defined?	5				1.7	
Is the process stable?	3				1	
Are there customer benefits?	4			1.3		
Are there company benefits?	4				1.3	
Can the project be completed in 6 months?	2	0.7				
Is the solution unknown?	3		1			

A discovered solution can be implemented?	5			1.7		
Would a new solution cost little to no cash?	2			0.7		
Are Six Sigma members available for the project?	2				0.7	
Can inputs in the process be controlled?	5					1.7
Can the process be improved without a full redesign?	3		1			
Will the improvements ameliorate the quality?	3					1
Weighted scores		0.7	2	3.7	7.4	4.4
					Total score	**3.7**

A. Define phase

In the Define phase of a DMAIC project, the Six Sigma team is selected and they start creating the project charter. Process maps and a SIPOC (Supplier, Input, Process, Output, and Customer) diagram are usually created to help to understand the process. In the following, a SIPOC diagram is outlined in figure 2.2.2.1.

The SIPOC diagram captures information critical to the project and verifies that process inputs match outputs of the upstream process and inputs of the downstream process. Therefore, it provides the first global understanding of the process under analysis. In the process mapping stage, a flowchart visually documents the process and provides valuable insights like poor flow or delays.

It helps the Six Sigma team understand where improvements should occur for eliminating waste. In figure 2.2.2.2 a basic flowchart of the WGA manufacturing process is delineated with a specific detail of the flow at station two.

Suppliers	Input	Process	Output	Clients
ABC Electronics	PCB	PCB and case pressing	Good products	Customer
CCCT	Case		Non-conforming products	Quality department
XYZsteel	Screw		Scrap	
Industriale K&L	Screwdriver		Production reports	Production manager
Maintenance Department	Maintenance			

Fig. 2.2.2.1 The SIPOC diagram for the WGA production system

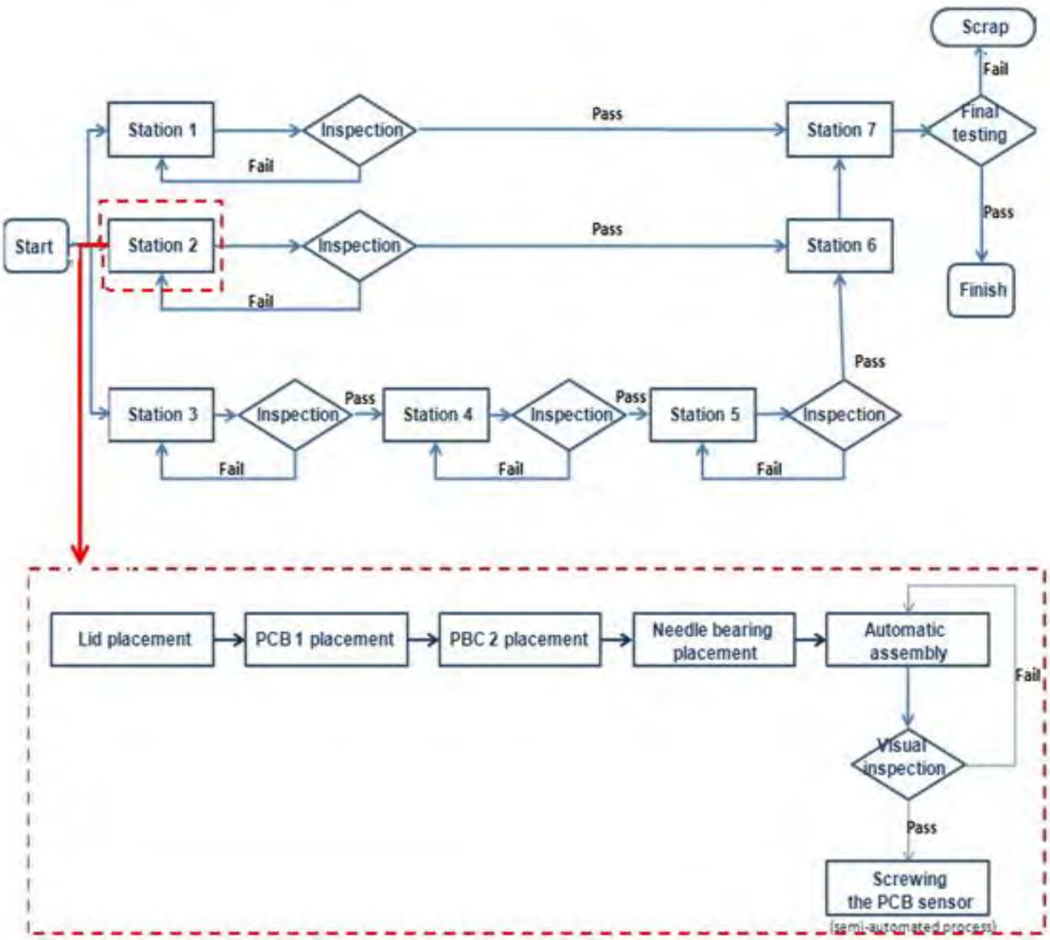


Fig. 2.2.2.2 The flowchart for the WGA flow line

Fig. 2.2.2.3 The resulting element of station 2

We can easily see a much entangled overall process that determines time delays and rework loops. In station 2 the PCB and needle bearing assembly in the lid occur (Figure 2.2.2.3).

It is a semi-automated station where there is a lack of repeatability of torque measurements for the screwing process of the PCBs on the lid and a lack of control of the distance between the screw head and the PCB.

B. Measure phase

After understanding the problems and specificities of the process from the define phase, the Six Sigma team delves into a more profound and even laborious measurement phase to understand the process more fully trough collected data.

Data has been collected resulting in different types of problems for the screwing process like wrong screw, case or PCB position, and operator fatigue.

A Pareto diagram has been created (Figure 2.2.2.4) for 10000 analyzed pieces, 278 defects have been observed.

Pareto chart is sorting the problems by their frequency of occurrence.

Thus, we can see which types of problems need to be addressed in the first instance for relevant results.

Another important step in the measurement phase is determining the capability of the screwing process, especially of the tightening torque.

For this purpose, 20 samples of 5 pieces each have been measured. In the first instance, we wanted to see if the normal distribution is appropriate for the data because the Gaussian distribution is one of the most important distributions related to continuous data from a statistical analysis standpoint.

To determine if the 100 measurements of the tightening torque process come from a normal distribution several tests have been run (Table 2.2.2.2).

DEFECT CATEGORY	FRECQUENCY	FRECQUENCY %	CUMULATIVE FRECQUENCY %
WRONG SCREW POSITION	140	50,36%	50,36%
WRONG PCB POSITION	92	33,09%	83,45%
WRONG CASE POSITION	34	12,23%	95,68%
OPERATOR FATIGUE	12	4,32%	1

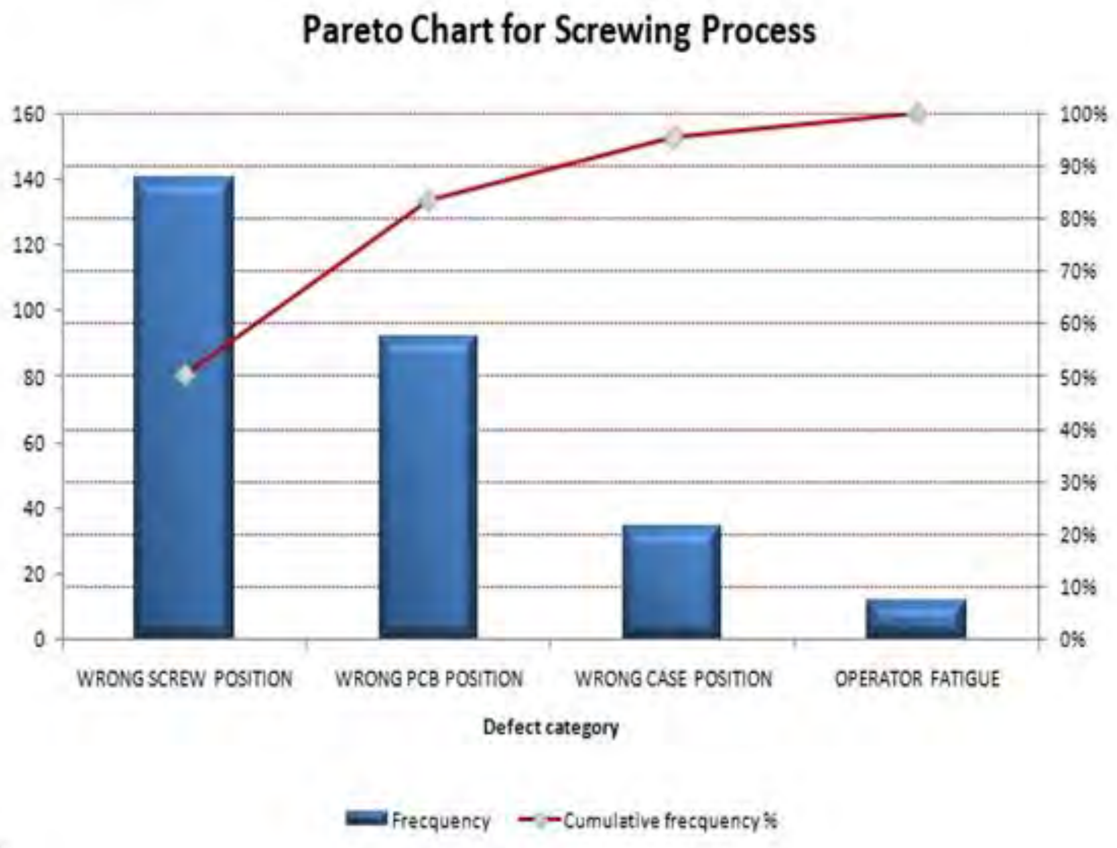


Fig. 2.2.2.4 Pareto chart for the screwing process in station 2

Tab. 2.2.2.2 Tests for normality for the tightening torque process

Test	Statistic	P-value
Chi-square	150.08	0.0
Skeweness Z-score	0.380684	0.703434
Kurtosis Z-score	-3.37776	0.000730891

Since the smallest P-value among the tests performed is less than 0.05, we can reject the idea that the data comes from a normal distribution with 95% confidence. But when several alternative distributions are compared for the goodness of fit, (Table 2.2.2.3) according to the log-likelihood statistic, the best fitting distribution is the normal distribution.

Tab. 2.2.2.3 Comparison of alternative distributions

Distribution	Est. Parameters	Log-likelihood	KSD
Normal	2	334.389	0.130145
Gamma	2	334.222	0.133979
Log normal	2	334.111	0.134520
Weibull	2	333.178	0.133221

Thus, we will continue our analysis by using the normal distribution. In figures 2.2.2.5 and 2.2.2.6 the control charts (average and range chart) are presented. R chart determines if the data comes from a process that is in a state of statistical control. Of the 20 non-excluded points shown on the charts, none are beyond the control limits. Thus, the process is in a state of statistical control at a 95% confidence level. But being in control is not enough; it represents only the prerequisite for the capability analysis presented in Figure 2.2.2.7.

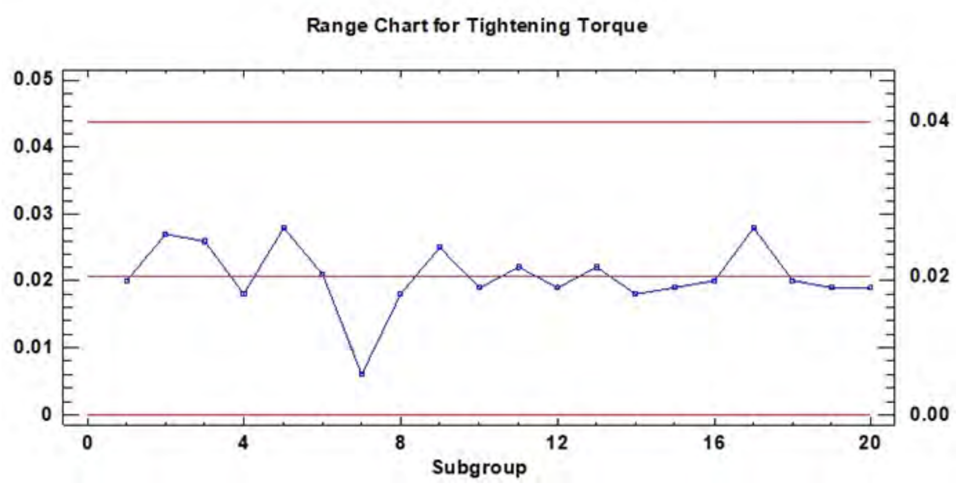


Fig. 2.2.2.5 Range Chart for Tightening Torque

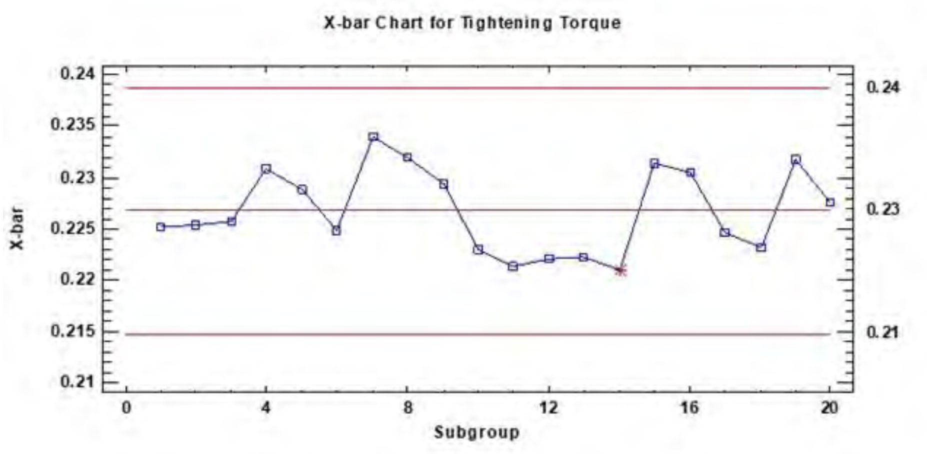


Fig. 2.2.2.6 Xbar Chart for Tightening Torque

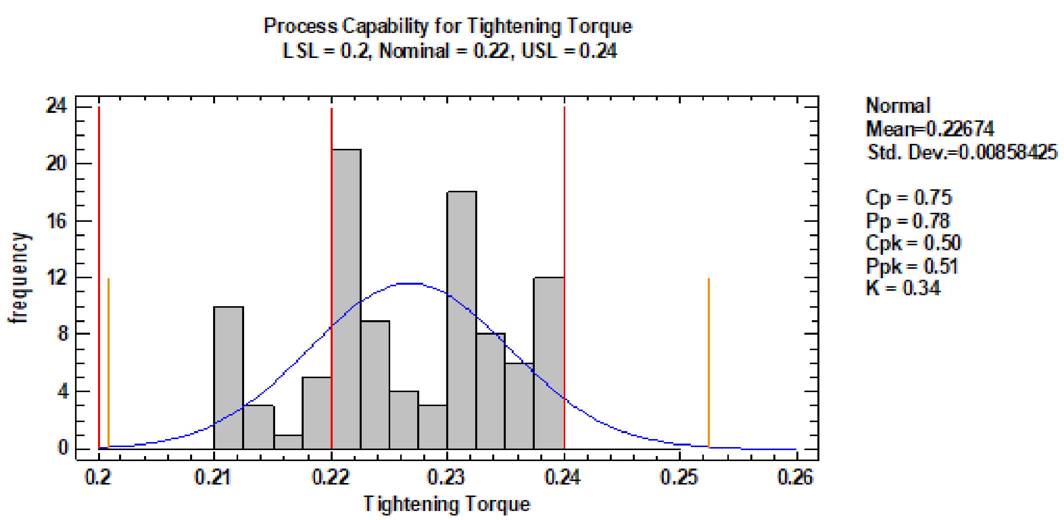


Fig. 2.2.2.7 Process Capability analysis for tightening torque

For Cp ≈ 0.75 and Cpk ≈ 0.50, we have a Sigma short term level of ≈ 2.2 and a Sigma long term level of ≈ 0.7. Thus, the DPMO (defects per million opportunities) can reach 242,000. This situation is not acceptable. The problem needs a thorough analysis for determining its root causes.

C. Analysis phase

The usual tools in the analysis phase are the Ishikawa diagram, also known as the cause and effect diagram, together with the 5Whys method. These techniques allow creative thinking and are very popular for brainstorming about the causes of observed problems. An Ishikawa diagram has been drawn (Figure 2.2.2.8) in which we can easily see that many of the causes which trigger the problem reside from the "Machine" side, namely the screwing station. For a deeper understanding of the root causes in the screwing station determined by the "Machine" side of the process, the 5 Whys method has been used. In Table 2.2.2.4 three main potential causes of the high number of scrap at the screwing station have been analyzed. For the three main causes of the high number of scrap we have a technical root cause, namely the poor semi-automated screwing process, and an administrative technical issue, namely the lack of periodical operator training.

Tab. 2.2.2.4 Five Whys analysis for the high number of scrap at the screwing station

Possible causes	**Too low /high torque**	**Inadequate screwing rotation angle**	**Cracked PCB**
1. Why?	Wrong screw position	Too much inertia of the screw bolt	Too much screwing force
2. Why?	Improper fasteners	Over-dimensioning of the device related to use	Imprecise control of the screw force
3. Why?	Manual process	Standard device	Lack of calibration
4. Why?			Negligent operators
5. Why?			Lack of operator training
Corrective actions	*Implementation of the automated screwing process*	*Redesigning the screwdriver for the automatic application*	*Periodic training*

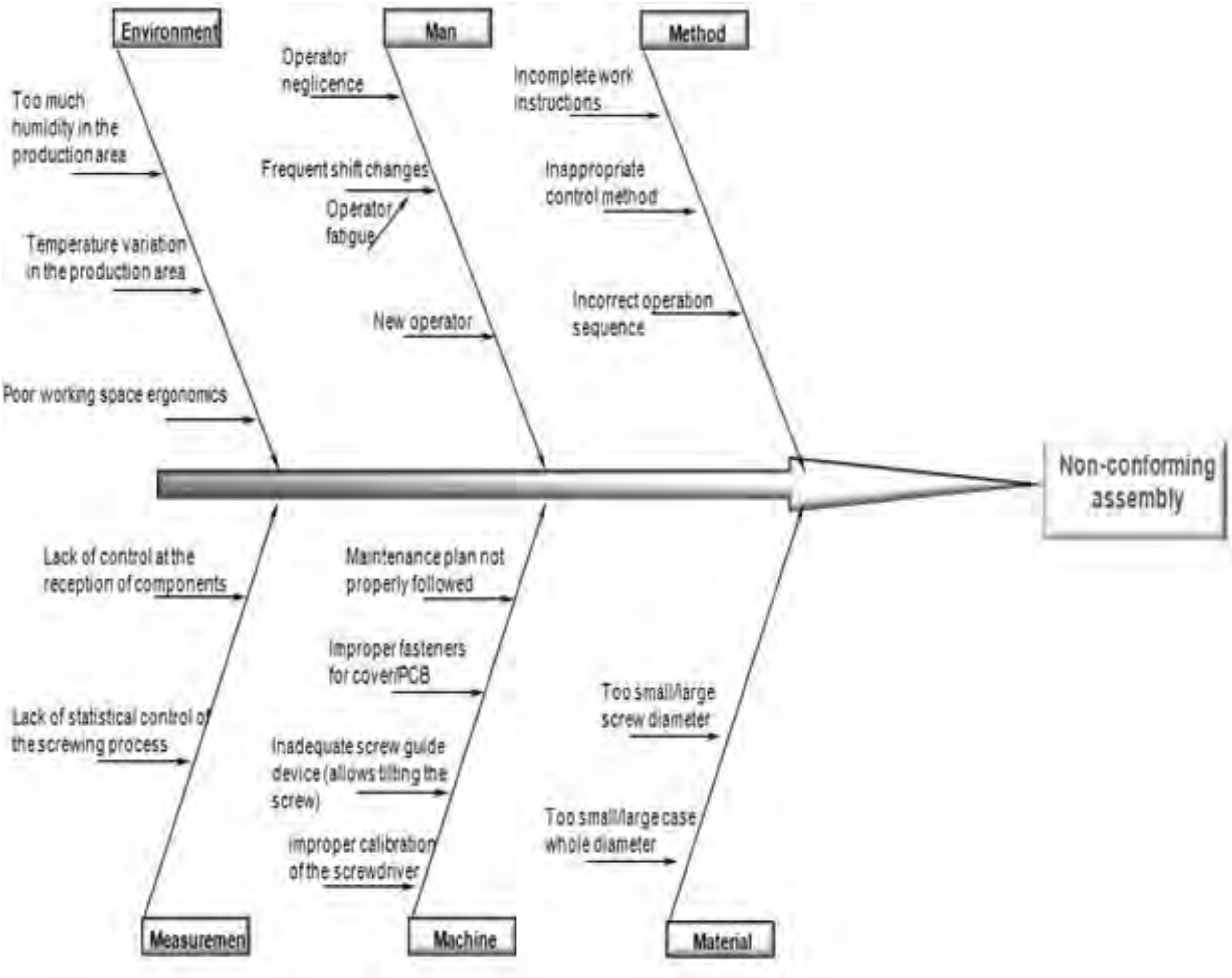


Fig. 2.2.2.8 The Ishikawa diagram for non-conforming assembly

It is easier to control a machine than a human operator; this is the reason why in the improvement phase the Six Sigma team will focus on implementing a fully automated process at the screwing station.

D. Improvement phase

In this phase, the Six Sigma team determines possible solutions for the root causes identified in the previous phase and ranks them according to costs and implementation difficulty. After a thorough payback analysis, the team has determined as necessary to have an automated manufacturing process for the WGA product. A new fully automated production line with only three operators and a production cycle of 12 seconds has been designed and purchased. With the help of this production line, the company will be able to produce over two million WGA products in a year with a short payback time of 2.5 years. The flowchart for the automated line can be seen in Figure 2.2.2.9.

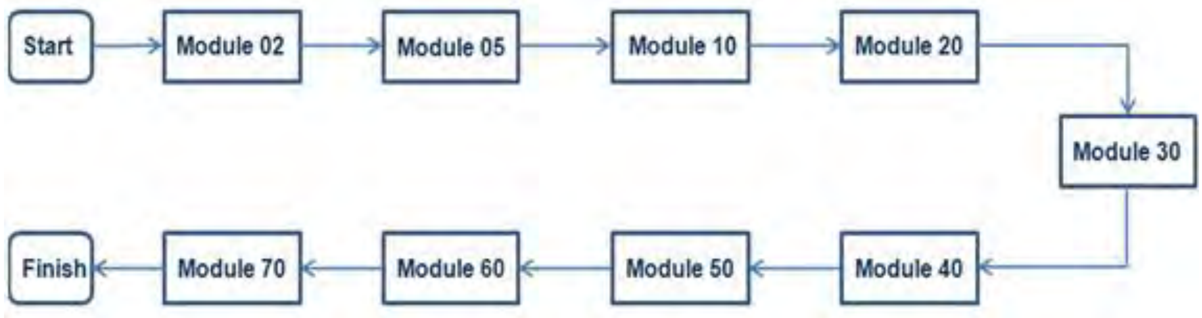


Fig. 2.2.2.9 The automated production line flowchart

E. Control phase

The last phase of a DMAIC project has the purpose of monitoring the process to ensure continuous performance. An average range chart and a range chart were drawn for verifying the statistical process control state (Figures 2.2.2.10 and 2.2.2.11).

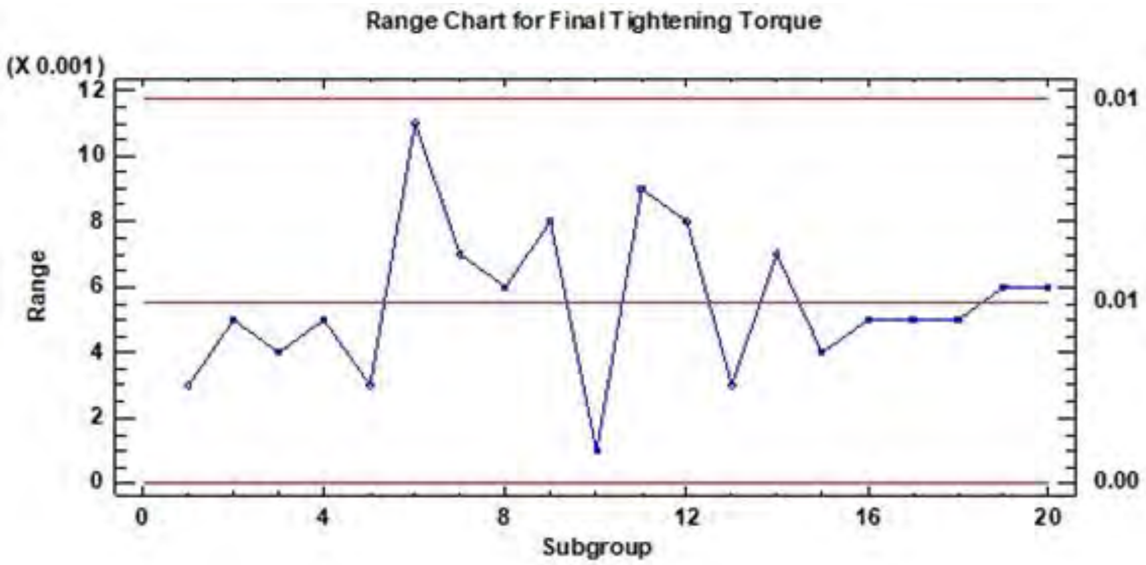


Fig. 2.2.2.10 R chart for the automated WGA production line

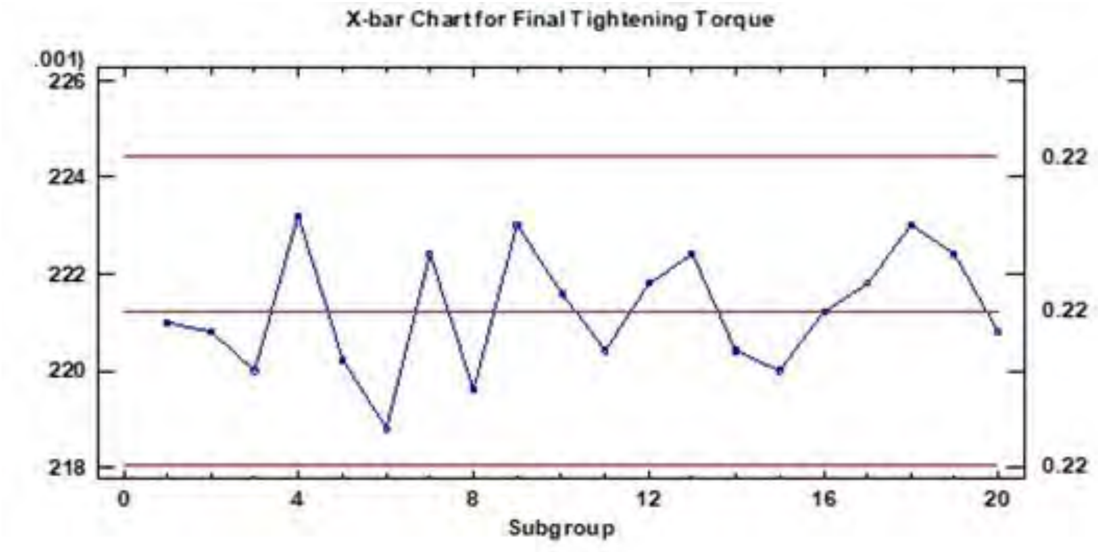


Fig. 2.2.2.11 R chart for the automated WGA production line

Also, the process capability (Figure 2.2.2.12) was assessed to see if the Sigma level is acceptable. The process will be monitored for future adjustments if necessary.

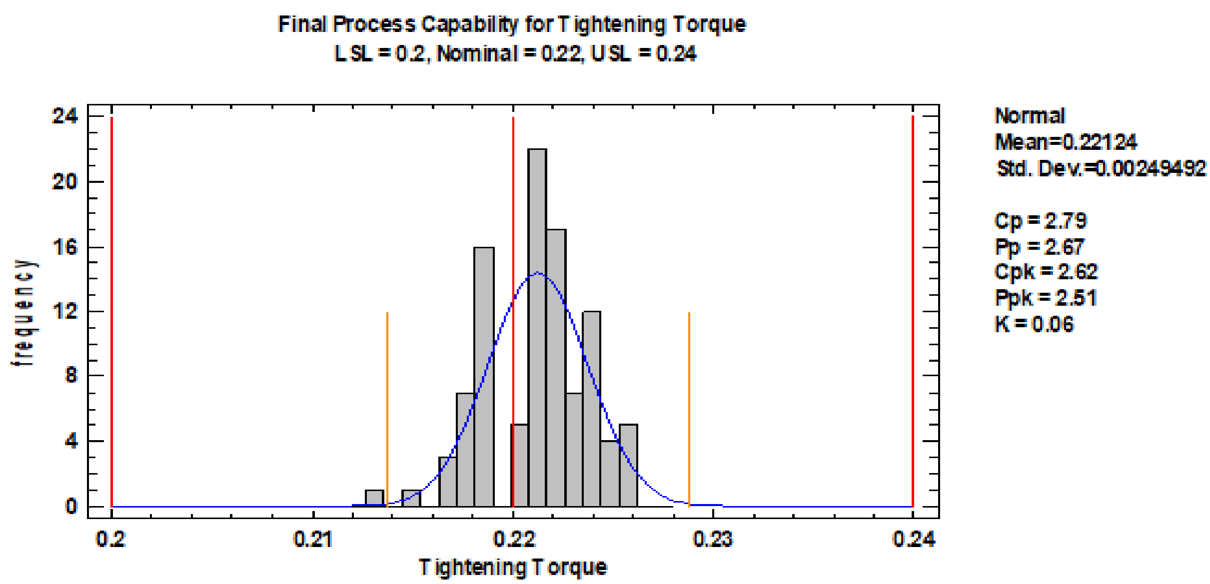


Fig. 2.2.2.12 Final process capability for the automated WGA production line

One can see that for Cp ≈ 2.79 and Cpk ≈ 2.62 we have a Sigma level short term ≈ 7 and Sigma level long term ≈ 5.5 respectively and therefore DPMO ≈ 0. This situation ensures performance in the production line. The problem of a high number of scrap from the screwing station of the WGA manufacturing line has been analyzed for determining if it represents a viable DMAIC project. After confirming the viability of the project, the process has been mapped and 10000 pieces have been measured for determining the most occurring defect types. 20 samples of 5 pieces each have been also measured for determining if the process is in statistical control and to visualize the process capability. Because the process had a Sigma long time level of less than 1, the DPMO was not acceptable and thorough analysis and improvement have been required. After an Ishikawa diagram and a “Five Whys” analysis, a technical root cause has been established. In the improvement phase, a fully automated process at the screwing station has been proposed. According to the payoff analysis, the process automation purchase and implementation period of 11 months had a short payback time of 2.5 years. In the control phase, the control charts have been updated and the capability of the process has been continuously monitored. The Sigma long time level has been 5.5, an excellent result. Thus, the decision making has been based on rigorous statistical measurements and analysis, leading to performance results and lowering the risk of damaging investments.

2.2.3 Improving Complex Processes

Achieving a high degree of performance through continuous improvement is a desideratum of all companies because it ensures their success in ever-changing contemporary markets. Quality improvement theory has seen the emergence of several programs, such as Six Sigma, Total Quality Management, ISO Type Certification, Agile & Lean Manufacturing, Re-engineering, Process Excellence, etc. But in the case of complex processes, the introduction and application of the Six Sigma methodology have proved most successful. The reason for this outcome can be the fact that Six Sigma incorporates the TQM philosophy and tools, offers a structured improvement model (DMAIC) with more advanced statistical tools, and involves the top management through its belts system with the final purpose to tackle complex projects. Moreover, the application of the Six Sigma methodology is the one that creates a strong culture of continuous improvement.

Pugna, Potra, Negrea, and Mocan, (2018), presented a solution for complex process improvement in an automotive company by using DMAIC Six Sigma methodology.

To achieve the ultimate goal of “Zero Defects” and ”Business Excellence” in all corporate activities to deliver perfect products and services, the management team needs to apply a sustained and continuous improvement process. Nevertheless, to fulfill these objectives, the companies must not focus only on implementing the Six Sigma methodology, but also on motivating, involving, and training all the staff. McCarty et al. (2005) have labeled Six Sigma as a metric, a methodology, and a management system. Sigma is considered a relevant measurement that reflects the level of control over a process to meet its standard performance or a technical measure of how many unhappy customers experiences a company has per million opportunities (Eckes, 2003). The Six Sigma methodology takes the Sigma metric one step further, by analyzing the process to find sources of unacceptable variation and propose alternatives to reduce them.

The DMAIC (define-measure-analyze-improve-control) model represents a Six Sigma specific and widely used technique because “it encourages creative thinking and helps people find permanent solutions to tricky business problems" (George et al. 2003).

The Six Sigma management system builds on the metric and the methodology with a wider scope, to transform Six Sigma into a corporate culture from the top of a company to every employee. It is not easily reachable, but desirable for a sustainable organization in today’s competitive environment.

Thus, Six Sigma is considered the best way to decrease constantly non-conformances and related costs, to meet customer requirements, to optimize resources consumption and waste reduction (Pyzdek and Keller, 2010). Also, Six Sigma represents the new paradigm for the 21st century (Park, 2003), which eliminates negative quality by reducing defects and costs and increasing the speed of the improved processes (Lunau, 2009).

This methodology is seen as “a strategic initiative to boost profitability, increase market share, and improve customer satisfaction through statistical tools that can lead to breakthrough quantum gains in quality” (Harry, 1998). Pande et al. (2000), delimit six benefits of the Six Sigma implementation: sustained success, a performance goal for every employee, greater value for the customer, improvement rate acceleration, promotion of continuous learning, and strategic change execution.

Therefore, Six Sigma represents valid method managers can use for improving process performance. But in what kind of projects is it advisable to opt for the Six Sigma implementation?

If Lean can be used to reduce waste in simple processes, McCarty et al. (2005) argue that Six Sigma is a great tool for looking at complex process interactions because it takes the statistical process control to the next level, by providing a structured and adaptable DMAIC methodology with the appropriate statistical tools for a systematic approach to process improvement.

Also, the DMAIC framework can be expanded to other problem-solving tools like Theory of Inventive Problem Solving (TRIZ), Lean, 5 Whys, and so on. When do we use the DMAIC model? Because not all projects are viable for this approach.

Tellier (2018) describes some possible ways to select a DMAIC project. First of all, the managers need to implement the S-C-P Model (Structure-Conduct-Performance) which uses a topdown approach as a key to an effective project. Structure in this case measures the economic value of the project, conduct is the ability to exploit the maximum value from the project and performance evaluates the potential for its success. After that, a SWOT analysis continues to determine the relevant information for the final VRIO analysis (valuable, rare, imitable, organized), which assesses a strong project and a candidate for DMAIC.

Török (2018), provides another method we can use to select a possible project for Six Sigma, the 1-2-3 model which always shows that strategic improvement initiatives need to start from the top of a company and continue downwards until every employee understands his or her critical role in the project. But the 15 key selection criteria matrix of Tej Mariyapa is an all-encompassing tool for project selection, based on a variety of pieces for an optimal decision to use or not the Six Sigma and specifically the DMAIC methodology. The proposed criteria are:

1) *Customer impact* – will the project, if successfully improved, have an impact on the customer?
2) *Process stability* – has the process been or reached a stable level of performance?
3) *Defect definition* – can we define the operational defect of the process? (according to metrics such as cycle time, error rates, rework rates, first-time call handling percentage, straight-through processing rates, lead times, and complaint rates).
4) *Data availability* – can we attain data around the process metrics?

5) *Solution clarity* – do we know the solution? (If this is the case, the project does not need DMAIC)
6) *Benefits* – what are the cost-benefits and the soft benefits (related to customer satisfaction) of an improved process?
7) *Impact on service quality* – will the improvement contribute to enhancing service quality along the value chain?
8) *Project sponsorship* – is the difference between the project's success and failure important enough? (a strong sponsorship is a prerequisite for Six Sigma projects)
9) *Project alignment* – is the project aligned with the objectives of the company? (if not, it is not viable)
10) *Project timeline* – how long do we need for the completion of the improvement? (more than 6 months is not a reasonable period for DMAIC)
11) *Probability of implementation* – can the solution for the project be implemented without high resistance/high costs/corporate change?
12) *Investment* – will the improvement solution include large capital investments? (If so, Six Sigma may not be the methodology to use)
13) *Team availability* – do the team members have enough time to support the project? (if we do not have Green or Black Belts involved, the project cannot move forward)
14) *Controllability of inputs* – can we assess if we have sufficient measurable and controllable inputs? (it is difficult to achieve a project if we do not have control over the inputs)
15) *Project redesign* – can we improve the process without redesigning it? (if not, the project viability is low for DMAIC).

The project viability matrix can be built by compliance with the following rules:

- ✓ the relative importance of each of the criteria (the weighting scale ranges from 1 = least important to 5 = most important).
- ✓ after assigning a weight to each of the criteria, practitioners should answer each question about the project (1 = definitely no and a 5 = definitely yes)
- ✓ to find the individual weighted scores we need to:
    - divide each weighting by 3
    - in each rating column, the X marking = 1
    - multiply each X marking by its weighting
    - find the sum of all X marks for each rating column.

- ✓ to find the total score we need to:
    - multiply each weighted score by its rating and sum these products
    - divide the sum of the products by the sum of the weighted scores.

Thus, the total score will fall into one of three possible categories:

- less than 2.0 – The project is not a viable DMAIC project; it may be better to use another approach.
- 2.0 – 3.0 – This is a possible DMAIC project; it will require further validation.
- greater than 3.0 – This is a viable DMAIC project.

If for some questions the answer is a “definite no,” this will automatically disqualify the project from being a DMAIC project, regardless of the overall score.

An automotive company from Romania needed a solution for complex process improvement. We start by determining the project's viability for DMAIC Six Sigma (Table 2.2.3.1). After that, we proceed with the five steps of the method, namely, Define-Measure- Analyze- Improve-Control for a Six Sigma solution implementation. In this case, the total project score is 3.8, which qualifies it as a viable DMAIC project.

A. Define Phase

The study concentrates on the Body Control Unit (BCM) which is the central element necessary to achieve a variety of functions related to lighting, car access, radio control, and power. Over 12 months, defective proportion was high, with an average of 3240 ppm and it is desired to achieve at least half. The problems are due to microcontrollers rejected at Data I/O tests and parts rejected after the SMT process due to NXT programming. The product is an extremely complex one (Figure 2.2.3.1), including hundreds of electronics components (capacitors, resistors, diodes, etc.). The PCB is populated with elements through the SMT process, which is based on cutting-edge technology SMT (Surface-mount technology). The process at Data I/O station occurs before populating PCBs. In this process, microcontrollers (Figure 2.2.3.2) are taken by a robot from supplier`s rolls, programmed according to the customer's specifications, and then placed on another roll, which will then be transported to the

SMT line and will be placed automatically on PCBs. During the two robotic handlings, the microcontrollers may be damaged.

Tab. 2.2.3.1 The viability matrix for the automotive process improvement project

Project Viability Matrix						
Description	**W.**	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Are customers (internal/external) dissatisfied or defecting?	4			X		
Is the process relatively stable?	3				X	
Is the specific defect (defined by the customer) known?	4	X				
Is data related to the defect available or collectible?	5				X	
Is the solution not obvious?	3		X			
Are the expected benefits significant enough?	4				X	
Will service and/or quality be noticeably improved?	3					X
Does the project have Champion and Sponsor support?	4					X
Is the project aligned with department or company goals?	3				X	
Can the project be completed within 6 months?	2			X		
Considering the risk, is there a good probability of implementation?	5			X		
Will the solution likely involve little or no capital investment?	2			X		
Are the necessary team members available to support the project?	2				X	
Is the ability to make changes in the process largely in our control?	5					X
Will the solution likely not involve the redesign of the process?	3		X			
Weighted Scores		1.3	2	4.3	5.7	4.0
Total Score						3.8

The entire process is automated and involves elements to pass both through areas with the high temperatures where soldering takes place and cooling areas to ensure their fixing. To assemble these units, the following materials (which are purchased from various external suppliers) are needed: PCBs, electronic components; contact pins, plastic housings, boxes for packaging, and also the following machines and equipment: SMT line (laser marking machine, tin soldering machine, electronic components assembly machine, soldering oven, equipment for checking the presence of optical components and soldering of electronic components) and one assembly line (depaneling machine, contact pins inserting machine, ITCequipment, plastic housings soldering machine, radiofrequency checking machine, functional final test equipment, optical pin testing machine, logistic box to check the correctness of the number on the unit and on the box). Figure 2.2.3.3 presents the simplified flow chart for Data I/O programming.

Fig. 2.2.3.1 Body Control Unit

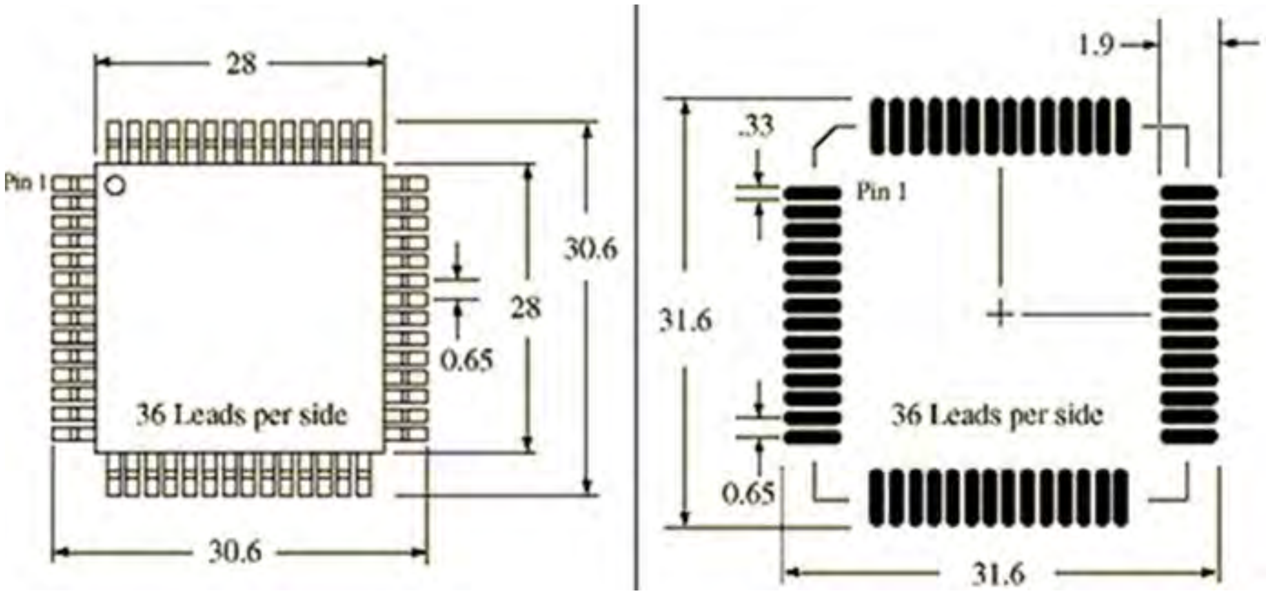


Fig. 2.2.3.2 Microcontroller

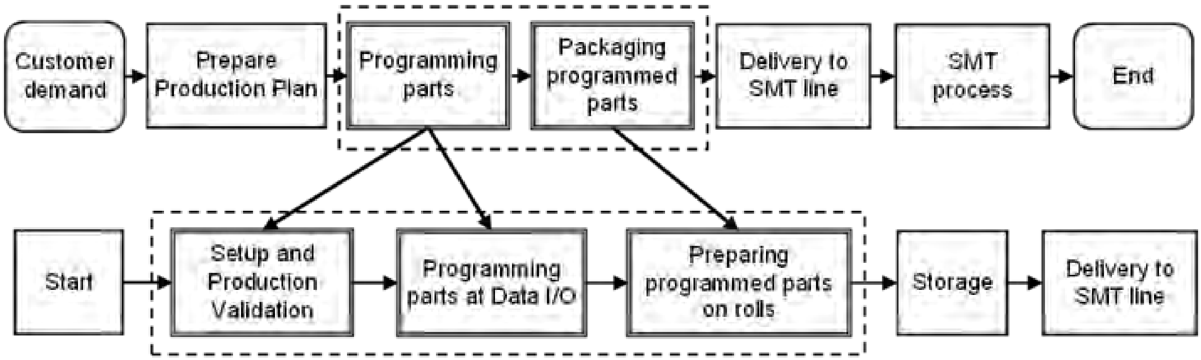


Fig. 2.2.3.3 Data I/O programming simplified flowchart

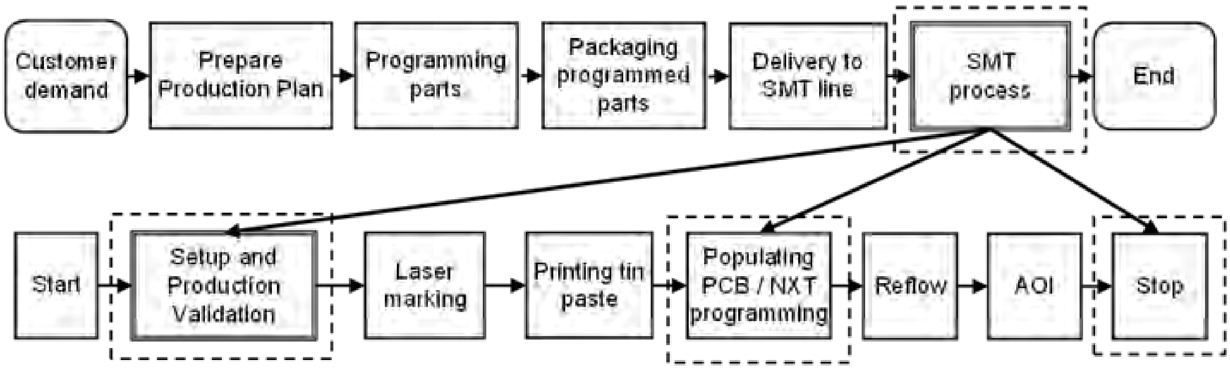


Fig. 2.2.3.4 SMT/NXT programming simplified flowchart

Figure 2.2.3.4 presents the simplified flow chart for SMT/NXT programming. Operators are involved in this process, who are directly productive staff and line technicians, maintenance technicians, and line supervisors, who are classified in the category of indirectly productive staff.

Employees from the departments of human resources, procurement sphere, material quality assurance, quality engineers, quality technicians, and product engineers are considered staff who provide support and their contribution is quantified based on percentage rates applied to directly productive costs.

B. Measure Phase

One-week production data (20,000 parts) were analyzed, detecting 7,000 parts with non-conformities in the Data I/O process and 6,000 in the SMT / NXT process.

B.1 Pareto Analysis for Data I/O

Table 2.2.3.2 presents Data I/O main non-conformities and Figure 2.2.3.5 represents the Pareto Analysis for Data I/O. One can see that the largest number of non-conformities occur due to faulty handling of microcontrollers (Class 2). Bent pins due to inappropriate handling situations cannot be fixed. If faulty programmed, microcontrollers can be reprogrammed (Class 4).

According to the company`s policy, a microcontroller can be reprogrammed only once. Within this project, it has been checked if microcontrollers can be functional after a second reprogramming. When testing is performed after the Data I/O programming, only the quality of the programming microcontroller is verified and if pins are bent or if the distance between them is not within specifications, such non-conformities will be determined only in the SMT/NXT process, when dimensional parameters of microcontrollers are checked. Also, in the Data I/O process, the lack of protection foil grip (Class 2) will be analyzed.

Tab. 2.2.3.2 Data I/O non-conformities categories

Non-conformities category	Category description	Quantity
Class 1	Errors in programming components	740
Class 2	Handling errors - bent pins	2780
Class 3	Handling errors - lack of protection foil grip	2115
Class 4	Mechanical errors	740
Total		7000

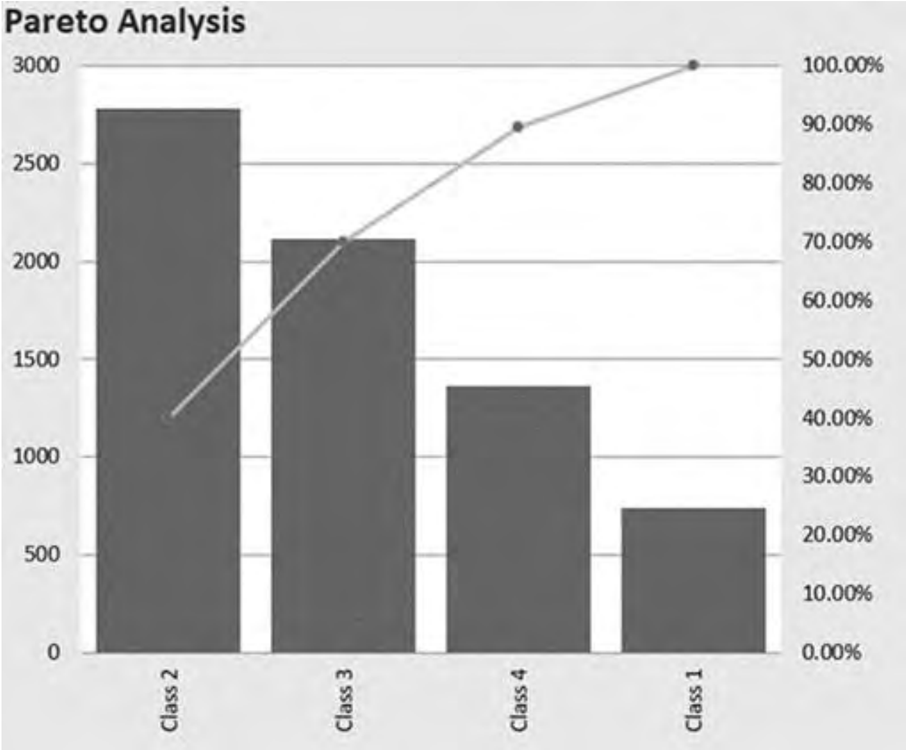


Fig. 2.2.3.5 Pareto Analysis for Data I/O

B.2 Initial Process Capability Analysis for Distance between Pins

Statistical checking was carried out by extracting 20 samples of 10 microcontrollers each. Because each microcontroller has 144 pins, it was considered the largest measured distance between pins. Tests were performed to detect the random character of the sample data, as well as tests to detect and remove outliers. It was assessed whether the distance between pins can be adequately modeled by a normal distribution (Tables 2.2.3.3 and 2.2.3.4) and also indicators of process capability were assessed.

Tab. 2.2.3.3 Tests for normality for the distance between pins

Test	Statistic	P-Value
Chi-Square	138.56	3.33067E-16
Shapiro-Wilk W	0.96391	0.00163232
Skewness Z-score	0.42535	0.670578
Kurtosis Z-score	-3.40875	0.000652708

Tab. 2.2.3.4 Goodness-of-fit tests for the distance between pins

EDF Statistic	Value	Modified Form	P-Value
Kuiper V	0.1362	1.94087	< 0.01*
Cramer-Von Mises W^2	0.146282	0.146648	0.0264*
Watson U^2	0.143826	0.144186	0.0194*
Anderson-Darling A^2	1.06373	1.06778	0.0084*

The chi-square test divides the range of distance between pins into 32 equally probable classes and compares the number of observations in each class to the expected number. The Shapiro-Wilk test is based upon comparing the quantiles of the fitted normal distribution to the quantiles of the data. The standardized skewness test looks for a lack of symmetry in the data. The standardized kurtosis test looks for a distributional shape which is either flatter or more peaked than the normal distribution. Since the smallest P-value amongst the tests performed is less than 0.05, we can reject the idea that distance between pins comes from a normal distribution with 95% confidence. The EDF statistics compare the empirical distribution function to the fitted CDF in different ways. *Indicates that the P-Value has been compared to tables of critical values specially constructed for fitting the currently selected distribution. Since the smallest P-value amongst the tests performed is less than 0.05, we can reject the idea that distance between pins comes from a normal distribution with 95% confidence. Table 2.2.3.4 compares the goodness-of-fit when various distributions are fit to the distance between pins. According to the log-likelihood statistic, the best fitting distribution is the Gamma distribution. Table 2.2.3.5 compares the goodness-of-fit when various distributions are fit to distance between pins. According to the log-likelihood statistic, the best fitting distribution is the Gamma distribution. The initial Capability Analysis for the distance between pins using Gamma distribution is presented in Figure 2.2.3.6 and using Normal distribution in Figure 2.2.3.7. Since the differences between Gamma and Normal distributions are relatively small for this particular set of data, as can be seen in Figures 2.2.3.8 and 2.2.3.9, presenting the Probability Plot for Gamma distribution and Normal distribution respectively, it has been decided to further analyze the capability indicators with Normal distribution.

Tab. 2.2.3.5 Comparison of alternative distributions

Distribution	Est. Parameters	Log-Likelihood	KSD
Gamma	2	259.052	0.0643689
Lognormal	2	258.839	0.0617867
Normal	2	258.656	0.0688474

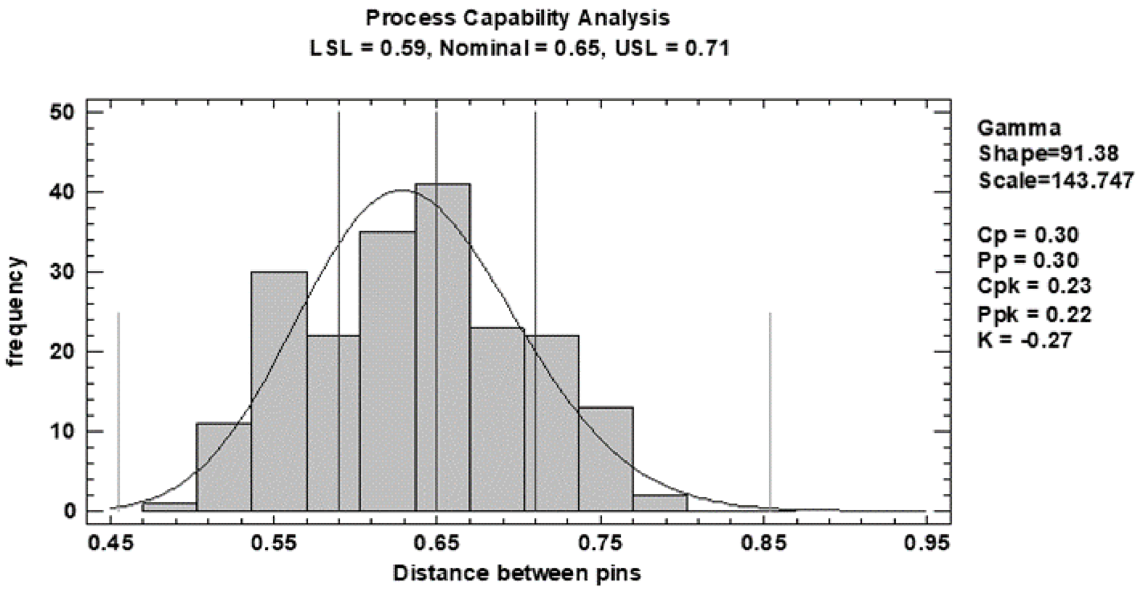


Fig. 2.2.3.6 Initial capability analysis for the distance between pins (Gamma distribution)

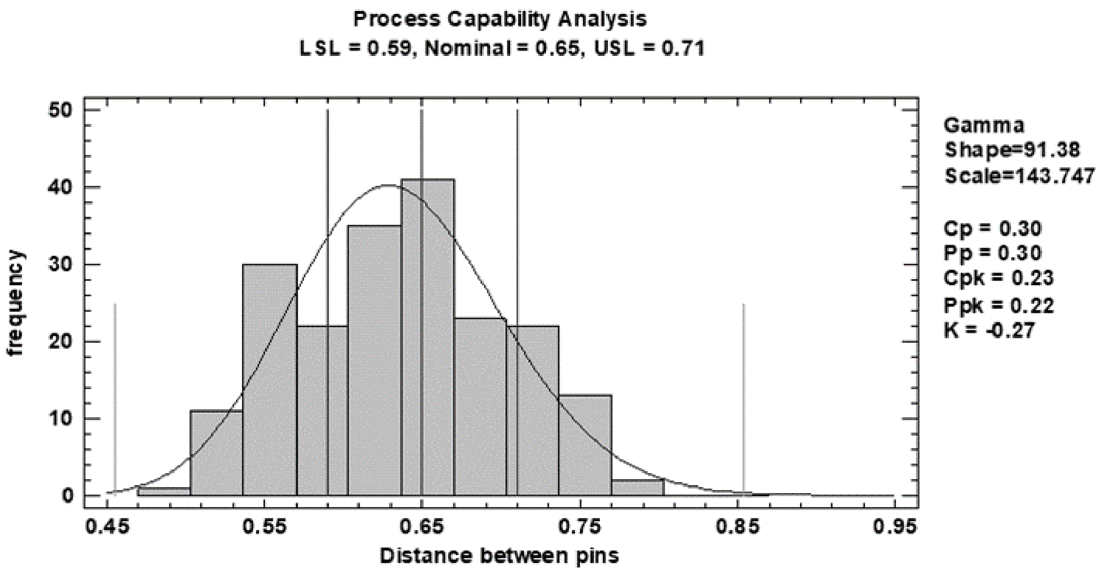


Fig. 2.2.3.7 Initial capability analysis for the distance between pins (Normal distribution)

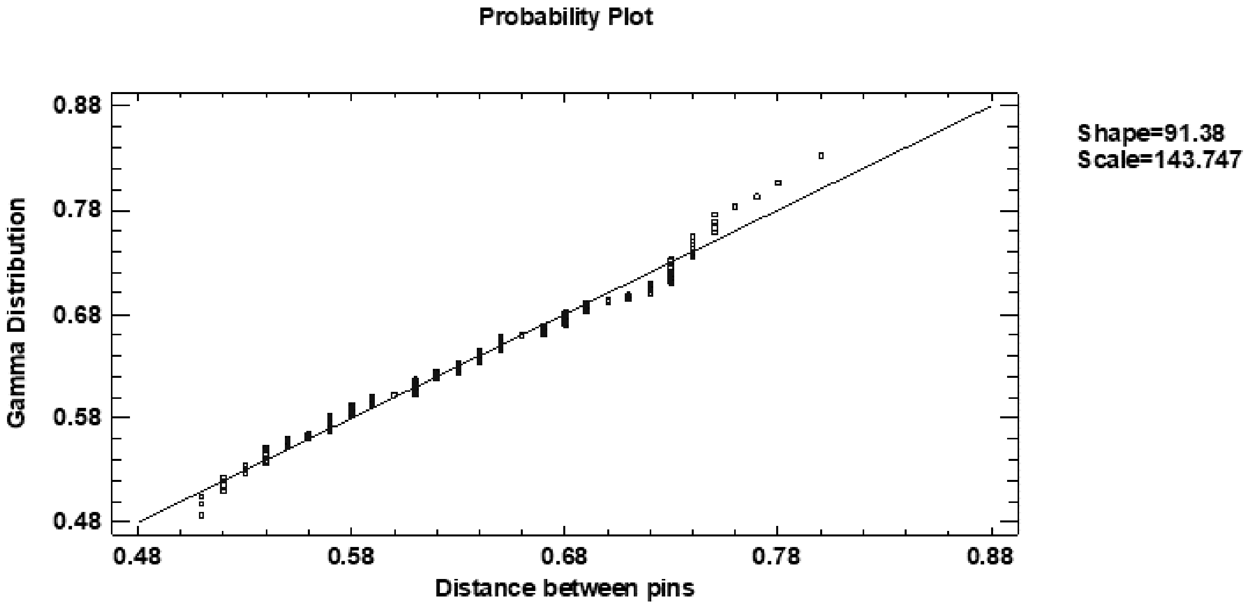


Fig. 2.2.3.8 Probability Plot for distance between pins
(Initial Capability Analysis using Gamma distribution)

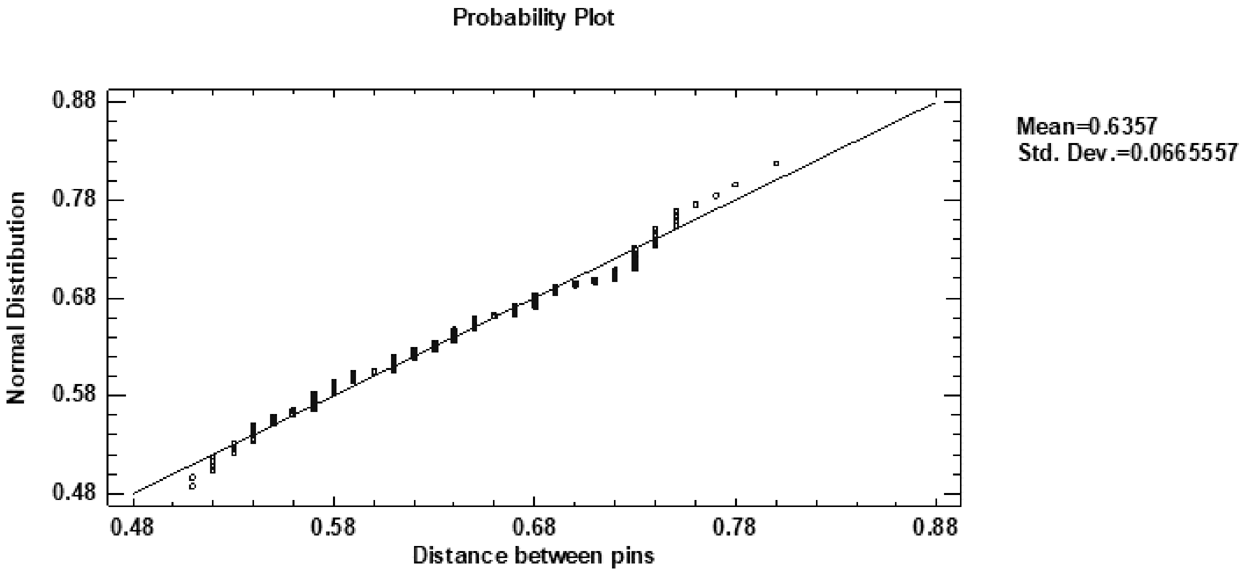


Fig. 2.2.3.9 Probability Plot for the distance between pins
(Initial Capability Analysis using Normal distribution).

Therefore a Normal distribution was fit to the set of 200 observations in the variable distance between pins. Table 2.2.3.6 presents the observed and estimated percentages of the fitted distribution which lies outside the specification limits.

Tab. 2.2.3.6 Percentages out of specifications for the distance between pins

Specifications	Observed beyond specifications	Z-Score	Estimated beyond specifications
USL = 0.71	17.000000%	1.12	13.213384%
Nominal = 0.65		0.21	
LSL = 0.59	26.500000%	-0.69	24.615258%
Total	43.500000%		37.828642%

Several capability indices have been computed to summarize the comparison of the fitted distribution to the specifications (Table 2.2.3.7). The Pp index in the case of the normal distribution equals the distance between the specification limits divided by 6 times the standard deviation. In our case, Pp equals 0.3005, which is considered to be very bad. Ppk is a one-sided capability index, which in the case of the normal distribution divides the distance from the mean to the nearer specification limit by 3 times the standard deviation. In this case, Ppk equals 0.228881 which is considered to be very bad. K equals the mean minus the nominal, divided by one-half the distance between the specifications.

Tab. 2.2.3.7 Capability Indices for the distance between pins

Capability Indices	Short-Term Capability	Long-Term Performance
Cp/Pp	0.304	0.3005
Cpk/Ppk	0.231547	0.228881
K		- 0.238333
% beyond spec.	37.3012	37.8286
Sigma Level	0.89	0.88

Since K equals - 0.238333, the mean is located 23.8333% of the way from the center of the specifications toward the lower specification limit. Thus, for Cp ≈ 0.3 and Cpk ≈ 0.23 is resulting in a Sigma Level short term ≈ 0.88 and Sigma Level long term ≈ - 0.62 respectively. Therefore DPMO ≈ 730,000 is unacceptable. Still, X bar and R charts show that the process is in control (Figures 2.2.3.10 and 2.2.3.11), but the process is not capable as presented beforehand.

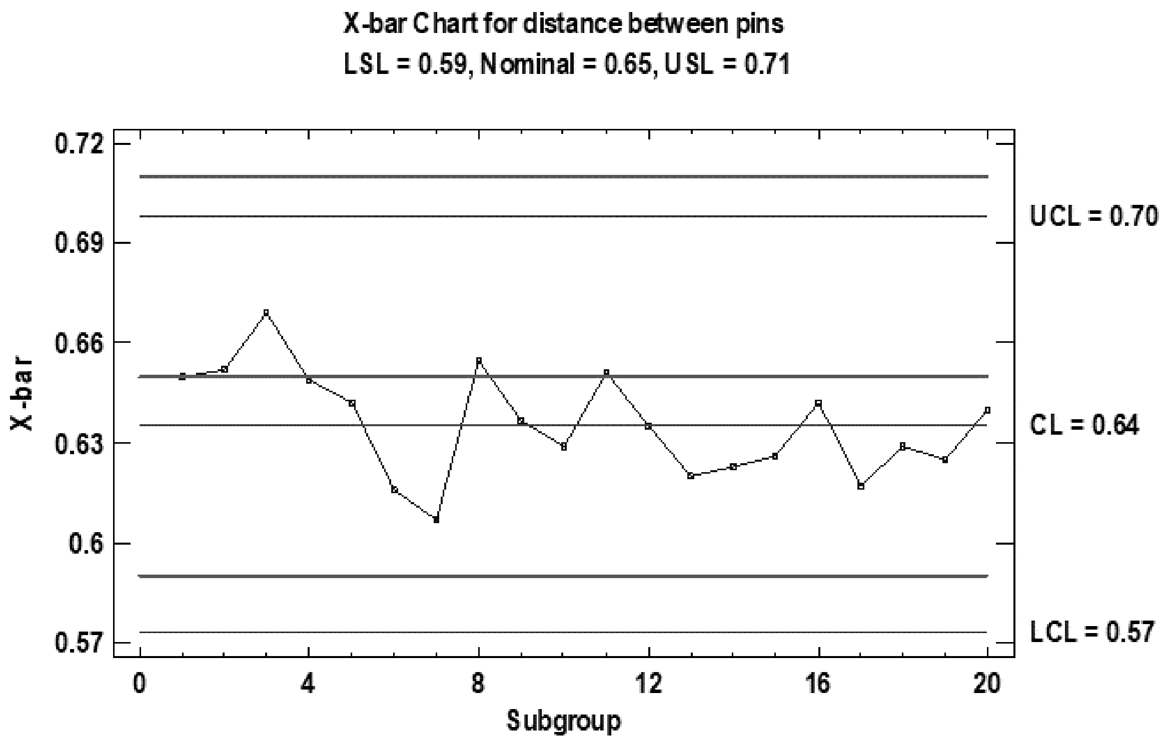


Fig. 2.2.3.10 Xbar Chart for the distance between pins

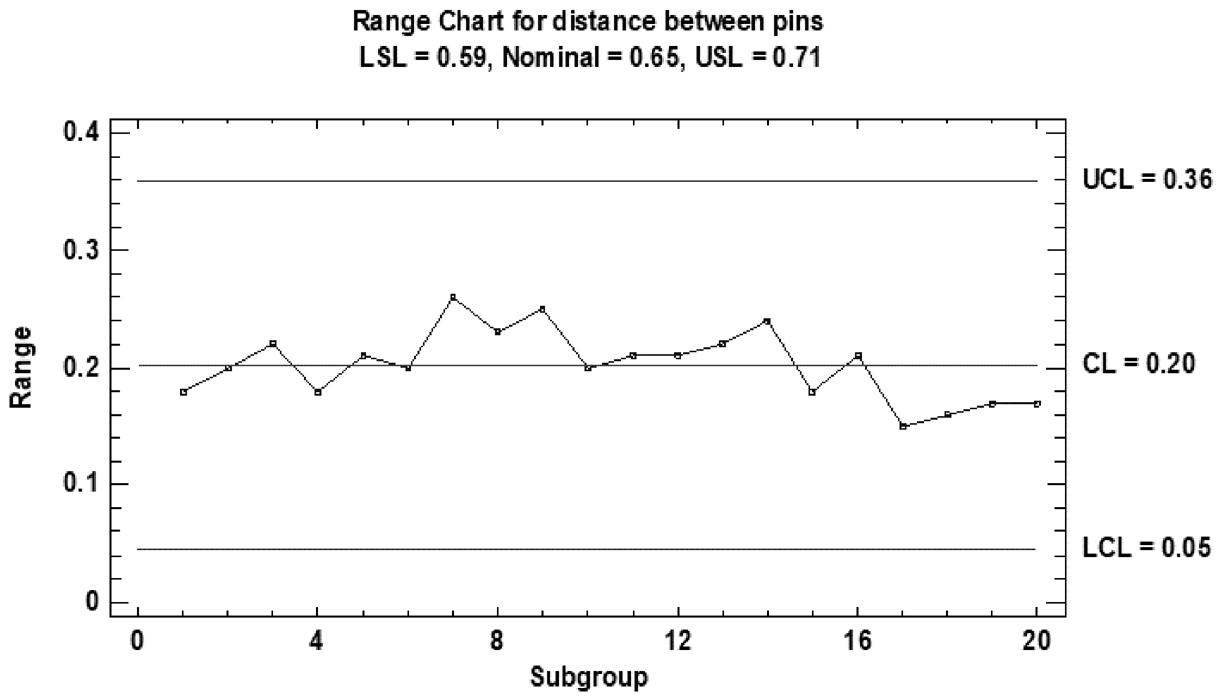


Fig. 2.2.3.11 Range Chart for the distance between pins

B.3 Assessing the Rejection Rate at Data I/O Due to Programming Errors

If there are programming errors, the components can also be reprogrammed once according to current specifications. In this respect, a record of the microcontrollers rejected after the first reprogramming in two weeks on all three shifts was analyzed. After the first reprogramming, the rejection rate dropped by 40%.

B.4 Pareto Analysis for Populating PCB/NXT

Table 2.2.3.8 presents the main non-conformities of the SMT/NXT processes and figure 2.2.3.12 the Pareto Analysis for the SMT/NXT processes. One can see that the first two largest numbers of non-conformities are the supplier`s responsibility and occur due to dimensional variations and rolls of different sizes on which microcontrollers are placed respectively. The third-largest number of non-conformities is due to mechanical causes (a robot that places components on the PCBs).

Tab. 2.2.3.8 SMT/NXT non-conformities categories

Non-conformities category	Subclass	Category description	Quantity
Class 1	1.1 SMT/NXT	Dimensional	600
	1.2 SMT/NXT	Appearance (color / hue)	150
	1.3.1 SMT/NXT	Robot speed	120
	1.3.2 SMT/NXT	Vacuum nozzles size	80
Class 2	2.1 Supplier	Dimensional variations	2390
	2.2 Supplier	Rolls of different sizes	1160
Class 3	3.1 Machine	Mechanical causes	1140
	3.2 Machine	Software errors	360
Total			6000

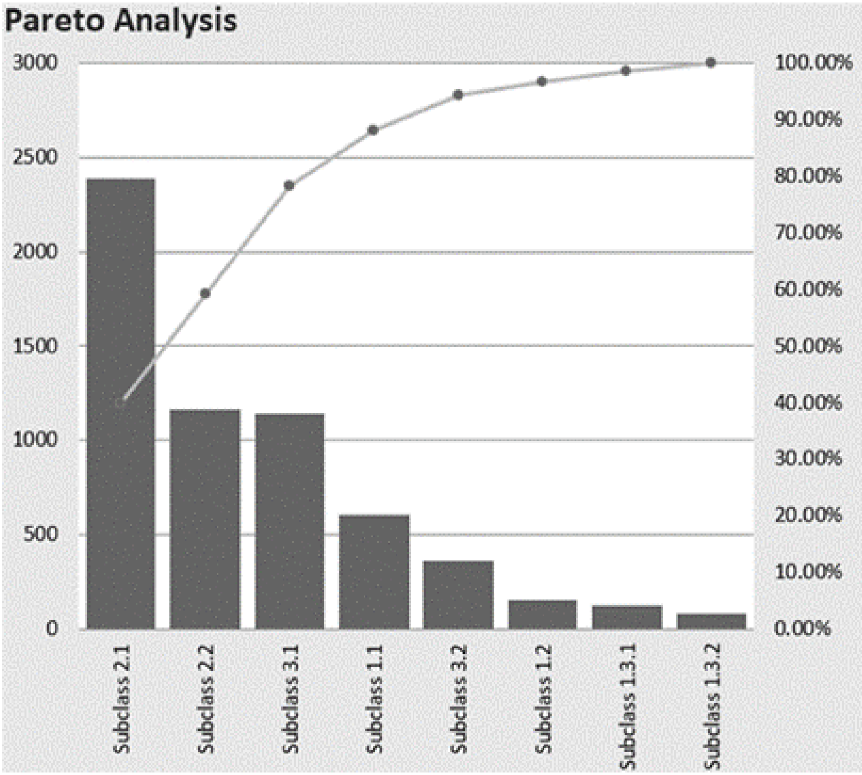


Fig. 2.2.3.12 Pareto Analysis for SMT/NXT

C. Analysis Phase

In this phase, the possible causes were identified for Data I/O and SMT/NXT through Ishikawa diagrams and also possible root-causes through the "5 Whys" analysis. In figure 2.2.3.13, the most important causes are presented, identified through the Ishikawa diagram, and root-causes identified through the "5 Whys" analysis at Data I/O station (Tables 2.2.3.9 and 2.2.3.10). The adaptor provides the electrical connection function between the programmer and the modules to be programmed and the recording function of the programming process. Another cause for rejected products is determined by bent pins. Because pins make the connection between the microcontroller and PCBs, they are an important element in the circuit and must make contact in a specified optimal position. If they are bent, they will not make correct contact. Causes for bent pins can be internal, due to improper grip and handling by the robot, or external, because suppliers do not have a capable process for the distance between pins and do not follow wrapping procedures on rolls.

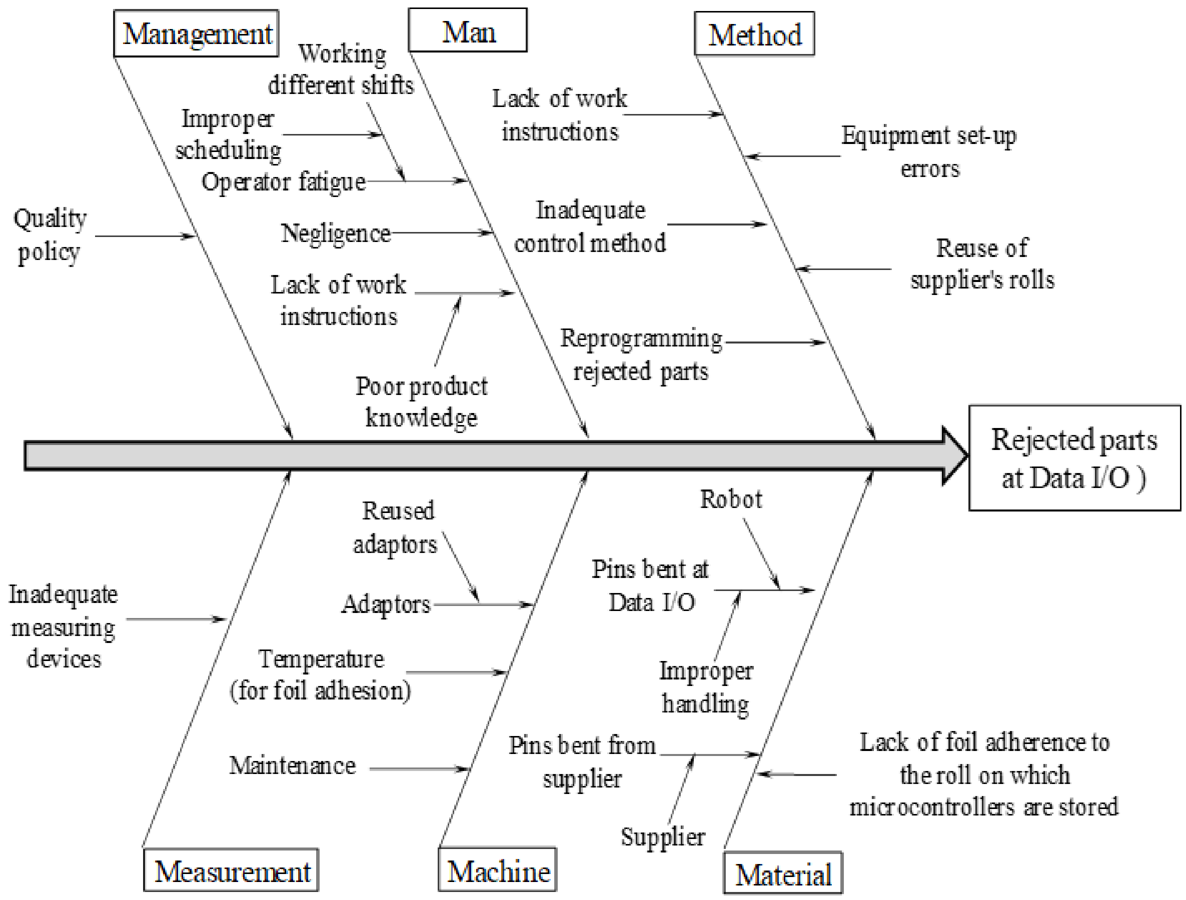


Fig. 2.2.3.13 Ishikawa diagram for Data I/O

Tab. 2.2.3.9 "5 Whys" analysis for adaptors and unprogrammed components

Causes from Data I/O Ishikawa diagram	Adaptors	Unprogrammed components
Why?	Old Data I/O Adaptors	Parts rejected at AOI
Why?	Adaptors have short life cycle	Uncalibrated camera
Why?	Adaptors are reused for 3 cycles	Unprogrammed camera after maintenance
Why?	-	Reprogramming is allowed only once
Corrective actions/ Inspections	Check rejected parts to see if only new adaptors are used	Check if second programming is feasible

In Figure 2.2.3.14, the most important causes are presented, identified through the Ishikawa diagram, and root-causes identified through the "5 Whys" analysis at SMT/NXT (Table 2.2.3.11).

Tab. 2.2.3.10 "5 Whys" analysis for bent pins

Causes from Data I/O Ishikawa diagram	**Microcontrollers with bent pins**		
Why?	Supplied with bent pins	Pins are bent during data I/O programming	
Why?	Rolls wrapping inconsistent at the supplier	Robot not properly programmed	Inconsistent distance between pins
Why?	-	-	Supplier's process not capable
Corrective actions/ Inspections	Audit supplier/Change supplier	Check robot programming	Audit supplier/Change supplier

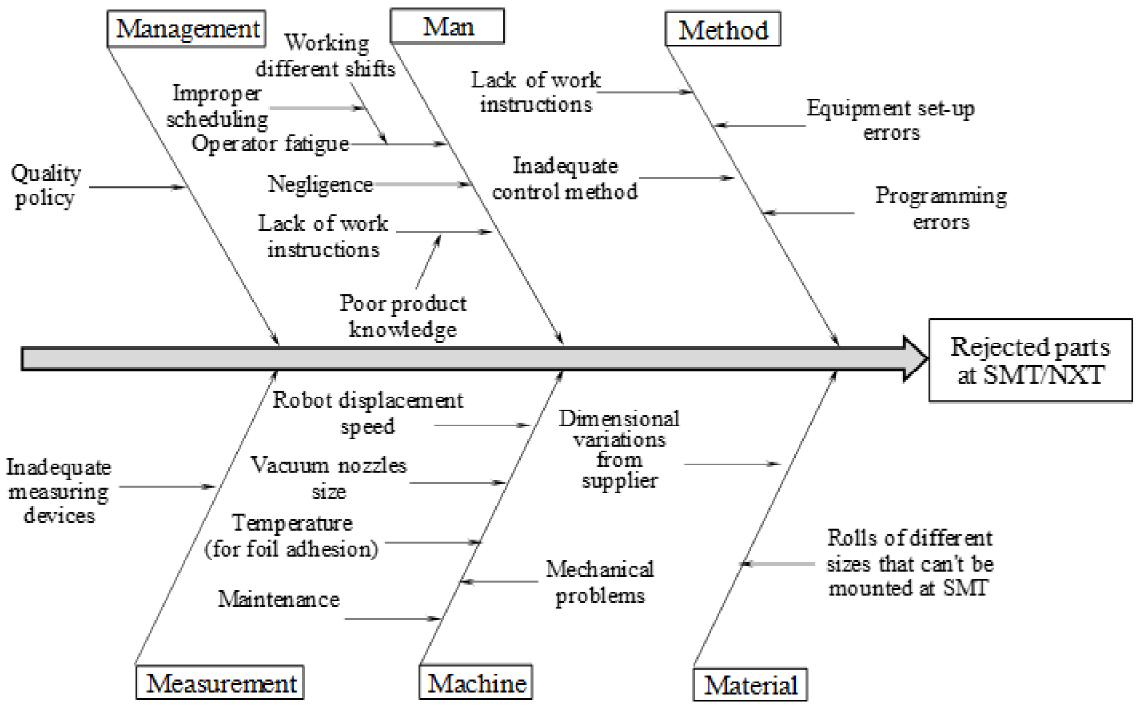


Fig. 2.2.3.14 Ishikawa diagram for SMT/NXT

Tab. 2.2.3.11 "5 Whys" analysis for SMT/NXT

Causes from SMT/NXT Ishikawa diagram	**Company reuses rolls from supplier**	**Programmed components wrapping**	**Parts rejected at AOI**
Why?	Rolls can cause rejection due to lack of protection foil flatness	Wrong glued foil (too strong adhesion) on rolls prevents the SMT/NXT robot to take components and place them on the PCB	Wrong polarity
Why?	Foil is deformed after the programming of flashcards at Data I/O	Operator must fix the foil so it does not stick to the roll again and must cover components that are to be taken	Wrong set-up at programming equipment
Why?	Foil is deformed due to high temperature	Manual operation	Operating error
Why?	Rolls are reused	Lack of proper training	Lack of proper training
Corrective actions/ Inspections	Usage of only new rolls for components programmed at Data I/O	Operators' training	Operators' training

C.1 Benchmarking Rolls Suppliers' Processes

To benchmark rolls suppliers' processes, the Analytic Hierarchy Process (AHP) was chosen. AHP (Saaty, 2001) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology.

The AHP algorithm is made up of two steps:

- Step 1. Determine the relative rankings (weights) of the decision criteria;

- Step 2. Determine the relative rankings (priorities) of alternatives.

Five potential roll suppliers have been selected from A to E (A being the current supplier), using five decision criteria, namely Delivery Time (DT), Experience (EXP), Quality Performance (QP), Technological Resources (TR), and Current workload (CW) as presented in Figure 2.2.3.15.

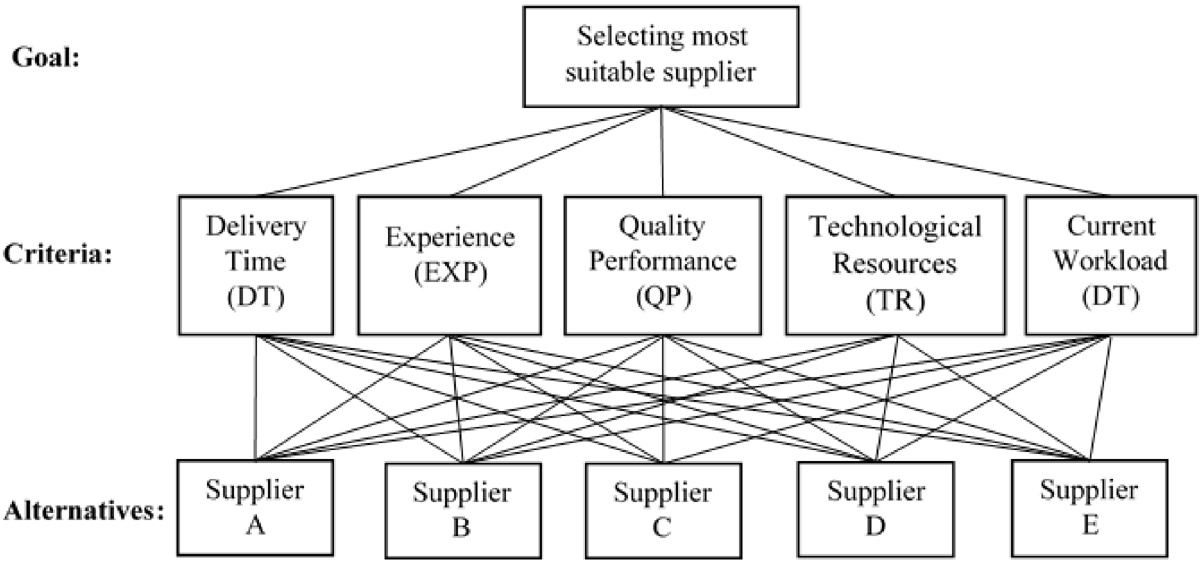


Fig. 2.2.3.15 AHP hierarchy for selecting a roll supplier

C.1.1 Ranking of Criteria and Alternatives

The criteria/alternatives pairwise comparisons are made with the grades ranging from 1-9, assuming that if criteria/alternative A is absolutely more important than criteria B and is rated at 9, then criteria/alternative B must be absolutely less important than A and is graded as 1/9 (Table 2.2.3.12).

The criteria ranking is presented in Table 2.2.3.13.

Tab. 2.2.3.12 AHP for ranking scale for criteria and alternatives

Ranking of importance	Definition	Reciprocal ranking of importance	Explanation
1	Equal importance	1	Two criteria/alternatives contribute equally to the goal/objective
3	Somewhat more important	1/3	Experience and judgement slighltly favour one over the other
5	Much more important	1/5	Experience and judgement strongly favour one over the other

7	Very much more important	1/7	Experience and judgment very strongly favor one over the other
9	Absolutely more important	1/9	Experience and judgment assign the highest possible validity of favoring one over the other
2, 4, 6, 8	Intermediate values	1/2, 1/4, 1/6, 1/8	When compromise is needed

Tab. 2.2.3.13 Criteria ranking for rolls supplier

	DT	**EXP**	**QP**	**TR**	**CW**
DT	1	3	1/3	4	3
EXP	1/3	1	1/2	5	4
QP	3	2	1	5	4
TR	1/4	1/5	1/5	1	1/2
CW	1/3	1/4	1/4	2	1

To determine criteria weights, relation (1) is considered:

$$A \cdot X = \lambda_{\max} \qquad (2.2.3.1)$$

where:

- A is the matrix of size n × n, for n criteria called the Priority Matrix.
- X is the Eigenvector of size n × 1, called the Priority Vector.
- λ_{max} is the Eigenvalue, $\lambda_{max} \in \Re > n$.

To find the Eigenvector X (Priority Vector), the column entries are normalized by dividing each entry by the sum of the column and then taking the overall row averages as presented in Figure 2.2.3.16. Figure 2.2.3.17 presents the weights for each criterion.

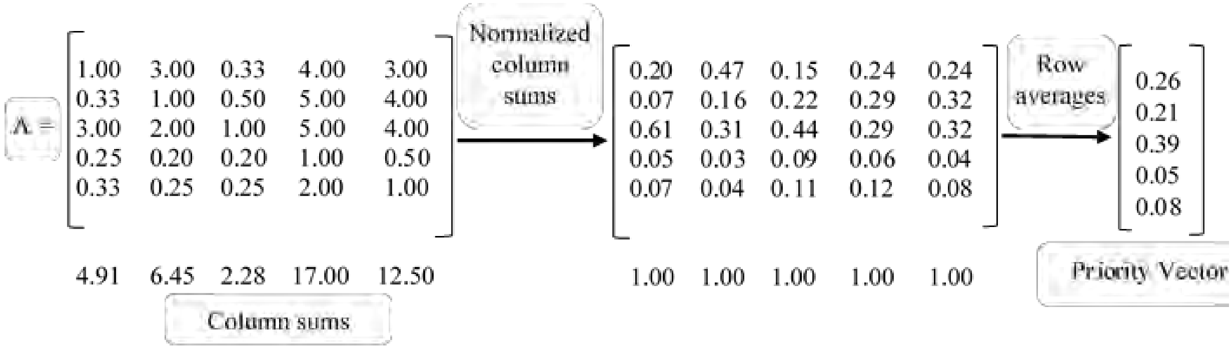


Fig. 2.2.3.16 Priority Vector for criteria

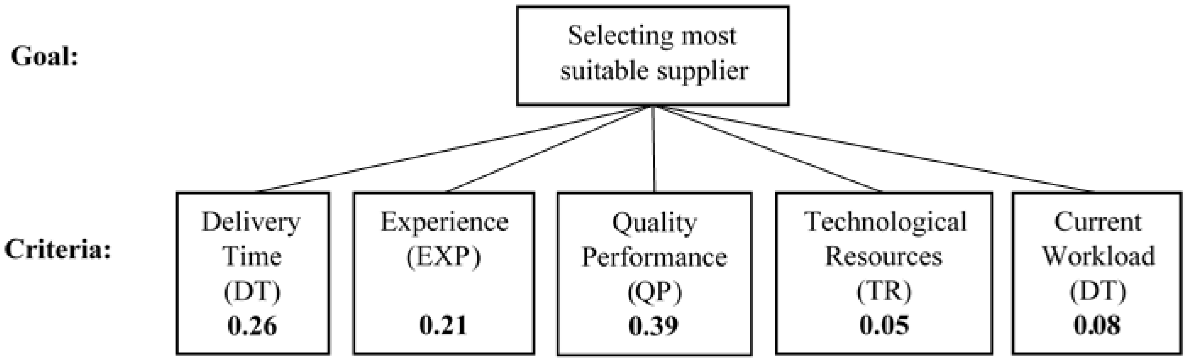


Fig. 2.2.3.17 Criteria weights

C.1.2 Checking for Judgments Consistency

The next step is to calculate the Consistency Ratio (CR) to measure how consistent the judgments have been. AHP evaluations are based on the assumption that the decision-maker is rational, i.e., if A is preferred to B and B is preferred to C, then A is preferred to C. If the CR is greater than 0.1 the judgments are untrustworthy because they are too close to randomness and the judgments must be rethought. The Eigenvalue λ_{max} is calculated from relation (1), in our case the calculations are presented in Figure 18.

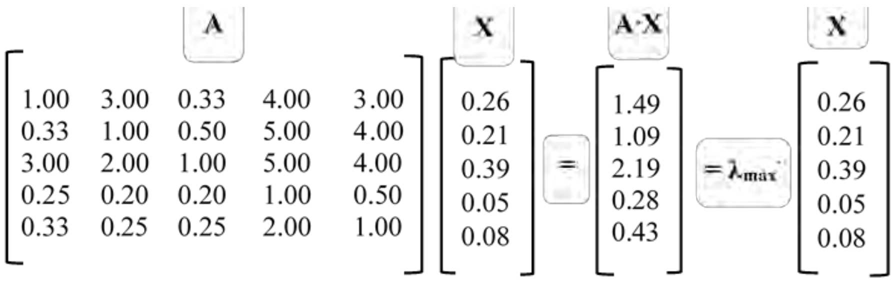


Fig. 2.2.3.18 Calculation of Eigenvalue λ_{max}

$$\lambda_{max} = \frac{\frac{1.49}{0.26} + \frac{1.09}{0.21} + \frac{2.19}{0.39} + \frac{0.28}{0.05} + \frac{0.43}{0.08}}{5} = 5.38$$

Consistency Index (CI) is calculated according to relation (2):

$$\text{CI} = \frac{\lambda_{max}}{n-1} \quad (2.2.3.2)$$

CI=(λ_{max}-n)/(n-1) = (5,38-5)/4 = 0,094

CR = CI/1,12 = 0,094 / 1,12 = 0,084 < 0,1 -> judgments are consistent

The final step is to calculate the Consistency Ratio (CR) by using table 2.2.3.14 (Saaty & Vargas, 2001). The upper row is the order of the random matrix, and the lower row is the corresponding Index of Consistency for random judgments.

Tab. 2.2.3.14 Corresponding indices of consistency to the order of random matrix

1	2	3	4	5	6	7	8	9	10
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In our case, $\text{CR} = \frac{\text{CI}}{1.12} = \frac{0.094}{1.12} = 0.084$ < 0.1 and therefore the judgments are consistent. Similar judgments, calculations, and verification of consistency were performed for ranking the alternatives. In our case Priorities matrix, Criteria weights, and Priority vector for the five potential rolls suppliers are presented in Table 2.2.3.15. Therefore, according to the Priority vector, supplier B was chosen.

Tab. 2.2.3.15 AHP for selecting the most suitable roll supplier

	DT (0.26)	**EXP (0.21)**	**QP (0.29)**	**TR (0.05)**	**CW (0.08)**	**Priority vector**
A	0.33	0.06	0.35	0.32	0.23	0.27
B	**0.41**	**0.46**	**0.24**	**0.22**	**0.35**	**0.34**
C	0.09	0.05	0.18	0.17	0.09	0.12
D	0.05	0.14	0.14	0.06	0.06	0.12
E	0.13	0.27	0.09	0.23	0.23	0.15

D. Improvement Phase

For non-conformities identified and analyzed in this paper, several possible measures were identified to improve the complex process and reduce the rate of rejections. The most serious problems were identified at Data I/O station and the parts rejected an SMT line processes are also influenced by the Data I/O processes. For these reasons, improvement measures that will be proposed in this section will be only for Data I/O station where microcontroller programming occurs.

D.1 Improving Microcontroller Programming

If there are programming errors, according to internal specifications, components can be reprogrammed only once. After the first reprogramming, it was checked that a second reprogramming was feasible. After assessing the data obtained from the second reprogramming, it was determined that this is feasible and the rejection rate dropped by 65%. Once approved, this measure will be implemented.

D.2 Purchasing Ready Programmed Microcontrollers from Supplier

In this case, a new Automatic Optical Inspection (AOI) machine is needed to check the components from the supplier and to test the quality of programming. Such equipment costs about €100,000.

There are several possibilities of return on investment: with the client's consent, costs for the acquisition of equipment will be allocated totally to the new client's project; costs are allocated to the following projects until the investment is recovered; costs recovered as amortization are included in the updated hourly rates of equipment. In any case, for an average of 20,000 pieces/week, costs will be recovered within 5 weeks of production.

It should be noted that this change can be implemented only with the client's agreement, which involves a testing period in which practically a stock of components will be produced.

This method is effective because it will reduce the time required for final product assembly by removing the activity of components' programming. Once reduced the time, costs will also decrease, by reducing AOI duration and because an operator is no longer needed.

D.3 Using Only New Adaptors at Data I/O Station

Adapters reused after the end of a cycle seem to be one of the main reasons for which parts are not positioned correctly in programming and storage roll respectively.

To verify their influence, only new adaptors will be used. If the results are positive, henceforth only new adaptors will be used, because in any case the cost of a new adaptor will be recuperated by producing more conforming parts.

D.4 Purchasing of New Rolls for Microcontrollers' Storage

Unprogrammed microcontrollers are taken from the initial roll, that comes from the supplier, they are programmed and then stored on another roll which will then be used on the SMT line, where the programmed microcontrollers will be placed on the PCBs. It is extremely important when handling components between the two stations that these are not damaged. Thus, one of the reasons why there are scrap and non-conformities at Data I/O station (including bent pins) is determined by the roll on which the programmed microcontrollers are stored. Rolls being reused, the protective foil has no grip and as new components are placed, they fall and become scrap. The initially used rolls present sprocket holes only on one side (Figure 2.2.3.19 a) and it was decided to replace them with rolls presenting sprocket holes on both sides (Figure 2.2.3.19 b) for a better grip of protective foil. Figure 2.2.3.20 presents the Data I/O station with the elements that will be improved, that is new adaptors and new rolls.

Fig. 2.2.3.19 Rolls with sprocket holes on one side (a) and both sides (b)

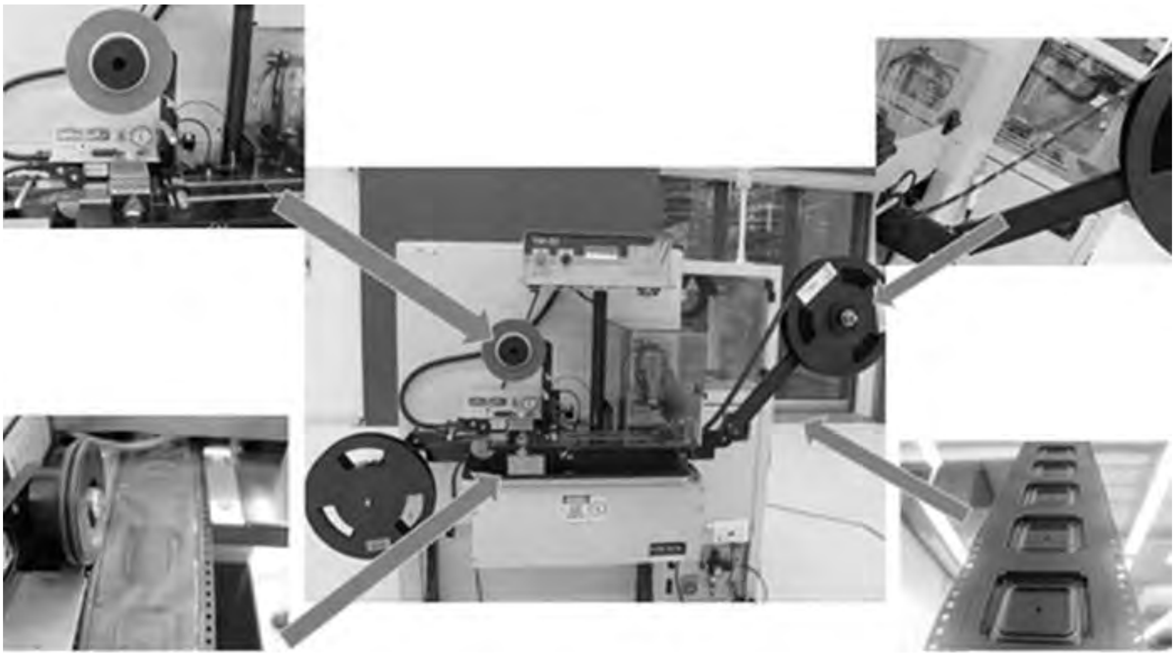


Fig. 2.2.3.20 Data I/O station optimization

D.5 Final Process Capability Analysis for Distance between Pins

After the microcontrollers supplier’s process audit and improvement, a statistical checking was carried out at SMT/NXT line by extracting 20 samples of 10 microcontrollers each. Tests were performed to detect the random character of the sample data, tests to detect and remove outliers, it was assessed whether the distance between pins can be adequately modeled by a normal distribution (Tables 2.2.3.16 and 2.2.3.17), and indicators of process capability were assessed as well.

Tab. 2.2.3.16 Tests for normality for the distance between pins

Test	Statistic	P-Value
Chi-Square	1379.2	0.0
Shapiro-Wilk W	0.96391	0.920085
Skewness Z-score	0.42535	0.612043
Kurtosis Z-score	-3.40875	0.984631

Tab. 2.2.3.17 Goodness-of-fit tests for the distance between pins

EDF Statistic	Value	Modified Form	P-Value
Kuiper V	0.164681	2.34999	< 0.01*
Cramer-Von Mises W^2	0.320000	4.58051	< 0.01*
Watson U^2	1.183580	1.18750	< 0.01*
Anderson -Darling A^2	1.183060	1.18729	< 0.01*

Since the smallest P-value amongst the tests performed is less than 0.05, we can reject the idea that distance between pins comes from a normal distribution with 95% confidence. The EDF statistics compare the empirical distribution function to the fitted CDF in different ways. Since the smallest P-value amongst the tests performed is less than 0.05, we can reject the idea that distance between pins comes from a normal distribution with 95% confidence. Table 2.2.3.18 compares the goodness-of-fit when various distributions are fit to the distance between pins. According to the log-likelihood statistic, the best fitting distribution is the Lognormal distribution.

Tab. 2.2.3.18 Comparison of alternative distributions

Distribution	Est. Parameters	Log-Likelihood	KS D
Lognormal	2	600.721	0.164681
Gamma	2	600.664	0.165817
Normal	2	600.510	0.166606

The final Capability Analysis for the distance between pins using Lognormal distribution is presented in figure 2.2.3.21 and using Normal distribution in figure 2.2.3.22. Since the differences between Gamma and Normal distributions are relatively small for this particular set of data, it has been decided to further analyze the capability indicators with Normal distribution.

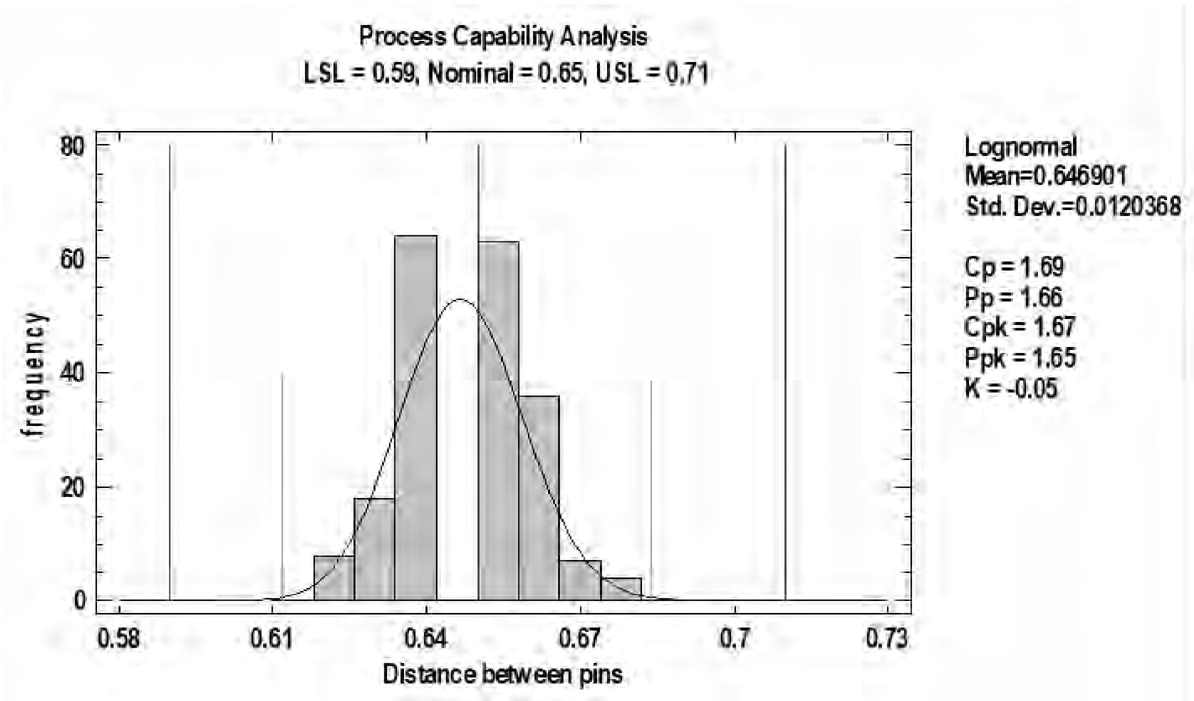


Fig. 2.2.3.21 Final capability analysis for the distance between pins (Lognormal distribution)

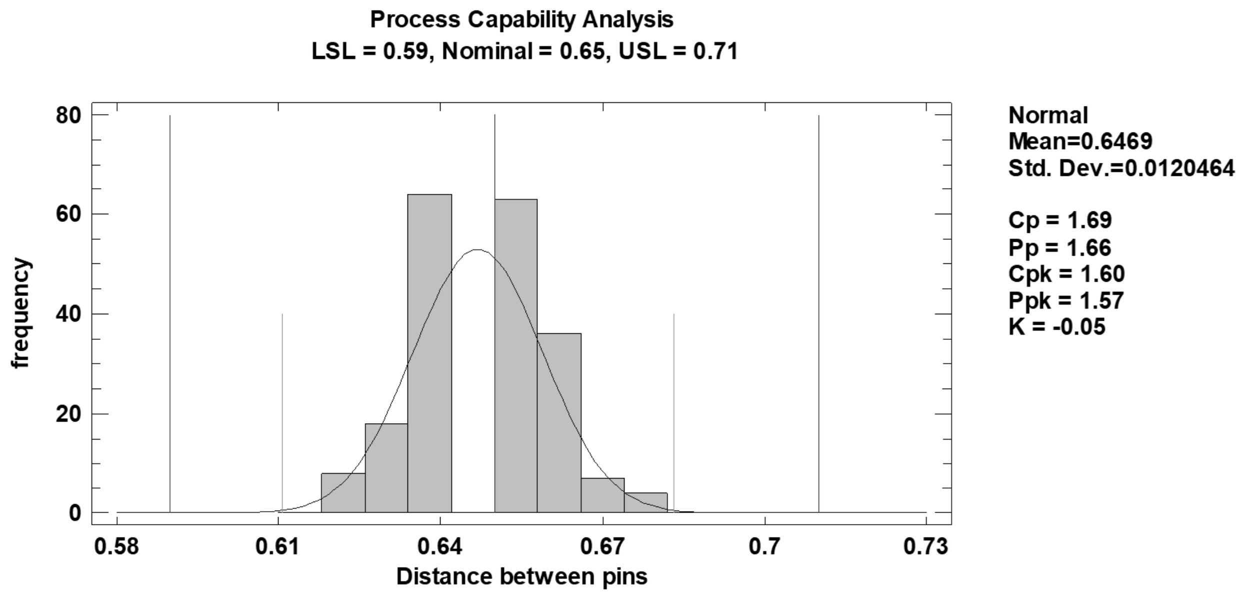


Fig. 2.2.3.22 Final capability analysis for the distance between pins (Normal distribution)

Therefore a Normal distribution was fit to the set of 200 observations in the variable "distance between pins. Table 2.2.3.19 presents the observed and estimated percentages of the fitted distribution which lies outside the specification limits.

Tab. 2.2.3.19 Percentages out of specifications for the distance between pins

Specifications	Observed beyond specifications	Z-Score	Estimated beyond specifications
USL = 0.71	0.000000%	5.01	0.000027%
Nominal = 0.65		0.27	
LSL = 0.59	0.000000%	-4.94	0.000039%
Total	0.000000%		0.000066%

Tab. 2.2.3.20 Capability Indices for the distance between pins

Capability Indices	Short-Term Capability	Long-Term Performance
Cp/Pp	1.68579	1.65841
Cpk/Ppk	1.67351	1.64633
K		-0.0511445
% beyond spec.	0.0000433449	0.0000662731
Sigma Level	5.05	4.97

Xbar and R charts show that the process is in control (Figures 2.2.3.23 and 2.2.3.24).

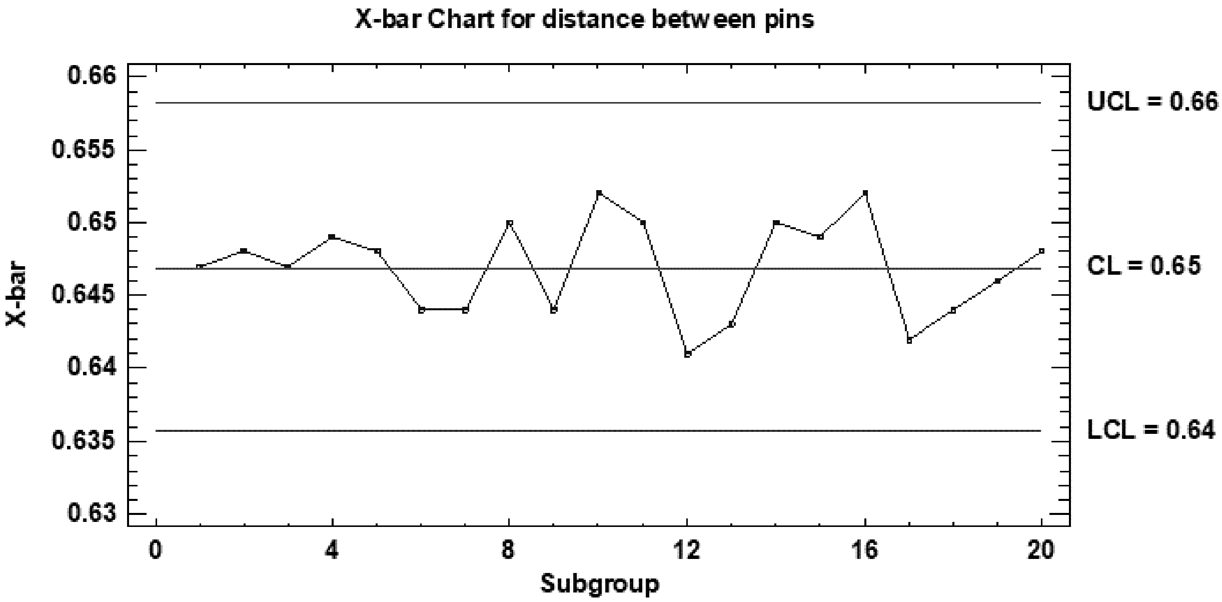


Fig. 2.2.3.23 Xbar Chart for the distance between pins

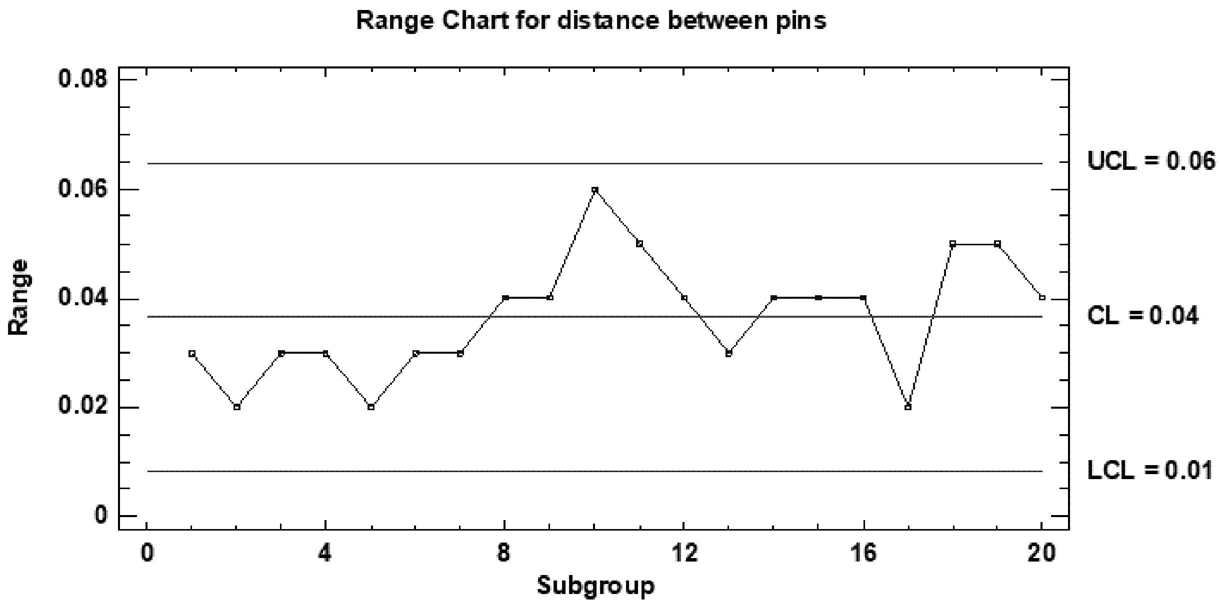


Fig. 2.2.4.24 R Chart for the distance between pins

Several capability indices have been computed to summarize the comparison of the fitted distribution to the specifications (Table 2.2.3.20). In this case, Pp equals 1.65841, which is considered to be acceptable, Ppk equals 1.64633, which is considered acceptable. Since K equals - 0.0511445, the average is located 5.11445% of the way from the center of the specifications towards the lower specification limit. Thus, for Cp ≈ 1.65 and Cpk ≈ 1.64 is resulting in a Sigma Level short term ≈ 5.05 and

Sigma Level long term ≈ 3.55 respectively. Therefore DPMO ≈ 233, which is acceptable.

To validate the improvement results, 20000 parts (one-week production) were assessed after improvement at both Data I/O and SMT/NXT processes. Table 2.2.3.21 and 2.2.3.22 present the non-conformities categories and quantities after improvements. First of all, one can see that the second reprogramming of microcontrollers dropped the reject rate by 65%. Secondly, bent pins due to supplier's process dropped practically to 0. In the third place, changing the rolls and foil suppliers and using only new rolls with sprocket holes on both sides improved both processes. For the Data I/O process, the total number of non-conformities dropped by 88% and for SMT/NXT by 76%. Other non-conformities must be tackled to improve the overall process performance as expressed in figures 2.2.3.25 and 2.2.3.26.

Tab. 2.2.3.21 Data I/O non-conformities categories after improvement

Non-conformities category	Category description	Quantity
Class 1	Errors in programming components	250
Class 2	Handling errors - bent pins	75
Class 3	Handling errors - lack of protection foil grip	55
Class 4	Mechanical errors	445
Total		**825**

Tab. 2.2.3.22 SMT/NXT non-conformities categories after improvement

Non-conformities category	Subclass	Category description	Quantity
Class 1	1.1 SMT/NXT	Dimensional	450
	1.2 SMT/NXT	Appearance (color / hue)	140
	1.3.1 SMT/NXT	Robot speed	90
	1.3.2 SMT/NXT	Vacuum nozzles size	60

Class 2	2.1 Supplier	Dimensional variations	42
	2.2 Supplier	Rolls of different sizes	35
Class 3	3.1 Machine	Mechanical causes	700
	3.2 Machine	Software error	320
Total			**1440**

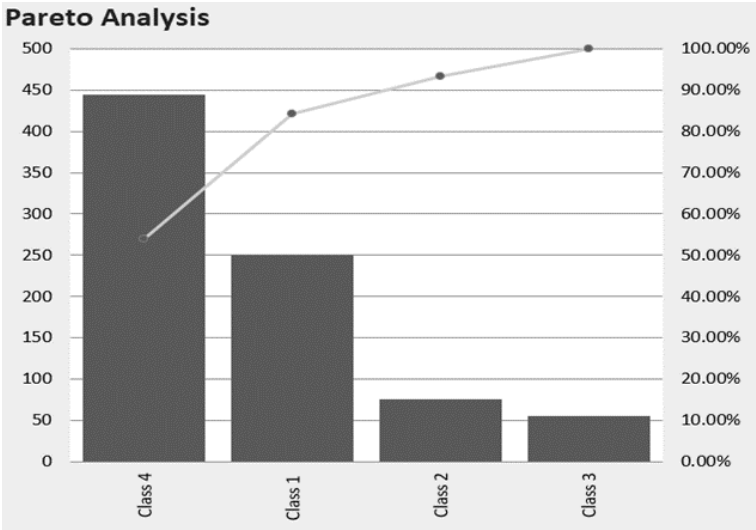


Fig. 2.2.3.25 Pareto Analysis for Data I/O after improvement

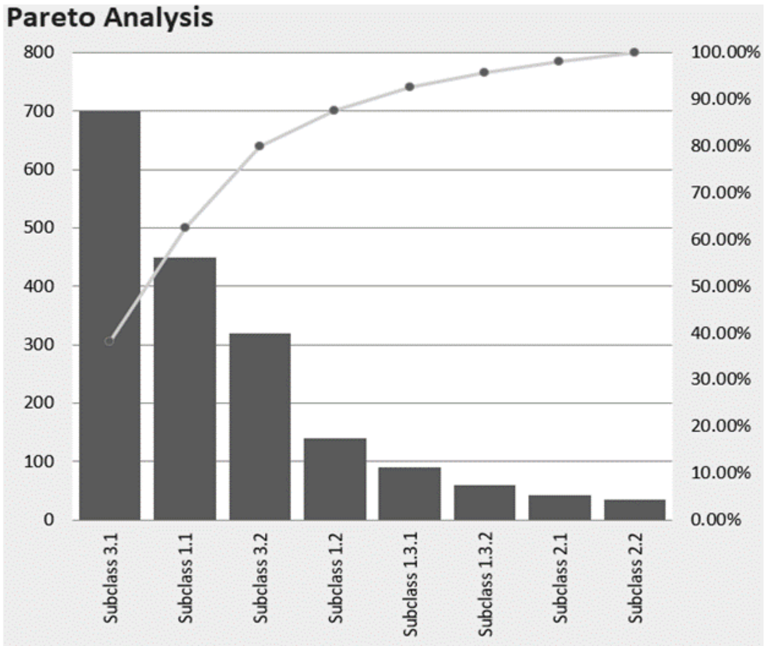


Fig. 2.2.3.26 Pareto Analysis for SMT/NXT after improvement

Using the DMAIC Six Sigma methodology for improving complex processes proved to be the correct approach in the presented case study. Due to the complexity of issues, major improvements have been achieved and a lot of lessons have been learned for the future. We analyzed the causes of rejections after Automated Optical Inspection (AOI) and verifications of microcontrollers programming at the Data I/O station and the SMT/NXT line. The main causes are related to aspects of programming and manipulation of microcontrollers. In the special case of the programming microcontrollers, the management has decided to approve the improvement measure by allowing a second reprogramming if the first reprogramming component fails the test at Data I/O station. As a result, we could notice a significant decrease in the defective rate. To solve the problems caused by mechanical aspects, it was decided to use only new adaptors, precision programming of devices that handled microcontrollers, and new storage rolls with sprocket holes on both sides to ensure a better protection foil grip. Continuous training of the operators has been seen as necessary, together with adequate monitoring of improvement results. In conclusion, Six Sigma is not only a buzz word but an adaptable
methodology which promotes a continuous improvement mentality along with the entire organization, from top to bottom. It is suited for complex processes and if adequately applied (by using all the DMAIC steps without jumping to improvement ideas), it can provide breakthrough improvements.

3. Design of Experiments

3.1. Introduction

The experimental design is a tool used to systematically examine different types of problems that arise within, e.g., research, development, and production. If experiments are performed randomly the result obtained will also be random and therefore, it is a necessity to plan the experiments in such a manner that useful pieces of information will be obtained. (Lundstedt et al., 1998).

➢ *Experimentation strategies*

Obtaining experimental models that best approximate real systems can be difficult when they are highly complex, with many influencing factors. It is important to analyze as many influencing factors as possible, but careful planning of experiments (to reduce them) must be done to take into account the economic aspect and the duration of the experiment. In the case of experimental research, the most important objective is represented by the mathematical modeling of the action of the influencing factors x_1, x_2,…, x_k on the objective function y of the studied system (object, phenomenon, process), by specifying the functional dependence, as in relation (3.1.1).

$$y = f(x_1, x_2, \dots, x_k) \tag{3.1.1}$$

Mathematical modeling aims to:

- Obtaining complete data in case of studying and analyzing the researched system, using the mathematical model
- Knowledge of the influencing factors that act on the researched system; their mechanism of action will be highlighted
- Hypothesis testing is done using system interactions
- Optimizing the system concerning different criteria, respectively the management of the system in space and time
- System design and calculation.

Among the requirements imposed on the general but also experimental models are the ability of the system to reflect the values of the objective function, which must not differ from the real values, as well as the provision of precise information leading to the achievement of the optimal objective function. In the case of experimental modeling, a certain form of the mathematical model is accepted a priori, which best approximates the real model, the data necessary to explain the model will allow the effective determination of the numerical coefficients of the form adopted for the mathematical model. The experimental modeling strategy provides information on the direction that the research should follow to move the obtained experimental model to the optimum, through a minimum number of experiments.

The classical experimentation strategy (Gauss-Seidel) is characterized by the slogan “one factor at a time” and reduces any experimental research to one-factor research, in the sense that at one point a single influencing factor is regulated (modified). ; for the other influencing factors, constant values are assigned, more or less arbitrary, which can exert a significant influence on the obtained result. Thus, only a part of the experimental tests is used to highlight the influence of a factor, which significantly amplifies, in the case of a large number of influencing factors, the volume of experimentation.

The modern (factorial) experimentation strategy (Box-Wilson) is characterized by the slogan "all factors at all times" and uses factorial experiments, so each experimental test changes the value of all influencing factors and consequently, each factor influences the values objective function which is determined by all the tests performed, which leads to a considerable decrease in the experimental volume.

The main objectives of this strategy are:

- ✓ Progressive acquisition of information following the experiments, with the possibility of making a small number of determinations to formulate conclusions.
- ✓ Obtaining a maximum precision for estimating the model, for a required number of measurements;
- ✓ Providing information on the direction of movement of the determinations to achieve the optimal range of the objective function.

It can be shown that, given the existence of random measurement errors, the modern experimentation strategy, applied with the help of factorial experiments, is optimal, and the factorial experimentation program is an optimal experimentation plan.

- *Design of Experiments (DOE)*

The strategies were originally designed to model physical experiments but can also be applied to numerical experiments. The objective of "Experimental Design" is to select the points where the answer must be evaluated. Most criteria for the optimal design of experiments are associated with the mathematical model of the process. Usually, these mathematical models consist of polynomials of unknown structure so that the corresponding experiments are designed for each particular case. The type of experiments chosen decisively influences the accuracy of the approximation and the cost of the experiment. The following is a comparison of the main experimental design strategies.

- *Taguchi method of designing experiments*

The strategy of Genichi Taguchi's approach (Fig. 3.1.1) is based on minimizing the impact of parasitic factors (noise factors), acting experimentally on controlled factors by finding combinations of their values so that the process or product respects functional performance and at the same time is robust to noise factors (Taguchi and Wu, 1980). Regarding product design, Genichi Taguchi has a new approach (Fig. 3.1.2).

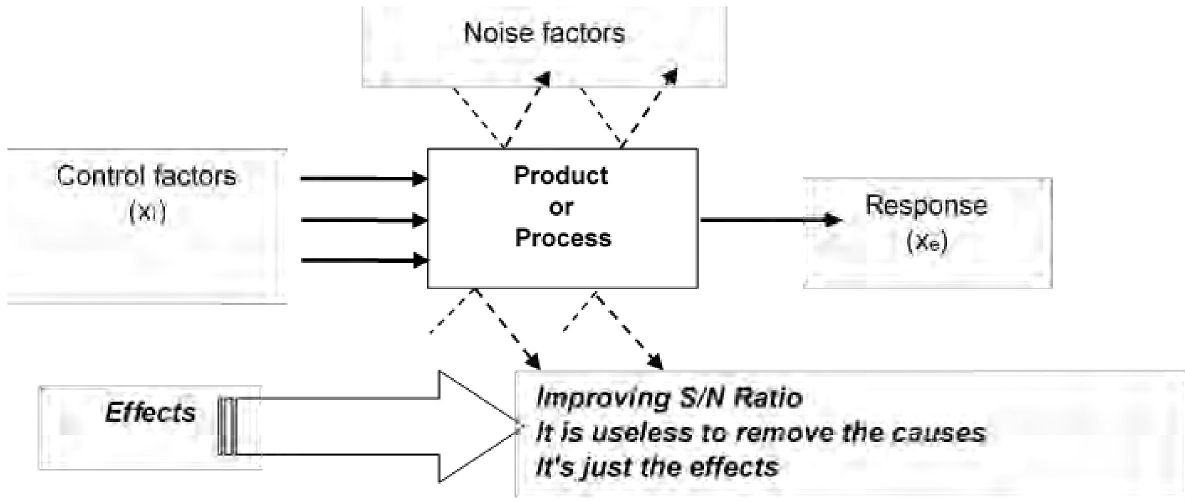


Fig. 3.1.1 Taguchi's strategy for minimizing the impact of noise factors

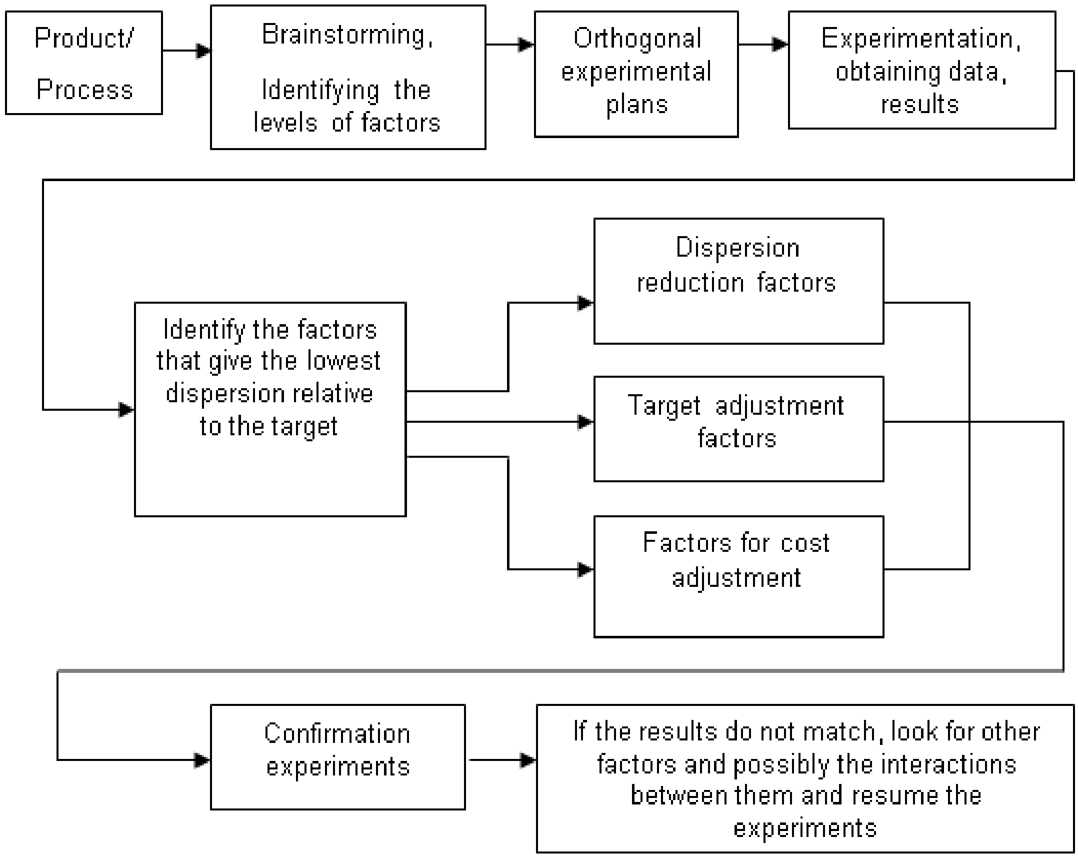


Fig. 3.1.2 Taguchi's approach to product design

- *Taguchi's Quality Loss Function*

The "Quality Loss Function" is one of the major contributions that Genichi Taguchi has made. In common terms, the "Quality Loss Function" is a way to show how each imperfect product results in a loss for the individual, company, society. Dr. Edwards W. Deming once said: "*A minimal loss in face value and an eternal increase in loss in the two directions*". Genichi Taguchi defines quality as a feature that avoids the loss of money both for the manufacturer during the manufacturing process and for the user, as well as at the global level of society.

A product will start to wear and deteriorate from the moment it was put into operation and there is a possibility that if it fails during the warranty period it will be repaired or replaced, in which case the cost will be borne by the manufacturer. However, if the defect occurred during the post-warranty period, then the costs of repairing or replacing the product will be borne by the user/consumer. The problem is that a high-quality product only generates low costs because (according to the definition of Quality

- ISO 2000), it meets the expectations during the period that the user/consumer considers appropriate. However, when the user/consumer is dissatisfied or considers that the product does not meet his needs, it is difficult to appreciate and calculate its negative reaction. Indirectly, the producer is the one who will bear all the material consequences, image, and / or loss of the markets.

The "loss of quality" function expressed by Genichi Taguchi allows the quantification in the form of financial losses of the consequences for the manufacturer and customers/users / consumers of the quality level of a product. The use of the quality loss function is presented in figure 3.1.3.

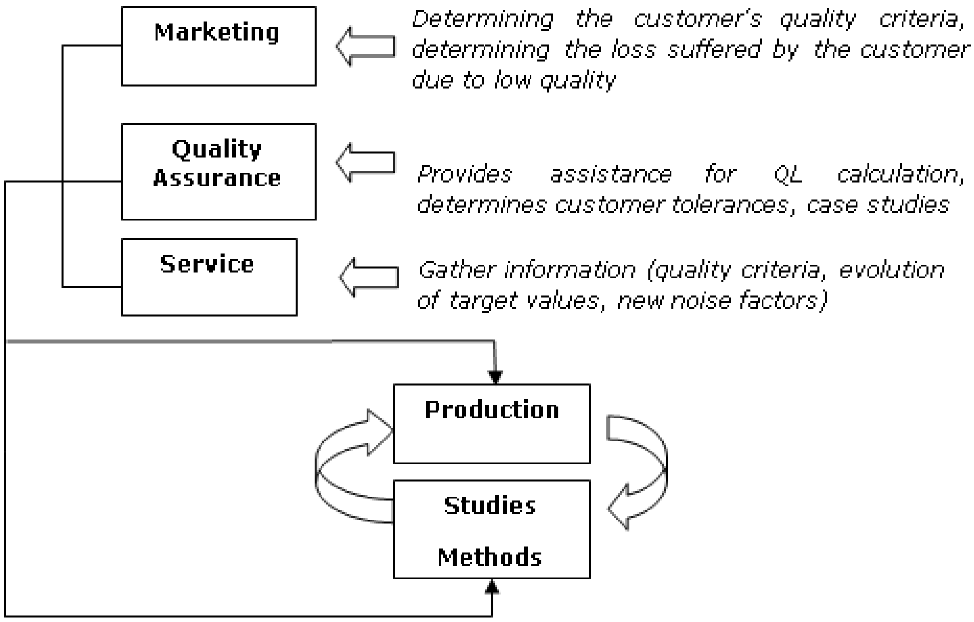


Fig. 3.1.3 Using the Quality Loss Function

A technical definition of the Taguchi loss function is given by William Duncan *"A parabolic representation that estimates the loss of quality expressed in monetary units that results when the quality characteristic deviates from the target value, the cost of this deviation increasing square as the characteristic moves away beyond the target value* ". Denote by Y a quality characteristic that has the target value y_N, a continuous symmetric quadratic loss function is shown in figure 3.1.4 and which represents the simplifying hypothesis of Taguchi according to which the loss is proportional to the square of the deviation of the quality characteristic about the fixed value.

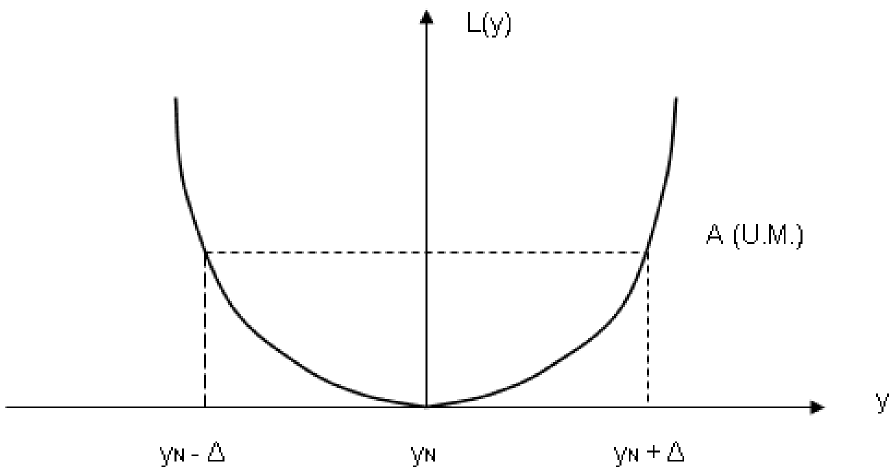


Fig. 3.1.4 Continuous Symmetric Quadratic Loss Function

As can be seen from figure 3.1.4, the quality loss denoted by L(y) is equal to 0 when the quality characteristic is exactly on the target ($Y = y_N$), the quality loss increasing as the quality characteristic moves away from the target value in both directions. At each tolerance limit (specification), the loss of quality is equal to A (M.U.), the deviation of Y from y_N in any direction is therefore considered undesirable. It is generally considered for the quality characteristic Y, the loss function L(y) which represents the monetary value of the losses, induced to an arbitrary customer, for a unit of product.

In the case of target criteria, the Taguchi quadratic loss function applies to characteristics that have a specified nominal value, the target criterion being exactly the face value. The mathematical expression for a single product is given in relation (3.1.2). Graphically, the relation (3.1.2) represents a parabola (Figure 3.1.4).

$$L(y) = k(y - y_N)^2 \tag{3.1.2}$$

where: L(y) is the value of the unit loss expressed in monetary units
y is the value of the measured quality characteristic
y_N is the specified nominal value (target value)
k is a constant for quantifying financial losses

The expression of the Quality Loss Function for a batch of products is given in relation (3.1.3). If we consider a sample of "n" parts on which the measurements are made, then the estimated values of the mean $\bar{y}$, and the standard deviation "s" will be used, resulting in the Quality Loss Function relation (3.1.4).

$$L(y) = k[\sigma^2 + (m - y_N)^2] \quad (3.1.3)$$

$$L(y) = k[s^2 + (\bar{y} - y_N)^2] \quad (3.1.4)$$

In the case of the criteria to be minimized, the Taguchi Square Loss Function is applied to the characteristics whose nominal value is zero ($y_N = 0$), the criterion to be minimized is: “The smaller the better”. The Quality Loss Function for a single product is given in relation (3.1.5) and for a batch of products in relation (3.1.6). The graphical representation of the Quality Loss Function in the case of the criteria to be minimized is a half-parabola as in figure 3.1.5.

$$L(y) = ky^2 \quad (3.1.5)$$

$$L(y) = k(s^2 + \bar{y}^2) \quad (3.1.6)$$

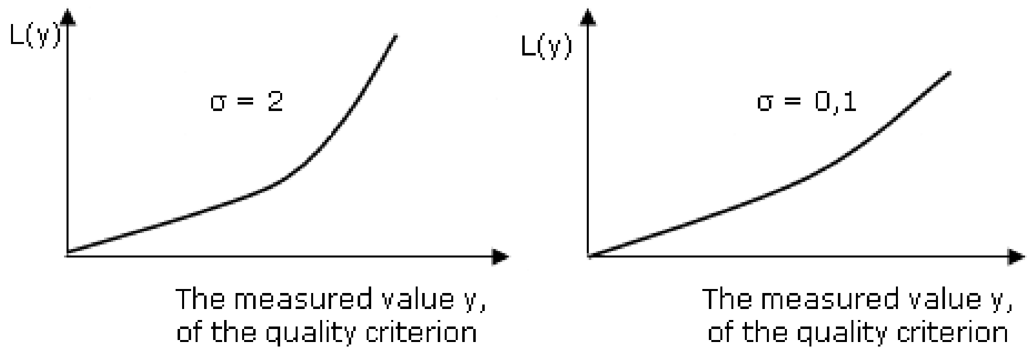


Fig. 3.1.5 Quality Loss Function for a criterion to be minimized

In the case of the criteria to be maximized, the Taguchi Square Loss Function for the characteristics whose target value is theoretically infinite, the criterion to be maximized being: “*The higher the better*”. The Quality Loss Function for a single product is given in relation (3.1.7) and for a batch of products in relation (3.1.8).

$$L(y) = \frac{1}{y^2} \quad (3.1.7)$$

$$L(y) = k\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2} \quad (3.1.8)$$

Because the relation (3.1.8) is relatively difficult to use, for the evaluation of the average quality of a batch of products, the average $\frac{1}{y_i^2}$ is used, also called the mean square deviation or MSD and which can be calculated according to the relation (3.1.9).

$$\mathrm{MSD} = \frac{1}{m^2}\left[1 + 3\left(\frac{\sigma}{m}\right)^2\right] \tag{3.1.9}$$

So the Quality Loss Function for a batch of products in case of maximizing criteria is given in relation (3.1.10).

$$L(y) = k\frac{1}{m^2}\left[1 + 3\frac{\sigma^2}{m^2}\right] \tag{3.1.10}$$

If m and σ are replaced by their estimated values, the relation (3.1.11) results. The graphical representation of the quality loss function in the case of the criteria to be maximized is a hyperbola as in figure 3.1.6.

$$L(y) = k\frac{1}{\bar{y}^2}\left[1 + 3\frac{s^2}{\bar{y}^2}\right] \tag{3.1.11}$$

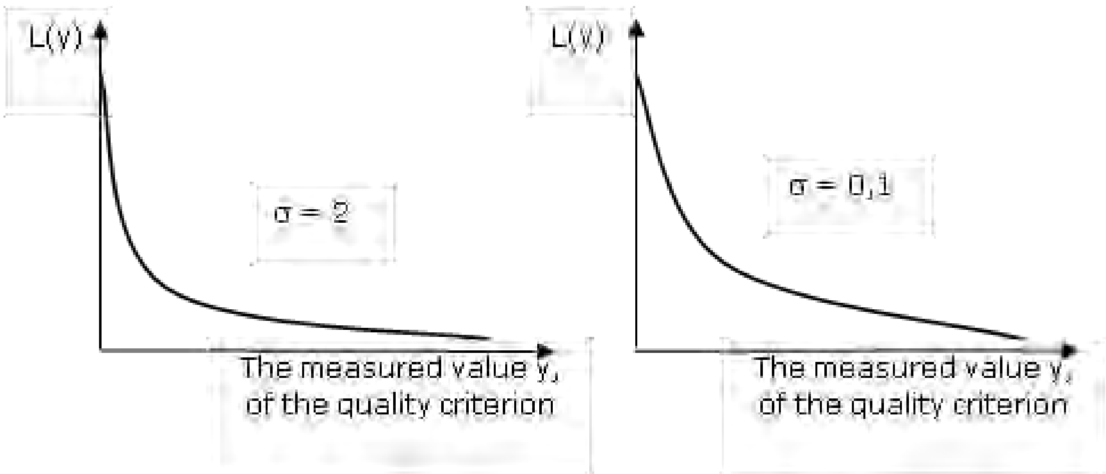


Fig. 3.1.6 Quality Loss Function for a criterion to be maximized

- *S/N Ratio*

When trying to quickly optimize a new product or process, the means chosen to evaluate the performance of a system have a critical role, the goal being to reduce the costs associated with the product or process development cycle. Using the traditional method of evaluating performance by going through a detailed list of specific problems (check-list), then a one-off improvement of the product or process can be obtained, the overall improvement of their quality being uncertain.

Taking these things into account, it is essential to develop a "specific and synthetic metrology" that allows performance to be assessed efficiently. We consider that "Performance" represents the "output" of a system with one or more "inputs", and when it is desired to evaluate the performance of a system, we must consider in turn both the "desired outputs" (those we want to obtain) and "Unwanted exits" (the ones we want to avoid).

The first we refer to as "Signals" and the other as "Noises", by analogy with the traditional use of the two notions of the expression "Signal to Noise Ratio (S / N)" used in the field of electronic or optoelectronic communications. Unlike the classical (traditional) approaches that treat these two components separately, G. Taguchi uses to evaluate the quality of a product or process, a synthetic measure of performance with the same name (signal/noise ratio) that simultaneously takes into account both the average and the and dispersion.

The purpose of an experiment is to set certain values for the input parameters (inputs) of a product or process so that they achieve the desired performance (desired outputs) and also have a minimum sensitivity to uncontrollable factors (noise), ie the unwanted outputs, then it is logical that the two components (average and dispersion) are optimized together.

There are systems in which the output characteristic must frequently meet an objective such as: "the optimum is the nominal value" or the expression "quality characteristic is a target criterion" is used. Both expressions, target criterion or nominal value, are a way to define a preferential nominal value for the output of a system to be optimized. All other values are less desirable than the nominal or target value.

The expression of the Signal/Noise ratio for the target criteria is given in relation (3.1.12). It is mentioned that the logarithm of the ratio is used to improve the additivity and by analogy with the electronics and acoustics convention, the ratio is expressed in decibels, respectively the formula is adjusted with the ratio 1/n to maintain mathematical rigor when the number of measurements is relatively small.

$$\frac{S}{N} = 10\log\left[\frac{\bar{y}^2}{s^2} - \frac{1}{n}\right] \quad [dB] \tag{3.1.12}$$

The higher the algebraic value of the S/N ratio, the better the performance of the product or process to be optimized (obviously the loss generated will be lower).

The S/N ratio allows the relativization of the value of the standard deviation about the average value, eliminating at the same time the problem of the unit of measurement.

If all measured values are equal ie s = 0, then the direct calculation of the S/N ratio is not possible. However, to be able to evaluate the performance by calculating the S/N ratio, a very small value is assigned to the standard deviation.

If the performance characteristics take positive and negative values, there is the possibility that the average value becomes algebraically lower than the standard deviation and then the variation interval is measured using the variance s^2. For the calculation of the S/N ratio, the relation (3.1.12) is used, in which the sign “-“ indicates that the algebraic value of the S/N ratio will be the higher the smaller the variance s^2.

In many cases, the target value, for performance measurement, is zero. Starting from the expression of the quality loss function for criteria to be minimized (relation 3.1.6), it is observed that to minimize the loss the expression $s^2 + \bar{y}^2$ must be minimized. The expression of the Signal/Noise ratio for the criteria to be minimized is given in relation (3.1.13).

$$\frac{S}{N} = -10 \log \left(s^2 + \bar{y}^2\right) \quad [dB] \tag{3.1.13}$$

To keep the rule of using the Signal / Noise ratio, it is also expressed in decibels and is preceded by the sign "-", (relation 3.1.13), meaning that the loss will be even smaller (ie the performance is even higher) as the dispersion decreases.

The expression of the Signal/Noise ratio for the criteria to be minimized is given in relation (3.1.14).

$$\frac{S}{N} = -10 \log \left[\left(\frac{1}{\bar{y}^2}\right) \cdot \left(1 + 3\frac{s^2}{\bar{y}^2}\right)\right] \quad [dB] \tag{3.1.14}$$

- *Standard Taguchi matrices (arrays)*

Experimental plans consist of performing a priori established experiments to determine, with minimum tests and maximum accuracy, the possible influences of different parameters to optimize the performance of a system and were developed by Jacques Hadamard and Ronald A. Fisher.

The realization of a Taguchi fractional factorial experiment plan is based on the idea that some possible combinations of the tested factors bring more efficient information, thus achieving a considerable reduction in the number of experiments performed. To be able to calculate the effects of a factor independent of other factors, the experiment plan must be orthogonal. In an orthogonal matrix, each level of each factor is combined with each level of the other factors in an equal number of times. In real cases, the effects of one factor may depend on the level of another factor.

It is said that there is an interaction between factors. The number of degrees of freedom (DOF) of a system is defined as the minimum number of comparisons that are performed. The degree of freedom of a factor is equal to the number of comparisons needed to study its effect (for example a factor with 3 levels will have two DOF). In the case of interactions, the number of degrees of freedom is equal to the product of the degrees of freedom of the individual factors. The number of degrees of freedom of a matrix of experiences is equal to the number of trials (experiments) minus 1.

Determining the number of degrees of freedom is important to choose the matrix of experiences suitable for each application. Standard Taguchi matrices prove to be broad enough to satisfy the vast majority of situations involved in industrial practice. The symbolization of standard Taguchi matrices depends on the number of experiments (number of rows of the matrix), the number of factors and interactions (the number of columns of the matrix), and the number of levels. For example $\mathbf{L_{18}}$ (2^1 X 3^7) is a matrix that has 18 trials, 2^1 = 1 factor at 2 levels, 3^7 = 7 factors at 3 levels.

The smallest matrix should be chosen to provide the desired information following the objectives of the experiment. Calculate the total number of degrees of freedom and choose the appropriate standard Taguchi matrix. Triangular tables and line graphs are associated with most standard Taguchi matrices and are used to define the columns used to study interactions and to adapt matrices to specific needs.

Consider the standard matrix $\mathbf{L_8}$ in table 3.1.1, the corresponding linear graphs $\mathbf{L_8}$ is presented in figure 3.1.7.

Tab. 3.1.1 Standard Taguchi $\mathbf{L_8}$ matrix

Trial No.	Factors							Trial results
	A	B	C	D	E	F	G	
1	1	1	1	1	1	1	1	R1
2	1	1	1	2	2	2	2	R2
3	1	2	2	1	1	2	2	R3
4	1	2	2	2	2	1	1	R4
5	2	1	2	1	2	1	2	R5
6	2	1	2	2	1	2	1	R6
7	2	2	1	1	2	2	1	R7
8	2	2	1	2	1	1	2	R8

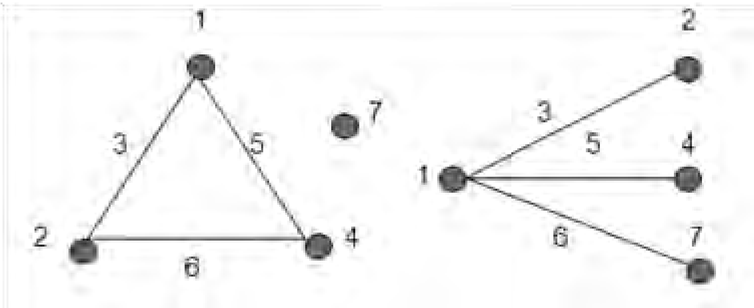


Fig. 3.1.7 Linear graphs associated with the $\mathbf{L_8}$ matrix

The factors are represented by circles, the number corresponding to each being that of the matrix column. The column number for interactions corresponds to the link segments between circles. For example, if factor A is on column 2 of the $\mathbf{L_8}$ matrix and factor B is on column 4 of the $\mathbf{L_8}$ matrix, then the I_{AB} interaction will be distributed on column 6. If you wants to neglect the interaction between two factors, the number of the segment that joins them can be assigned to another factor. For each standard Taguchi matrix, there are as many linear graphs as possible combinations of distributions can exist.

There are cases when the use of standard Taguchi matrices cannot be done directly and their modifications are necessary. First of all, the number of degrees of freedom that the modified matrix should contain must be determined. The minimum matrix is then searched among the standard Taguchi matrices, which after the modification meets the imposed requirements. In this way, 4-level factors can be introduced in 2-level matrices, etc. The Taguchi experiment plan method is a particular application of classical experiment plans. Taguchi's experimental plans treat the media and variability of the measured characteristics in a unitary way. By using the S / N ratio, a combination of input signal levels (controllable factors) can be found in the first instance, which proves to be the most insensitive to noise factors. The expression of the S / N ratio in dB independent of the nature of the measured characteristics allows the comparison of the performances of several characteristics that are optimized simultaneously.

Taguchi combined experiment plans are a particular configuration of experiment plans and are used to study the sensitivity of a system to well-specified noise factors. In the combined plans are found both the factors kept under control (which control the system) and the noise factors (which the system supports). Two matrices of experiences are used as follows:

- an internal matrix containing controlled factors.
- an external matrix containing noise factors.

The external matrix aims to repeat each test in the internal matrix for each configuration of the noise factors. Figure 3.1.8 shows a combined Taguchi experiment plan in which the internal matrix is $\mathbf{L_8}$ with 7 factors at 2 levels, and the external matrix is $\mathbf{L_4}$ with 3 noise factors at two levels.

Internal Plan								External Plan					
								Nr. of repeated attempts				Noise factors	
								1	2	3	4		
								1	1	2	2	P	
Control factors								1	2	1	2	Q	
Trial No.	A	B	C	D	E	F	G	1	2	2	1	R	
1	1	1	1	1	1	1	1						
2	1	1	1	2	2	2	2						
3	1	2	2	1	2	2	1						
4	1	2	2	2	1	1	2						
5	2	1	2	1	1	2	2						
6	2	1	2	2	2	1	1						
7	2	2	1	1	2	1	2						
8	2	2	1	2	1	2	1						

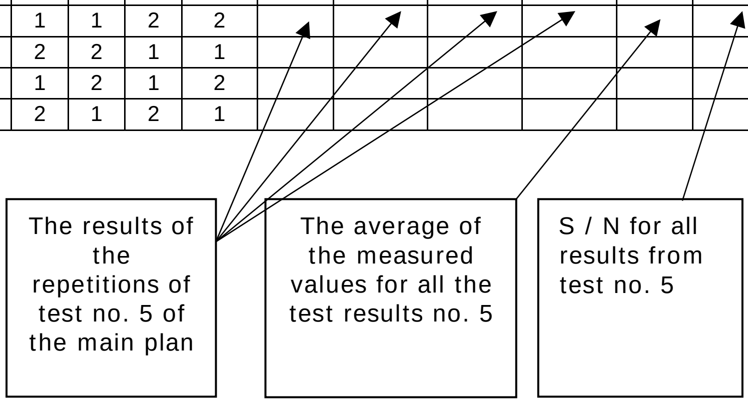


Fig. 3.1.8 Taguchi combined experimental plan

➢ *Full factorial experimental plans*

A full factorial experimentation plan may be required to define an approximate model containing all possible interactions between q design variables. In this case, the limits (upper and lower) of each of the q variables must be defined. Then this interval is discretized at how many levels are considered necessary. If, for example, only the range limits (2 levels) are used, then the experimental plan is called 2^q full factorial experimental plan, and if intermediate points (3 levels) are also used, is called 3^N full factorial experimental plan, as can be seen from figure 3.1.9.

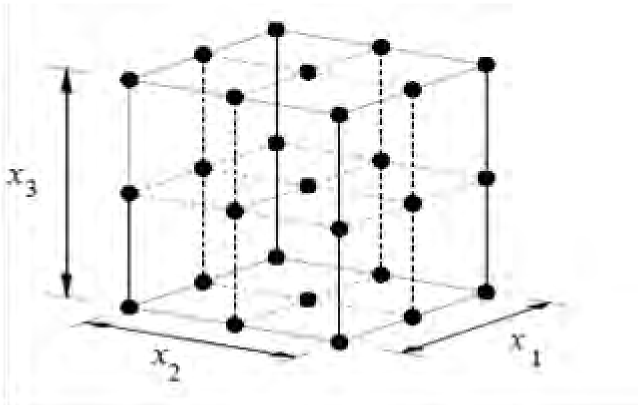


Fig. 3.1.9 3^N full factorial experimental plan (27 points = 27 experiments)

Factorial experiment plans can be used on second-order models, which significantly improve process optimization when first-order models do not fit. In general for a large number of variables, the number of experiments increases exponentially, and therefore a complete factorial experiment plan is used for a maximum of 4 or 5 variables. If, however, the number of variables is relatively large, a fraction of the complete factorial experiment plan can be used at the cost of estimating fewer combinations of variables. These experimental plans are called fractional factorial experimental plans (which include Taguchi experimental plans). Fractional factorial experiment plans are usually used to identify the most important design variables.
For example for a complete 3^q factorial experimental plan, a fraction of $(1/3)^k$ can be used resulting in 3^{q-k} points (experiments). For k = 1 in an experiment plan 3^3, the result is a fraction of a third called the experiment plan 3^{3-1} (Figure 3.1.10).

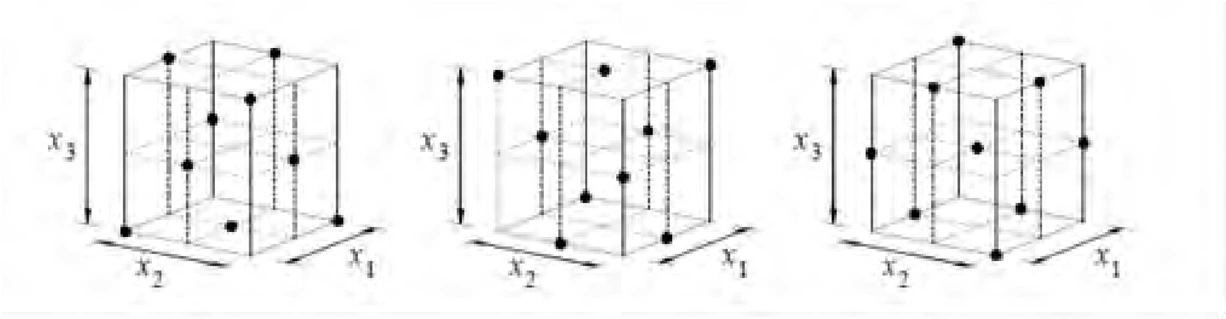


Fig. 3.1.10 Three fractional factorial experiment plans 3^{3-1} (9 points = 9 experiments) from a complete factorial experiment plan 3^3 (27 points = 27 experiments)

- *Central Composite Design (CCD)*

A second-order model can also be built efficiently with a Central Composite Design (CCD). CCDs are full factorial plans of type 2^q that have been enlarged by adding central and axial points (experiments) that allow the estimation of the adjustment parameters of the second-order models (see RSM). In figure 3.1.11, the experimental plan involves 2^q factor points (experiments), 2^q axial points (experiments), and 1 central point (experiment). CCD is an alternative to the 3^q experiment plan in building a second-order model due to the smaller number of experiments (15 in the case of the CCD plan compared to 27 in the case of the full factorial plan). However, if the number of variables is large, even the use of CCD plans can be prohibitive.

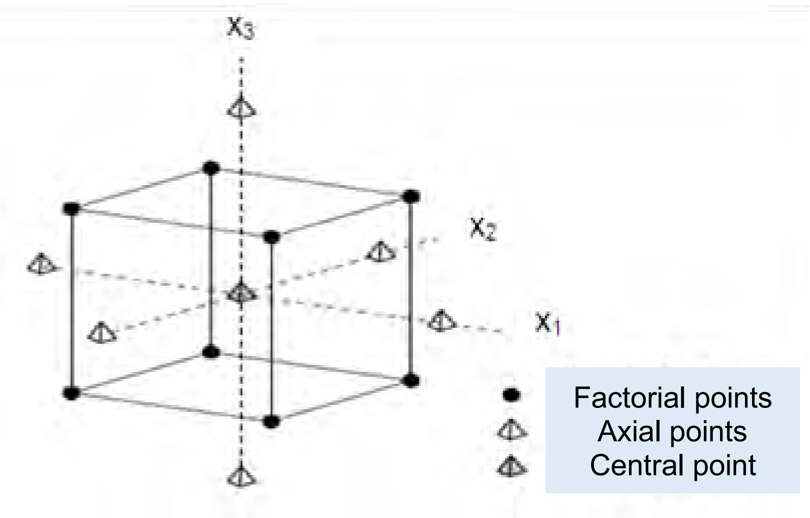


Fig. 3.1.11 CCD plan for 3 design variables at 2 levels

- *Response Surface Method*

The Response Surface Method (RSM) is a conglomeration of statistical-mathematical techniques for constructing empirical models. By designing the experiments we want to optimize the response (output variable), which is influenced by several independent variables (input variables), and changing the behavior of the input variables leads to the identification of changes in the response variable (output).

Initially, the Response Surface Method (RSM) was used to model the experimental responses and later to model the numerical experiments. The difference lies in the way errors are generated by the response. If in physical experiments the error can occur due to measurement errors, in computer-generated experiments, noise (error) can be the result of incomplete convergence of the iterative process, rounding, or discrete representation of actually continuous processes. In the Response Surface (RSM) method, errors are considered to be random.

The approximation of the response function y = f (x_1, x_2,…, x_q) + e can be considered at the limit as the essence of RSM. The application of the Response Surface Method (RSM) to project optimization aims to reduce costs compared to other methods (such as the Finite Element Method) and reduce the numerical noise associated with them.

For example, consider the response function y in relation (3.1.15) by which it is desired to find the level of the input variables x_1 and x_2 for which y is maximum and where ε represents the noise or error observed in it.

$$y = f(x_1, x_2) + \varepsilon \qquad (3.1.15)$$

The surface represented by f (x_1, x_2) is called the response surface. The response can be graphically represented either three-dimensional or two-dimensional (contour) to facilitate visualization of the shape of the response surface. The contours represent constant response curves presented in the plane x_i, x_j, keeping the other variables fixed. Each contour corresponds to a particular height of the response surface (Figure 3.1.12).

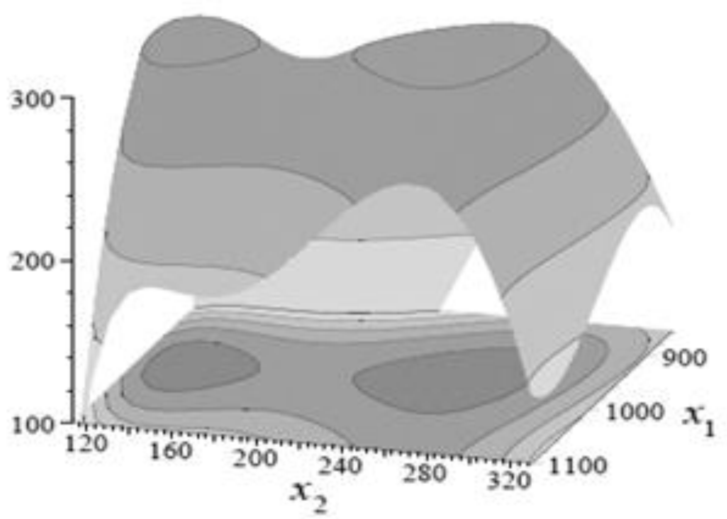


Fig. 3.1.12 Three-dimensional response surface and two-dimensional contour

In most RSM applications, the response function y is unknown and usually, to construct a correct approximation for y it starts with a polynomial of rank 1 in a small area. If the response can be defined by a linear function of independent variables, then the approximation function is called the "*First-order model*". For example, such a model for 2 independent variables is given in relation (3.1.16):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon \qquad (3.1.16)$$

If there is a certain curvature in the response surface, a higher degree polynomial must be used. For example, the approximation function for 2 variables is called the "*Second-order model*" (relation 3.1.17).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \varepsilon \qquad (3.1.17)$$

In general, in the RSM issue, either one of the two models is used separately or a mixture of them. In any of the above situations, the levels of each factor must be independent of the levels of the other factors. It is also important that the experiment plan used for data collection is chosen correctly to obtain efficient results in approximating polynomials. After data collection, the Least Squares Method (LSM) is applied to estimate the parameters of the polynomials.

It is considered that the objective of studying RSM can be achieved by understanding the topography of the response surface (local maximum and minimum, level lines) and finding the region where the optimal answer is located by moving quickly and efficiently on a trajectory to obtain the maximum (or minimum) answer so that the answer is optimized.

Today it is considered that the first goal of RSM is to find the optimal answer. If there are several answers, then it is important to find the optimal compromise that does not optimize a single answer. The second goal is to understand how the response changes in a certain direction when the design (input) variables change.

3.1.1 Applying Experimental Design to TiO_2 Doped Sintered Basalt

Based on earlier researches, (Ștefănescu, **Pugna**, Pleniceanu., 2008), (Ștefănescu, **Pugna**, Pleniceanu., 2009), (Pleniceanu, 2009), **Pugna** et al. (2010) presented in 2 papers possibilities of applying the Taguchi Method to TiO_2 doped sintered basalt, describing also a method and installation for wearing testing of sintered basalt.

- *A. Basalt sintering*

Sintering is a processing technique utilized for manufacturing materials with controlled density from metallic powders and/or ceramic powders (including basalt). One of the most important applications of sintering is manufacturing sintered basalt parts with high wearing resistance. Figure 3.1.1.1 presents the general process of manufacturing sintered parts. Unlike other manufacturing technologies, the different stages of processing and the corresponding variables must be considered. Depending on the "forming" technique, sintering conditions may change and also the sintering properties can vary considerably. In the sintering stage may be used different techniques and process variables that can induce changes in the microstructure and properties of sintered material.

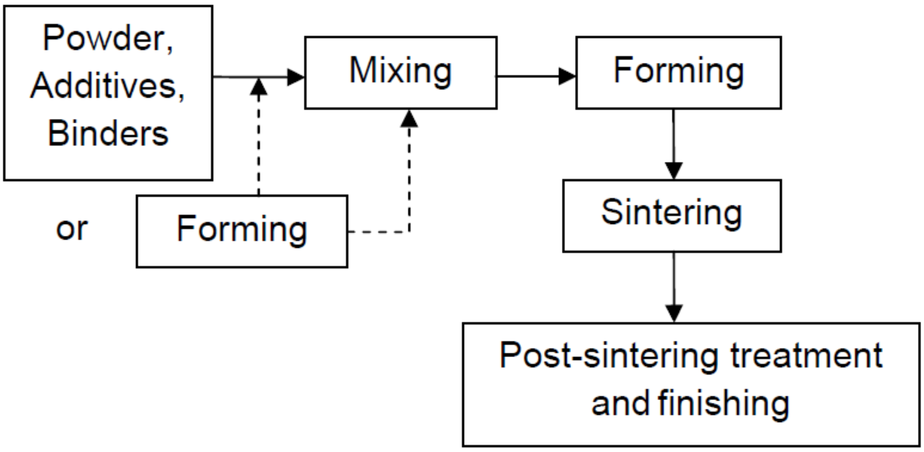


Fig. 3.1.1.1 General process of manufacturing sintered parts

Sintering processes can be divided into two categories (Kang, 2005): solid-state sintering and liquid state sintering. Solid-state sintering (below solidus line) occurs when the compacted powder is fully densified in the solid-state at the sintering temperature, while the liquid phase sintering occurs when the liquid state is present in the compacted powder during sintering. Different types of sintering are explained using a schematic phase diagram, although the optimal type of sintering depends on the material and / or to sintering scope. The "Engine" of the sintering process is represented by interfacial total energy reduction. The interfacial total energy of compacted powder is expressed as λA, where λ is the specific interfacial energy and A is total area (interface) of compacted powder. The total energy reduction is expressed in relation (1).

$$\Delta(\lambda A) = \Delta\lambda A + \lambda\Delta A \tag{3.1.1.1}$$

In this relation, the change in interfacial energy (Δλ) is due to densification and the change in interfacial area is due to particle growth. In solid-state sintering case, Δλ is related to surface replacement of solid / vapor (interfaces) with solid/solid interfaces. Figure 3.1.1.2 shows how total interfacial energy reduction occurs through densification and particle growth.

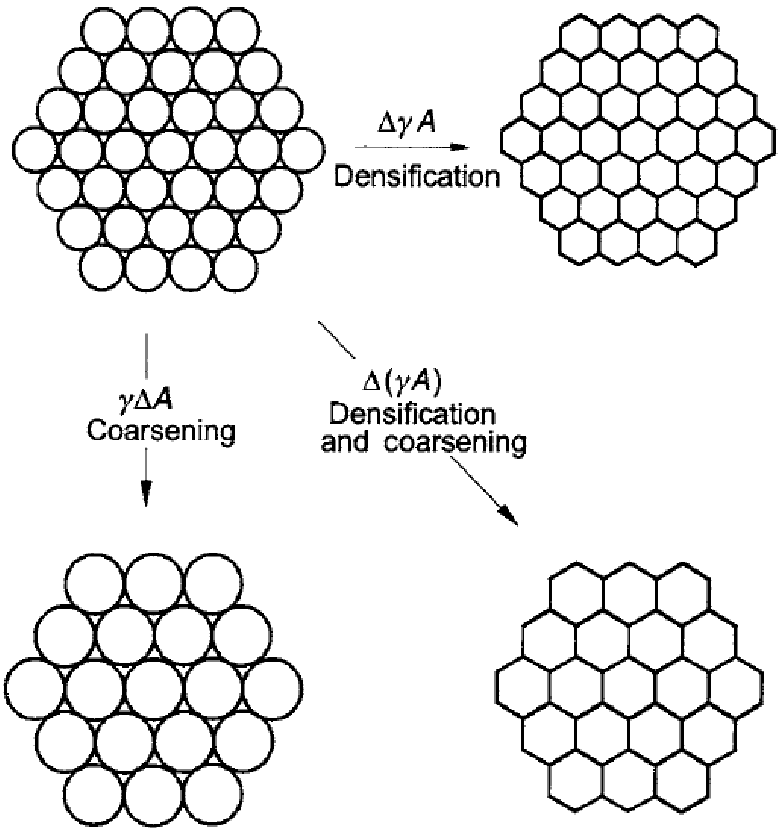


Fig. 3.1.1.2 Basic phenomena occurring during sintering (Kang, 2005)

- *B. Sintering variables*

The variables that determine the sinterability and microstructure of sintered parts fall into two categories: material variables and process variables. The material variables are influencing the compressibility of the powder (densification and particle growth). Other variables are mainly thermodynamic variables. Variables affecting the sinterability and microstructure of sintered parts are presented in Table 3.1.1.1.

Tab. 3.1.1.1 Variables affecting sinterability and microstructure of sintered parts

Material variables	Powder	Shape,size, distribution, agglomeration, mixing possibility etc.
	Chemistry	Composition, impurities, non-stoichiometry, homogenity etc.
Process variables	Temperature, time, pressure, heating and cooling ratio etc.	

- *C. Basaltic materials composition*

Chemical analysis shows that basalt materials are mixtures of binary oxides with a structural range between a maximum percentage of 52% for oxides of silicon and a minimum of 2% for oxides of titanium, and a variety of covalent-ionic type structural links for the elements silicon and aluminum, ion type links for alkali metals (Na, K) and alkaline earth (Mg, Ca) and the metal type links for transitional elements (Fe, Ti) respectively. The three types of chemical bonds present affect the structure and properties of chemical compounds. During sintering, depending on the substance introduced into recipes and temperature, the mass of the sample held a series of structural changes caused by chemical reactions that occur between oxide compounds participating in the formation of basalt. Being under the granular form, mixed oxides from the chemical reaction, causes the formation of oxide compositions in moles, existing the possibility of forming, at contact surfaces between granule constituents, of some mixed compounds. Chemical reactions (molar ratio 1:1), which can occur in the process of sintering (a combination of various binary oxides) shows that: sintering process causes the occurrence of combinations of ternary oxides (metasilicates, metatitanates, cyclosilicates) and mixed oxides (metatitanates, spineles), with a composition corresponding to normal valences or stoichiometric interstitial combinations; binary oxides participate in the sintering process in a relatively small percentage, even if the reaction is complete if one takes into account that reactions occur between the surfaces of granules.

- *D. Solid-state basalt sintering process and technology*

In the present study basalt rocks from Luncani, Timis county, Romania was used. This natural basalt rock, of volcanic origin, crystalline, compact, composed of a mixture of silicates, is the raw material for obtaining parts and is represented by Tectosilicates - plagioclases feldspars (albite anorthite), organized in three-dimensional networks of structures that allow cleavage and crystallizes in the triclinic system. In a proportion below 20% have a favorable effect on the process of crystallization; Nesosilicates - olivine, isomorphous compounds, consisting of forsterite and fayalit with island structure, allowing cleavage and crystallizes in the rhombic system. The presence of large quantities in finished products is undesirable; Inosilicates - pyroxenes (metasilicates of Mg, Fe, Mn, Ca, Al) with simple chain structure, looking slightly fibrous and cleaving, crystallizes in the monoclinic and rhombic system. Pyroxenes are the main phase of basalt and are in quantities between 34% and 80%. Pyroxenes give final products good chemical and mechanical properties, in mineralogical components containing less than 60% and content less than 10% magnetite and olivine, favors the crystallization process. Operations of forming and sintering, which causes interatomic links between particles, is the essence of the process of obtaining products by aggregating powders. Through forming, is aimed at processing powders in intermediate states, to facilitate and ensure obtain prescribed properties. The customary procedure for forming is pressing in a mold at compacting pressures ranging between (2-10) x 103 daN/cm2. Sintering is a heating operation of the semi-fabricate at a temperature at least equal to or greater than recrystallization temperature, basically, the sintering temperature being Ts = (2/3 – 4/5) · Tf, where Tf represents the melting temperature of the principal component. During sintering occurs an increase in compactness (more pronounced in the direction of pressing), a phenomenon influencing decisively the mechanical properties of finished products. The porous structure of sintered products, ranging from 1 to 30%, depends on the porosity obtained from the operation of forming and on sintering temperature and duration. Basalt, as raw material, to become a finished product through the sintering process, undergoes through a series of operations such as: choosing the raw material, processing to obtain the powder form, forming, calcination and sintering. Table 3.1.1.2 presents the oxide composition of basalt rocks from Luncani, Timis county, Romania, in comparison with the mean values from other basaltic basins from Romania and some value considered as optimum conditions.

Tab. 3.1.1.2 Oxide composition of basalt from Luncani, Romania, and optimum conditions

Oxide composition [%]	Mean values in basalt structures		
	Luncani	Romania	Optimum
SiO_2	47,65	44 – 52	43,5
Al_2O_3	15,84	14 – 16	11 – 13
Fe_2O_3 + FeO	10,06	9 – 14	5 – 8
CaO	8,92	9 – 12	10 – 12
MgO	8,80	7 – 10	8 – 11
Na_2O+K_2O	5,50	3 – 8	3 – 5
TiO_2	2,30	2 – 3	2 – 3,5
P_2O_5	0,11	-	0,3 – 1,0
MnO	0,10	-	0,2 – 0,3
P.C.	0,72	-	-

Operations performed on rocks to obtain basalt powder are washing, drying, sorting, crushing-sifting, disposal of metallic debris, milling, and powder sifting. The next step is to prepare the powder-binder mixture to ensure the necessary powder compactness for forming. Basalt powder is mixed homogeneously with a binder consisting of special glue, olein, and water.

To analyze the components of sintered basalt parts, microanalysis technique with X-rays (EDAX). Surface images of sintered basalt were analyzed using a scanning electronic microscope (SEM), as shown in figure 3.1.1.3

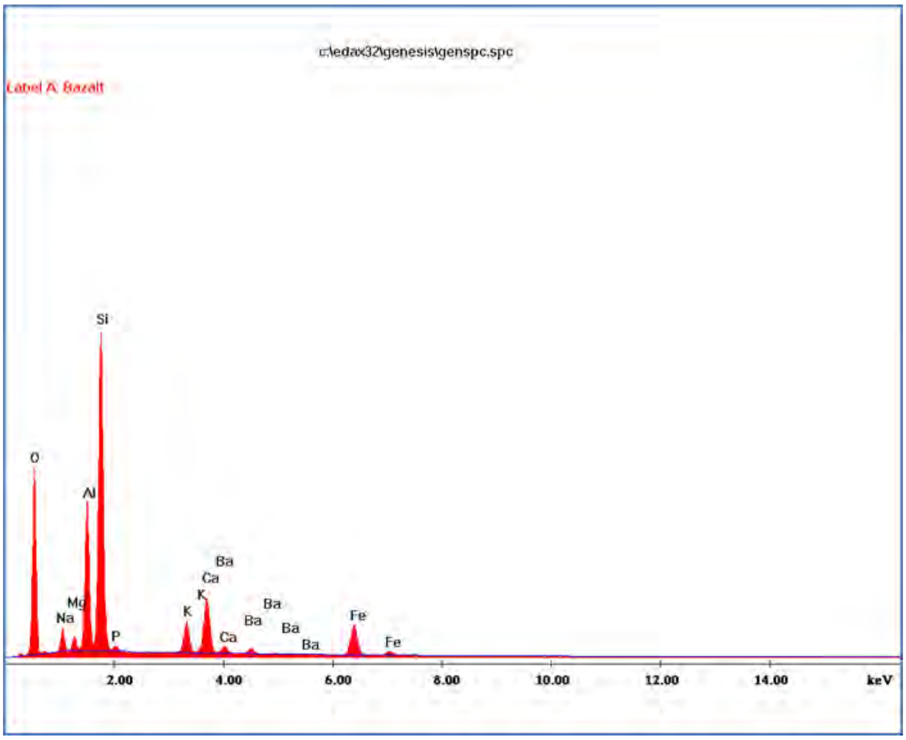
An energy dispersion spectrometer consists of three main parts: the detector, the signal processing electronics, and the multichannel analyzer (MCA). EDAX has the following functions:

- The detector generates an extra load, proportional to the energy of the characteristic radiations;
- This plus is converted into an electrical voltage;
- The signal is amplified directly by a field-effect transistor (FET), isolated from another plus, amplified again, then electronically identified;
- Finally, the digitized signal is stored in a channel for this energy in the multichannel analyzer.

An EDAX analyzer detects X-rays and separates them into a spectrum by their energy, hence the name energy spectrometer. Using an EDS system, all characteristic X-ray energies incident on the detector are measured simultaneously. Regarding the resolution of the EDS system, complex situations can arise, because there is the possibility of overlapping the peaks with close energies; many of the overlaps can be separated by calculating the deconvolution of the peaks.

Fig. 3.1.1.3 EDAX Analyzer

The components of basalt powder are shown in Figure 3.1.1.4.



Elem	Wt %	At %	K-Ratio	Z	A	F
O K	42.35	58.92	0.1188	1.0387	0.2699	1.0006
NaK	2.64	2.55	0.0074	0.9741	0.2864	1.0043
MgK	3.16	2.89	0.0124	0.9992	0.3891	1.0075
AlK	11.13	9.19	0.0540	0.9703	0.4952	1.0090
SiK	25.27	20.03	0.1322	0.9992	0.5230	1.0010
K K	1.74	0.99	0.0139	0.9487	0.8315	1.0103
CaK	3.92	2.18	0.0335	0.9721	0.8736	1.0068
BaL	2.75	0.44	0.0224	0.7622	1.0606	1.0099
FeK	7.03	2.80	0.0617	0.8914	0.9834	1.0000
Total	100.00	100.00				

Element	Net Inte.	Backgrd	Inte. Error	P/B
O K	417.18	6.24	0.48	66.89
NaK	41.91	18.54	2.07	2.26
MgK	73.87	24.87	1.47	2.97
AlK	327.57	24.73	0.58	13.25
SiK	765.94	26.04	0.36	29.41
K K	61.12	18.35	1.58	3.33
CaK	136.10	18.33	0.94	7.43
BaL	28.28	15.36	2.65	1.84
FeK	131.23	10.71	0.92	12.25

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Label :Bazalt tratat
Acquisition Time : 11:53:04 Date : 24-Jul-2009

kV: 24.99 Tilt: 0.00 Take-off: 36.30 AmpT: 12.8
Det Type:SUTW, Sapphire Res: 141.41 Lsec: 105

Fig. 3.1.1.4 Components of basalt powder

A melting furnace was used to melt the basalt powder (Figure 3.1.1.5), the absolute novelty being that the melting of the basalt powder was carried out inside a quartz capsule (Figure 3.1.1.6 (a), (b), (c)). The molten basalt parts are shown in figure 3.1.1.7.

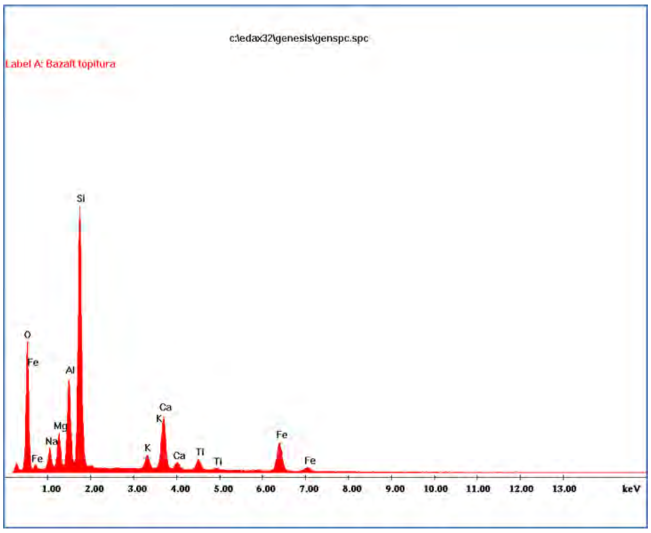
Fig. 3.1.1.5 Basalt powder melting furnace

(a)

Fig. 3.1.1.6 Basalt powder inside the quartz capsule

Fig. 3.1.1.7 Parts of molten basalt

The components of molten basalt are shown in Figure 3.1.1.8.



Elem	Wt %	At %	K-Ratio	Z	A	F
O K	39.37	55.22	0.0948	1.0365	0.2323	1.0007
NaK	3.17	3.10	0.0091	0.9721	0.2938	1.0046
MgK	4.22	3.90	0.0169	0.9971	0.3996	1.0078
AlK	9.30	7.73	0.0455	0.9683	0.5001	1.0104
SiK	27.90	22.29	0.1512	0.9971	0.5427	1.0012
K K	1.56	0.89	0.0124	0.9462	0.8279	1.0127
CaK	5.97	3.34	0.0507	0.9697	0.8720	1.0058
TiK	1.52	0.71	0.0125	0.8889	0.9161	1.0088
FeK	6.98	2.81	0.0612	0.8893	0.9850	1.0000
Total	100.00	100.00				

Element	Net Inte.	Backgrd	Inte. Error	P/B
O K	622.78	12.63	0.41	49.31
NaK	97.18	38.78	1.38	2.51
MgK	190.80	51.69	0.91	3.69
AlK	521.21	50.20	0.48	10.38
SiK	1655.19	51.26	0.26	32.29
K K	103.11	35.10	1.29	2.94
CaK	390.76	35.47	0.56	11.02
TiK	80.36	32.54	1.52	2.47
FeK	247.12	22.69	0.70	10.89

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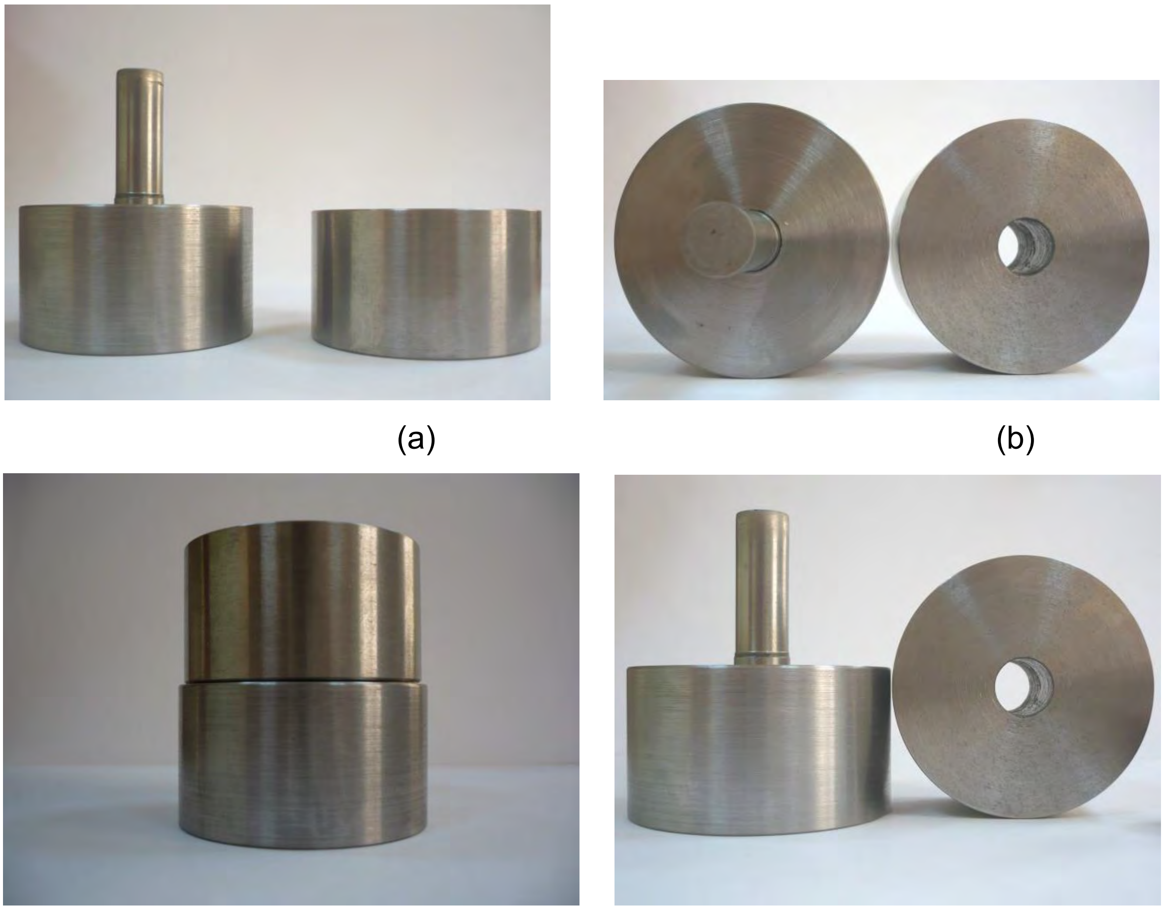
Acquisition Time : 08:37:52 Date : 15-Sep-2009

kV: 24.99 Tilt: 0.00 Take-off: 35.39 AmpT: 12.8
Det Type:SUTW, Sapphire Res: 141.41 Lsec: 97

Fig. 3.1.1.8 The component elements of molten basalt

The molding process in which the gravimetric dosed mixture is placed was used to form and press the basalt parts. The seats of the molds have the dimensions increased by approximately 15%, depending on the percentage of contraction of the mixture. Figure 3.1.1.9 (a), (b), (c), (d), presents a newly designed pressure die for this study.



(a) (b)

(c) (d)

Fig. 3.1.1.9 (a), (b), (c), (d) Pressing mold

Taking into account that the active part of the punch has a diameter of Φ 12 mm, its active surface A_0 was determined with relation (3.1.1.2).

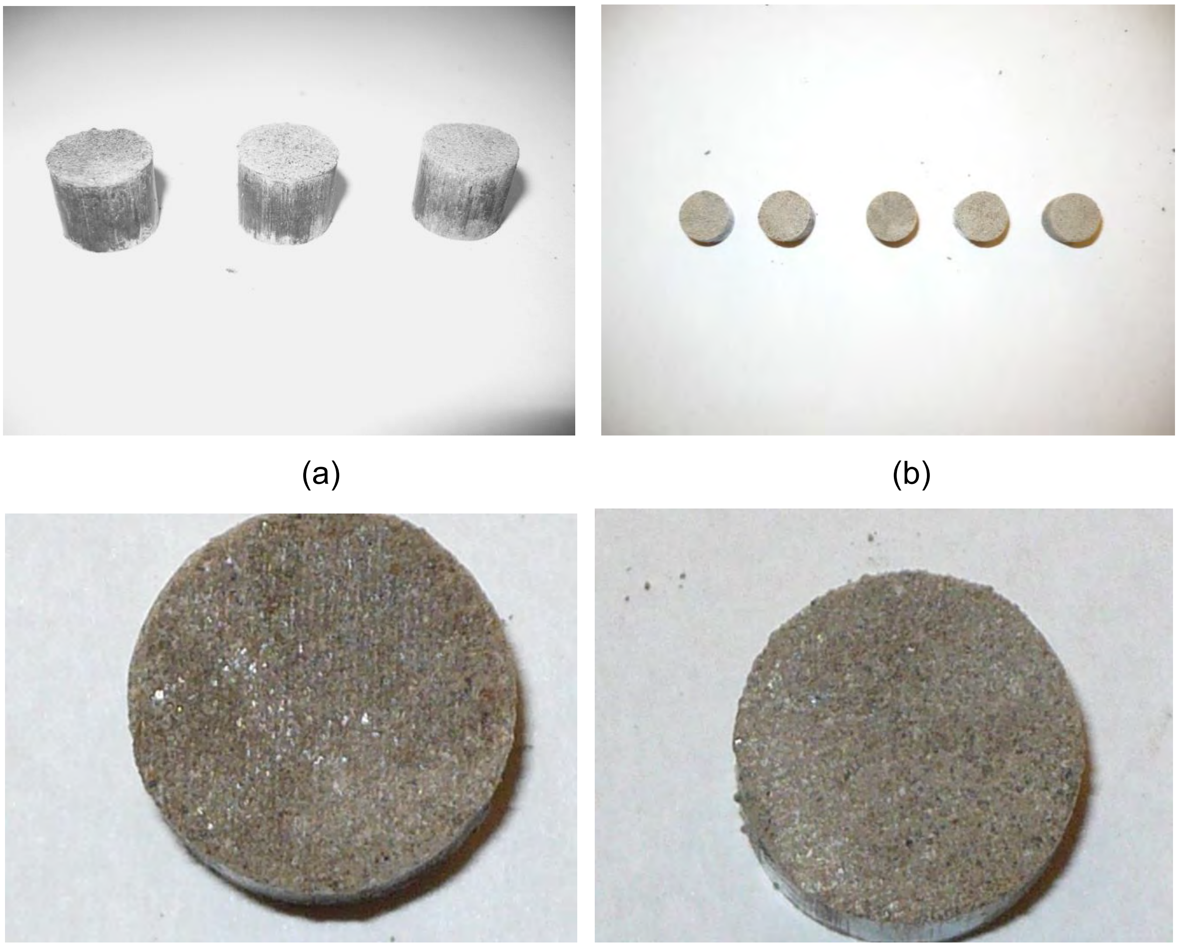
$$A_0 = \frac{\pi d^2}{4} = 1{,}13 \text{ cm}^2 \quad (3.1.1.2)$$

Since the two forming pressures p_1 = 1500 daN/cm^2 and p_2 = 2000 daN/cm^2, respectively, must be realized, the two pressing forces, F_1 and F_2, required for pressing the powder are given in relations (3.1.1.3) and (3.1.1.4), respectively.

$$F_1 = p_1 \cdot A_0 = 1695 \text{ daN} \quad (3.1.1.3)$$

$$F_2 = p_2 \cdot A_0 = 2260\ \text{daN} \tag{3.1.1.4}$$

The pressing of the basalt powder with binder was carried out, both those without TiO_2 content and those with 2% TiO_2 content (anatas), with a press capable of obtaining the previously calculated pressing forces, in figure 3.1.1.10 (a), (b), (c), (d) showing the compacted parts obtained after pressing.



(a) (b)

(c) (d)

Fig. 3.1.1.10 (a), (b), (c), (d) Compacted parts obtained by pressing

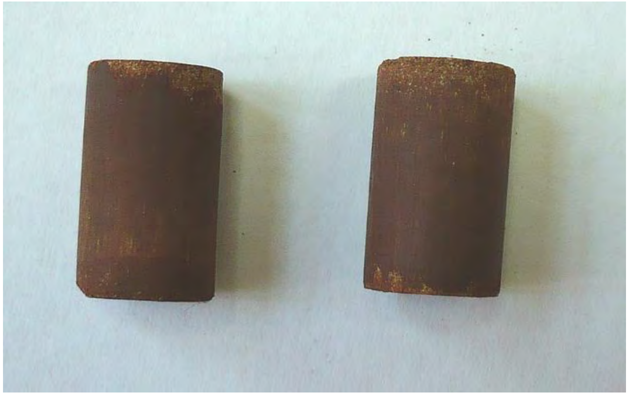
The drying and calcination of the parts were done by placing the raw parts in boxes and calcining the parts in a calcination oven (figure 3.1.1.11) at the two imposed temperature regimes of 900° C and 950° C, respectively.

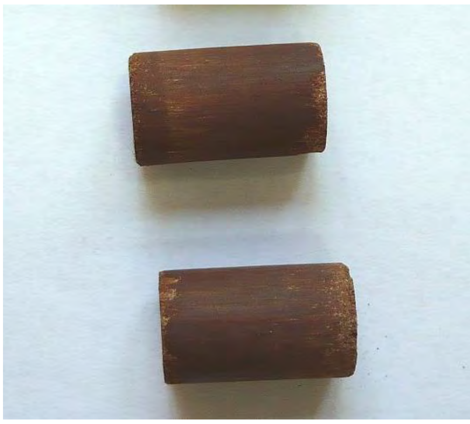
Fig. 3.1.1.11 Drying/calcination oven

The sintering and cooling of the compacted basalt parts were carried out in a sintering furnace (Figure 3.1.1.12) capable of realizing the sintering temperatures of 1000° C and 1100° C, the heating times of 8h and 10h, and the holding times of 1h and 1.5 h, respectively. It should also be noted that sintering and cooling were performed for the first time and in quartz capsules. Figure 3.1.1.12 presents the

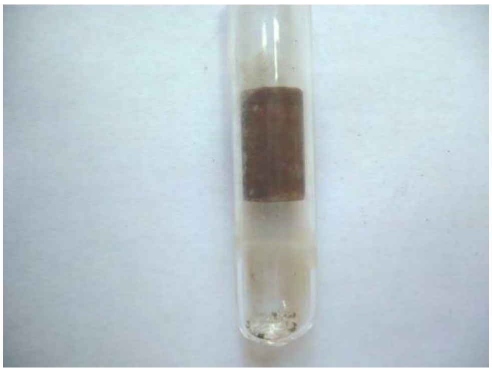
sintering/cooling furnace and figure 3.1.1.13 (a), (b), (c), (d) the parts obtained by sintering.

Fig. 3.1.1.12 Sintering / cooling furnace





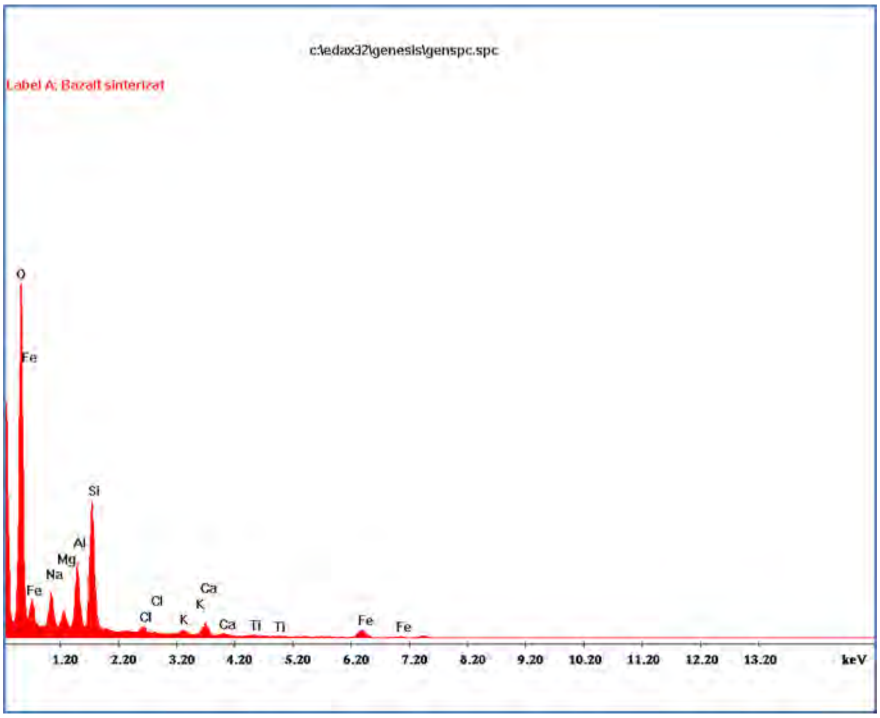
(a) (b)



(c) (d)

Fig. 3.1.1.13 (a), (b), (c), (d) Sintered and cooled parts

The components of sintered basalt are shown in Figure 3.1.1.14.



Elem	Wt %	At %	K-Ratio	Z	A	F
O K	66.90	77.53	0.2711	1.0170	0.3983	1.0005
NaK	6.70	5.41	0.0154	0.9554	0.2398	1.0027
MgK	2.36	1.80	0.0071	0.9805	0.3035	1.0046
AlK	7.02	4.82	0.0274	0.9527	0.4072	1.0053
SiK	13.61	8.98	0.0628	0.9815	0.4704	1.0005
ClK	0.64	0.33	0.0042	0.9345	0.6969	1.0015
K K	0.41	0.20	0.0033	0.9284	0.8556	1.0030
CaK	1.04	0.48	0.0089	0.9501	0.9062	1.0013
TiK	0.11	0.04	0.0009	0.8735	0.9670	1.0027
FeK	1.23	0.41	0.0110	0.8798	1.0167	1.0000
Total	100.00	100.00				

Element	Net Inte.	Backgrd	Inte. Error	P/B
O K	617.39	15.87	0.46	38.89
NaK	64.40	29.89	1.94	2.15
MgK	32.05	33.30	3.47	0.96
AlK	129.86	33.08	1.21	3.93
SiK	291.52	32.52	0.73	8.96
ClK	17.68	16.20	4.48	1.09
K K	12.63	11.78	5.33	1.07
CaK	32.19	11.11	2.57	2.90
TiK	2.77	8.63	18.09	0.32
FeK	22.75	4.16	2.74	5.47

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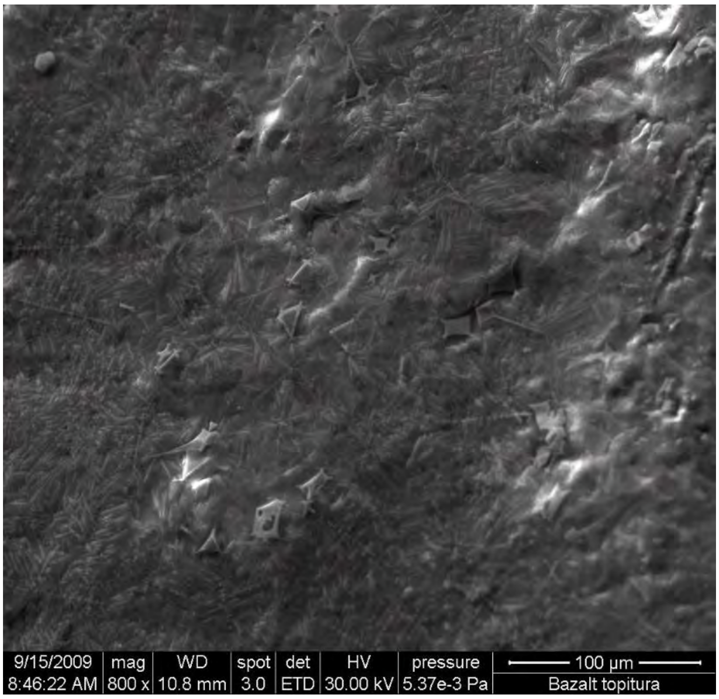
Acquisition Time : 08:46:32 Date : 15-Sep-2009

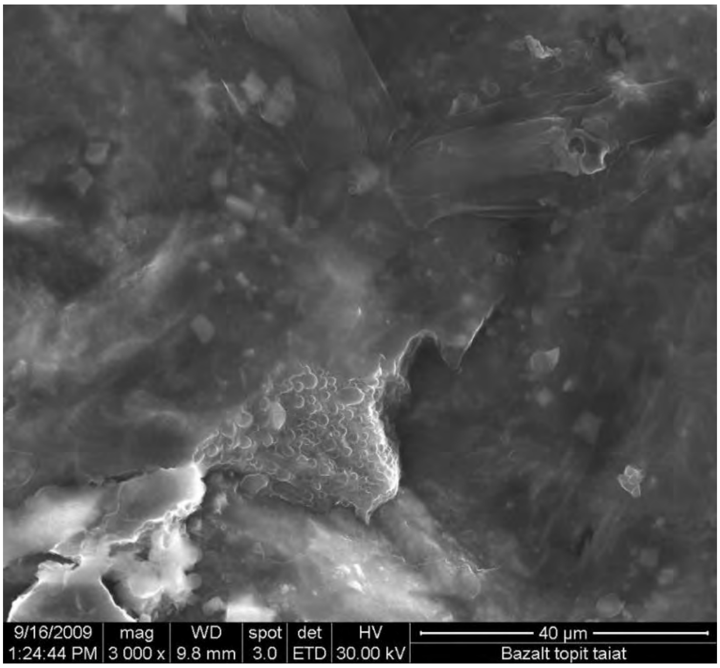
kV: 29.98 Tilt: 0.00 Take-off: 35.93 AmpT: 12.8

Fig. 3.1.1.14 Components of sintered basalt

Images of molten and sintered basalt surfaces were analyzed using an Inspect S scanning electron microscope. Figures 3.1.1.15 (a), (b) show the images for molten basalt, and figures 3.1.1.16 (a), (b) show the images for sintered basalt.

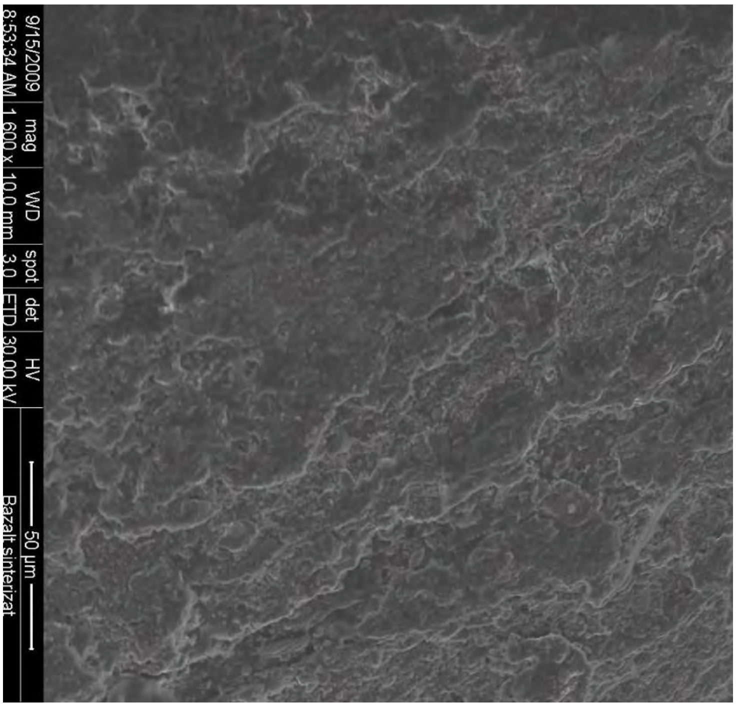


(a)

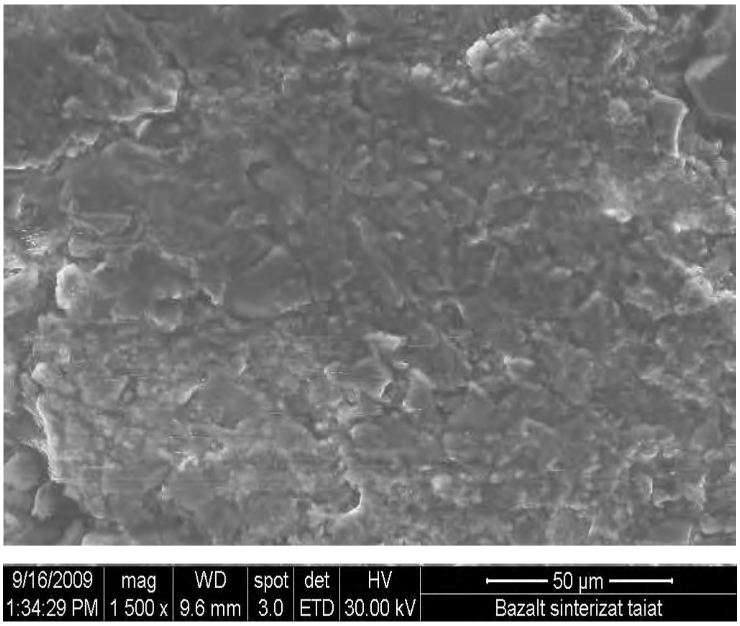


(b)

Fig. 3.1.1.15 (a), (b) Images of molten basalt



(a)



(b)

Fig. 3.1.1.16 (a), (b) Images of sintered basalt

For performing the experiments, an **L_8** Taguchi standard matrix was utilized, for which the controlled factors were assigned, determining their levels and the random order for the 8 experimental conditions. The chosen quality characteristic of sintered parts is Compression strength (daN/cm^2) and the seven controlled factors are

Composition; Calcination temperature; Cooling duration; Sintering temperature; Heating duration; Holding duration; Forming pressure. For each experimental condition, 5 basalt sintered pieces were manufactured, which were tested to compression. Figure 3.1.1.17 presents the controlled factors levels and figure 3.1.1.18 the experimental results and S/N ratios. Furthermore, all possible interactions between controlled factors were studied.

	Factors	Level 1	Level 2
1	Composition	0% TiO2	2% TiO2
2	Calcination temp	900 C	950 C
3	Cooling duration	4 h	5.5 h
4	Sintering temp	1000 C	1100 C
5	Heating duration	8 h	10 h
6	Holding duration	1 h	1.5 h
7	Forming pressure	1500 daN/	2000 daN/cm2

Fig. 3.1.1.17 Controlled factors levels

Conditions	Sample# 1	Sample# 2	Sample# 3	Sample# 4	Sample# 5	Sample# 6	S/N Ratio
Trial# 1	1125	1200	1150	1175	1160		61.298
Trial# 2	1175	1210	1165	1190	1180		61.464
Trial# 3	1300	1285	1250	1290	1295		62.168
Trial# 4	1230	1210	1220	1245	1235		61.782
Trial# 5	1310	1295	1275	1285	1300		62.23
Trial# 6	1290	1310	1285	1300	1275		62.224
Trial# 7	1250	1240	1210	1220	1215		61.774
Trial# 8	1695	1675	1685	1680	1700		64.541
							62.185

Fig. 3.1.1.18 Experimental results and S/N ratios

The presence of an interaction, regardless of how severe, doesn't mean necessarily that is significant. If an interaction is significant or not can be tested by using the ANOVA method (Figure 3.1.1.19). Changes in optimal condition, necessary due to an interaction presence, must be performed only if that interaction is significant.

The order of importance of controlled factors was established, in the optimums table being denoted the predictive equation for performance at the optimal condition and any other condition. The expected performance calculation includes only the significant factors (Figure 3.1.1.20), the optimal condition is determined based on the selected quality characteristic. One can observe that optimum factors levels are consistent with the one obtained after analyzing the factors mean effects and factors interactions.

Col # / Factor	DOF (f)	Sum of Sqrs. (S)	Variance (V)	F - Ratio (F)	Pure Sum (S')	Percent P(%)
1 Composition	1	2.055	2.055	36.571	1.999	27.788
2 Calcination temp	1	1.162	1.162	20.686	1.106	15.378
3 Cooling duration	(1)	(.056)		POOLED	(CL= *NC*)	
4 Sintering temp	1	.806	.806	14.353	.75	10.431
5 Heating duration	1	1.109	1.109	19.738	1.053	14.638
6 Holding duration	1	.619	.619	11.03	.563	7.835
7 Forming pressure	1	1.382	1.382	24.605	1.326	18.44
Other/Error	1	.057	.057			5.49
Total:	7	7.194				100.00%

Fig. 3.1.1.19 ANOVA table

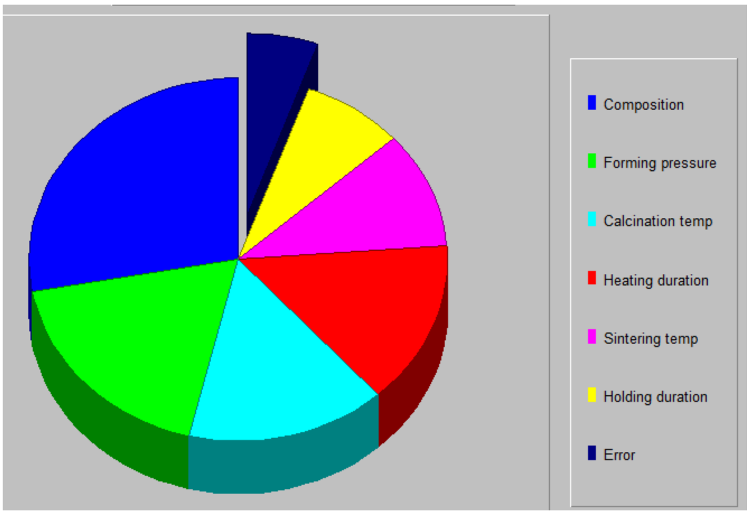


Fig. 3.1.1.20 Significant factor and interaction influences

The order of importance of the factors as well as the corresponding percentage is presented in table 3.1.1.3.

Tab. 3.1.1.3 The order of importance of the factors

Importance order	Factor	Percent [%]
1	Composition	27,788
2	Forming pressure	18,440
3	Calcination temperature	15,378
4	Heating duration	14,368
5	Holding temperature	10,341
6	Sintering duration	7,535
7	Error	5,490
TOTAL = 100%		

The optimal levels presented in Table 3.1.1.4 represents the predictive equation for performance at the optimal condition and any other possible condition. The values calculated and presented in the table are those for the optimal condition. The calculation of the expected performance includes only significant factors, the optimal condition is determined based on the quality characteristic selected for analysis.

Tab. 3.1.1.4 Optimal levels

Col # / Factor	Level Description	Level	Contribution
1 Composition	2% TiO_2	2	0.507
2 Calcination temperature	950 C	2	0.381
4 Sintering temperature	110 C	2	0.317
5 Heating duration	8 h	1	0.372
6 Holding duration	1 h	1	0.277
7 Forming pressure	2000 daN/cm2	2	0.415
Total Contribution from all Factors …………. 2.269 Current Grand Average of Performance……….62.185 Expected Result at Optimum Condition…………64.454			

Table 3.1.1.5 shows the calculation of the expected performance with factors at levels different from those identified as optimal. For the present study, the factor "Cooling time" is considered at level 2 and it is observed that the expected value at this level is 64.369, relatively close to the optimal one 64.454. On the one hand, it is considered that this factor is insignificant (according to the ANOVA analysis) and on the other hand, the cooling is performed in a quartz tube and therefore in confirmation experiments level 2 can be used.

Tab. 3.1.1.5 Expected performance for the "Cooling duration" factor at level 2

Col # / Factor	Level Description	Level	Contribution
1 Composition	2% TiO2	2	0.507
2 Calcination temperature	950 C	2	0.381
3 Cooling duration	5.5 h	2	0.085
4 Sintering temperature	110 C	2	0.317
5 Heating duration	8 h	1	0.372
6 Holding duration	1 h	1	0.277
7 Forming pressure	2000 daN/cm2	2	0.415
Total Contribution from all Factors …………. 2.184 Current Grand Average of Performance……….62.185 Expected Result at Optimum Condition…………64.369			

For a confidence level P = 95% (significance level α = 1 - P = 5%), the confidence interval Δ, is calculated with relation (5)

$$\Delta = \pm \sqrt{\frac{F(n_1,n_2) \cdot V_e}{N_e}} \qquad (3.1.1.5)$$

Where:

- $F(n_1,n_2)$ = 1.6 (calculated value)
- n_1 = 1 (degree of freedom of error)
- n_2 = 1
- V_e = 0.0562 (error variance)
- N_e = 1.14 (numărul efectiv al replicărilor)
- number of degrees of freedom of the factors (dof = 6) is included in the estimate

The value for for the confidence interval is Δ = ± 0.28 and therefore the expected value of the S/N ratio at the optimum is 64.454 ± 0.028, ie a confidence interval [64.174; 64.734]. Expected value expressed in units of quality characteristic based on S/N = 64.454 (optimal value) is $Y_{Expected}$ = 1669.937 daN/cm2

Expected value expressed in units of quality characteristic based on S/N = 64.734 (upper confidence limit) is $Y_{Expected}$ = 1724.745 daN/cm^2 and for S/N = 64.174 (lower confidence limit) is $Y_{Expected}$ = 1616,870 daN/cm^2. The confidence interval for the studied quality characteristic (compression strength) is [1616.870; 1724.745] daN /cm^2. The results are summarized in Table 3.1.1.6.

Tab. 3.1.1.6 Optimal expected values for S / N ratio and compression strength

Specific feature	**M.U.**	**Lower Confidence Limit**	**Upper Confidence Limit**	**Expected Optimal Value**
S/N Ratio	-	64.174	64.734	64.454
Compression Strength	daN/cm^2	1616.870	1724.745	1669.937

Another way to show performance improvement is to present the change in the normal distribution. Thus, the improved S/N ratio at optimal conditions corresponds to a reduction of the standard deviation. The normal distribution for current and improved conditions will be plotted (Figure 3.1.1.21), taking into account the following assumptions:

- ✓ Optimal performance is assumed to be on target (for graphical representation purposes only).
- ✓ When there is no nominal / target value (as in this case “the higher the better”), the average of the results will be used as the target value.
- ✓ The loss before the experiment is assumed to be $ 1 (100 cents) to calculate the achievable savings.
- ✓ The upper control limit (UCL) and the lower control limit (LCL) are assumed to be at ± 3σ to calculate the Cp and Cpk values.
- ✓ The standard deviation (σ) under the improved conditions is assumed to be proportional to the change in the S / N ratio.

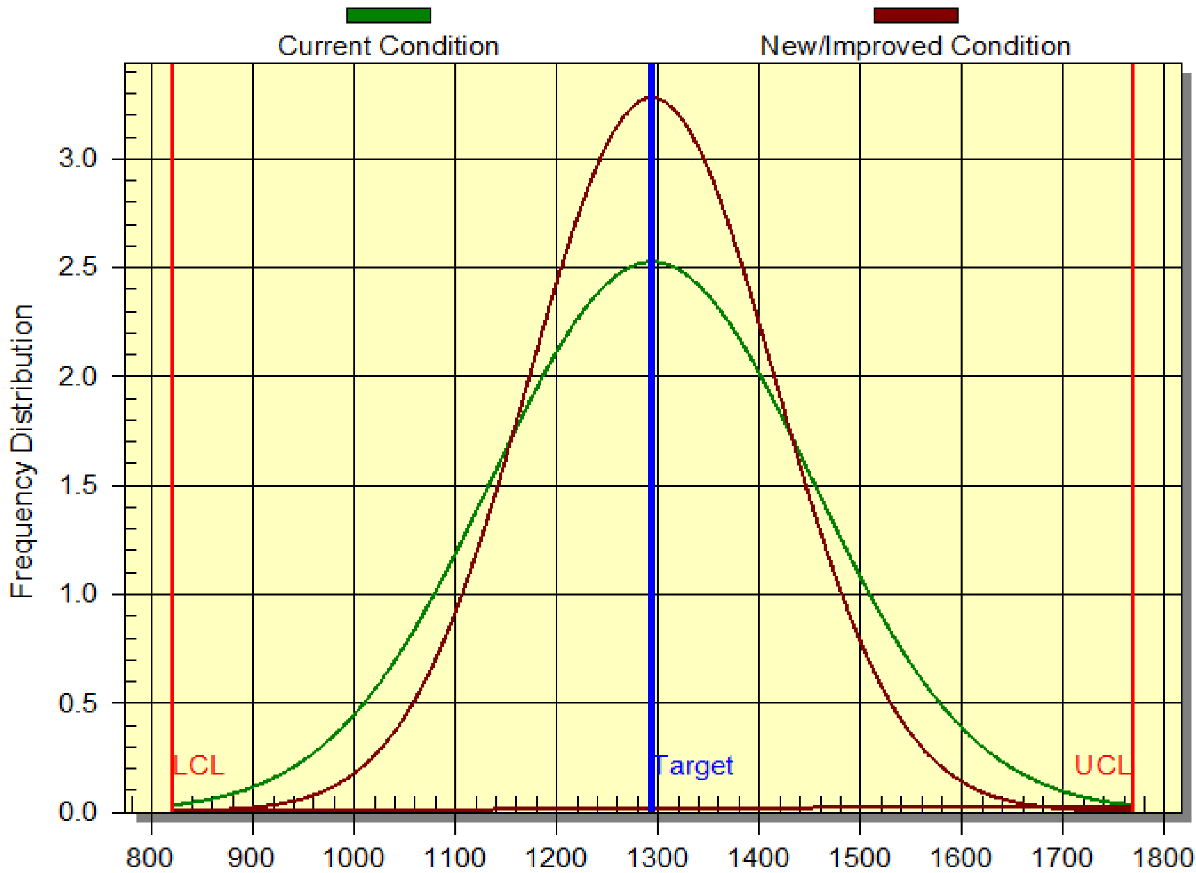


Fig. 3.1.1.21 Variation reduction plot-based an on assumed Normal Performance Distribution

Table 3.1.1.7 compares the situation of the parameters corresponding to the current and improved conditions.

Tab. 3.1.1.7 Current condition versus the improved condition – parameters comparison

Initial experiment	Current conditions	Predicted conditions	
S/N Ratio	62.185	64.454	
Average	1294.62	1294.62	
Standard deviation	158.054	121.707	
Cp	1	1.298	
Cpk	1	1.298	
Savings	-	40.7 cents/1$ loss	
Control limits		LCL	UCL
		820.462	1768.787

Two confirmation experiments were performed. The first experiment conditions are presented in table 3.1.1.8 and the second experiment conditions are presented in table 3.1.1.9.

Tab. 3.1.1.8 Conditions for carrying out confirmation experiment number 1

Col # / Factor	Level	Level Description
1 Composition	2	2% TiO_2
2 Calcination temperature	2	950 °C
3 Cooling duration	1	4 h
4 Sintering temperature	2	1100 °C
5 Heating duration	1	8 h
6 Holding duration	1	1 h
7 Forming pressure	2	2000 daN/cm^2

Tab. 3.1.1.9 Conditions for carrying out confirmation experiment number 2

Col # / Factor	Level	Level Description
1 Composition	2	2% TiO_2
2 Calcination temperature	2	950 °C
3 Cooling duration	2	5,5 h (in a quartz vial)
4 Sintering temperature	2	1100 °C
5 Heating duration	1	8 h
6 Holding duration	1	1 h
7 Forming pressure	2	2000 daN/cm^2

For each experiment, 25 pieces were sintered under the specified conditions. To perform the statistical analysis of the results of the confirmation experiments, for the quality characteristic (compression strength) NTB "Nominal The Best" (NTB) variant was chosen, taking into account the optimal values expected according to table 3.1.1.6. The target value (nominal) Y_{Target} = 1750 daN/cm^2, the Lower Specified Limit LSL = 1700 daN/cm^2 and the Upper Specified Limit USL = 1800 daN/cm^2 respectively.

Figure 3.1.1.22 shows comparatively the variation reduction graphs for the two confirmation experiments and in table 3.1.1.10 the comparative situation of the parameters of the predicted condition versus the conditions obtained through the confirmation experiments.

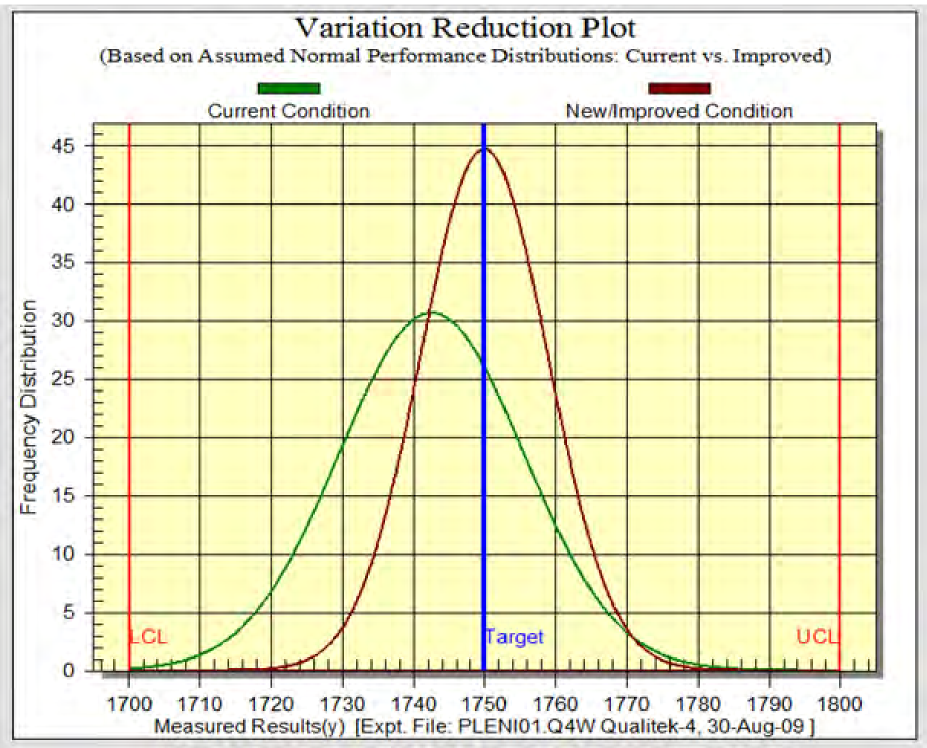


Fig. 3.1.1.22 Variation reduction plots for the two confirmation experiments

Tab. 3.1.1.10 Predicted conditions versus conditions obtained by confirmation experiments

<table>
<tr><th>Initial experiment</th><th colspan="2">Predicted conditions</th><th colspan="2">Predicted conditions based on Optimum S/N Ratio and Confidence Interval</th><th colspan="2">Obtained conditions in confirmation experiment 1</th><th colspan="2">Obtained conditions in confirmation experiment 2</th></tr>
<tr><td>S/N Ratio</td><td colspan="2">64.454</td><td colspan="2">64.454</td><td colspan="2">64.823</td><td colspan="2">64.868</td></tr>
<tr><td>Average</td><td colspan="2">1294.65</td><td colspan="2">166.937</td><td colspan="2">1742.599</td><td colspan="2">1754.599</td></tr>
<tr><td>Standard deviation</td><td colspan="2">121.707</td><td colspan="2">-</td><td colspan="2">14.798</td><td colspan="2">11.895</td></tr>
<tr><td>Cp</td><td colspan="2">1.298</td><td colspan="2">-</td><td colspan="2">1.129</td><td colspan="2">1.401</td></tr>
<tr><td>Cpk</td><td colspan="2">1.298</td><td colspan="2">-</td><td colspan="2">0,962</td><td colspan="2">1.272</td></tr>
<tr><td>Savings</td><td colspan="2">40.7 cents/1$ loss</td><td colspan="2">-</td><td colspan="2">45.8 cents/1$ loss</td><td colspan="2">52.9 cents/1$ loss</td></tr>
<tr><td rowspan="2">Confidence and Specified Limits</td><td>LCL</td><td>UCL</td><td>LCL</td><td>UCL</td><td>LSL</td><td>USL</td><td>LSL</td><td>USL</td></tr>
<tr><td>820</td><td>1768</td><td>1616</td><td>1724</td><td>1700</td><td>1800</td><td>1700</td><td>1800</td></tr>
</table>

To verify the precision of designing the experiments based on an L_8 orthogonal matrix, a full factorial simulation (27 = 128 experiments for a full factorial experiment) was performed. There is a possibility to work with a predefined set of equations that can be solved in full factorial condition (all possibilities). It has been utilized in first instance o generalized non-linear relation between the performance characteristic (Y= Compression strength) and the seven controlled factors (A = Composition; B = Calcination temperature; D = Cooling duration; E = Sintering temperature; F = Heating duration; G = Holding duration; F = Forming pressure).
Assuming that the characteristic equation represents the system behavior, the maximum value obtained from full factorial experiment combinations can be regarded as an exact solution which can be compared to the solution of the experiment based on orthogonal array **L_8**. Also, performance at optimal conditions can be compared with the exact solution to determine the **L_8** experiment accuracy of prediction. 2000 simulations were performed for the characteristic equation in relation (3.1.1.6).

$$Y = (10 \cdot A)^{1.97} + (0.1 \cdot B)^{1.55} + \frac{(10\cdot C)^{0.61}\cdot(0.1\cdot D)^{1.13}\cdot(10\cdot E)^{1.53}}{(5\cdot F)^{0.82}\cdot(0.1\cdot G)^{1.95}} \quad (3.1.1.6)$$

The orthogonal matrix **L_8** obtained from the simulation of the complete factorial experiment and the corresponding calculated values are presented in table 3.1.1.11.

Tab. 3.1.1.11 The **L_8** orthogonal matrix obtained after simulating the complete factorial experiment

Nr.	Factor combination							Calculated value	L_8
1	1	1	1	1	1	1	1	1149.59	L_8 - # 1
16	1	1	1	2	2	2	2	1141.11	L_8 - # 2
52	1	2	2	1	1	2	2	1218.41	L_8 - # 3
61	1	2	2	2	2	1	1	1315.61	L_8 - # 4
86	2	1	2	1	2	1	2	1413.25	L_8 - # 5
91	2	1	2	2	1	2	1	1423.48	L_8 - # 6
103	2	2	1	1	2	2	1	1431.32	L_8 - # 7
106	2	2	1	2	1	1	2	1681.43	L_8 - # 8

The optimal condition resulting from the simulation of the full factorial experiment is presented in table 3.1.1.12.

Tab. 3.1.1.12 Optimal condition resulting from full factorial experiment simulation

Full factorial experiment simulation	
Factor	**Leve[**
Composition	2
Calcination temperature	2
Cooling duration	1
Sintering temperature	2
Heating duration	1
Holding duration	1
Forming pressure	2

The optimal value resulting from the simulation of the complete factorial experiment is: $\mathbf{Y_{optimal}}$ **= 1696.389** and the error of using an orthogonal matrix $\mathbf{L_8}$ instead of a complete factorial experiment is **0.9%**. Table 3.1.1.13 presents a comparison between the values calculated following the simulation of the complete factorial experiment and the values obtained by measurement following the application of the experiment plan given by the orthogonal matrix $\mathbf{L_8}$.

Tab. 3.1.1.13 Values from full factorial simulation and $\mathbf{L_8}$ experiment – a comparison

Full factorial experiment number (simulation)	$\mathbf{L_8}$ **experiment number**	**Calculated value (simulation)**	**Average measured value** $\mathbf{L_8}$	**Relative error [%]**
1	1	1149.59	1162	
16	2	1141.11	1184	- 3.72
52	3	1218.41	1284	- 5.38
61	4	1315.61	1228	6.65
86	5	1413.25	1293	8.50
91	6	1423.48	1292	9.23
103	7	1431.32	1327	9.73
106	8	1681.43	1684	- 0.15

It is observed that the maximum relative error is about 9.73% and the error for the experimental condition number 8 (which offers the optimal combination of factors) is -0.15%, which allows us to conclude that the equation in the relation 6 represents the correct analytical solution of the relationship between the performance characteristic (compression strength) and the factors taken into account. Table 3.1.1.14 compares the expected values based on the $\mathbf{L_8}$ orthogonal matrix and the values obtained by simulation (taking into account a maximum error between - 5.38% and 9.73%) for the quality characteristic (compression strength).

Tab. 3.1.1.14 Comparison between expected values based on the **L8** orthogonal matrix and values obtained by simulation

Quality characteristic – Compression strength [daN/cm^2]					
Calculated values (simulation - 128)			**Expected values (L8)**		
Lower limit (-5.38%)	**Calculated optimal value**	Upper limit (+9.73%)	Expected lower limit	**Expected optimal value**	Expected upper limit
1605.124	**1696,389**	1861.144	1616.870	**1669.937**	1724.745

The relative error between the calculated optimal value and the expected optimal value is 1.55%. The final form of the equation that presents the correct solution, with a maximum error of 9.73% is given in relation 3.1.1.7.

$$S_{\text{Compression}}\left[\frac{\text{daN}}{\text{cm}^2}\right] = (10\cdot\text{Composition}[\%\text{TiO}_2])^{1.97} + (0.1\cdot\text{Temperature}_{\text{Calcination}}[\text{C}])^{1.55} + \frac{(10\cdot\text{Duration}_{\text{Cooling}}[\text{h}])^{0.61}\cdot(0.1\cdot\text{Temperature}_{\text{Sintering}}[\text{C}])^{1.13}\cdot(10\cdot\text{Duration}_{\text{Heating}}[\text{h}])^{1.53}}{(5\cdot\text{Duration}_{\text{Holding}}[\text{h}])^{0.82}\cdot\left(0.1\cdot\text{Pressure}_{\text{Forming}}\left[\frac{\text{daN}}{\text{cm}^2}\right]\right)^{1.95}} \quad (3.1.1.7)$$

Next, a Draper-Lin experimental plan was used, which is a small compositional plan consisting of a fractional factorial plan or a Plackett-Burman plan (for matrices with multiple experiments of 4 but not the power of 2) with lower resolution than the fifth order, with additional star points. Fifth-order plans can estimate all the main effects and interactions, fourth-order plans can estimate all the main effects but some of the interactions between two factors can be confused (mixed) with other interactions or effects of the blocks, and the plans with order III can only estimate the main effects requiring no interactions for a correct interpretation.

The statistical model on which the analysis of RSM plans (including Draper-Lin plans) is based expresses the response variable (compressive strength) as a linear function of the experimental factors, the interactions between factors, 2nd order terms (squares), and an error term. Two types of models can be used, presenting them for the present case, namely for 7 factors:

1. *The first-order model* - which contains terms that represent only the main effects.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \varepsilon \qquad (3.1.1.8)$$

2. The second-order model - which contains terms that represent the effects main, second-order interactions and square effects

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 + \\ & \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{14} X_1 X_4 + \beta_{15} X_1 X_5 + \beta_{16} X_1 X_6 + \beta_{17} X_1 X_7 + \\ & \beta_{23} X_2 X_3 + \beta_{24} X_2 X_4 + \beta_{25} X_2 X_5 + \beta_{26} X_2 X_6 + \beta_{27} X_2 X_7 + \beta_{34} X_3 X_4 + \\ & \beta_{35} X_3 X_5 + \beta_{36} X_3 X_6 + \beta_{37} X_3 X_7 + \beta_{45} X_4 X_5 + \beta_{46} X_4 X_6 + \beta_{47} X_4 X_7 + \\ & \beta_{56} X_5 X_6 + \beta_{57} X_5 X_7 + \beta_{67} X_6 X_7 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33}^2 + \beta_{44}^2 + \beta_{55}^2 + \\ & \beta_{66}^2 + \beta_{77}^2 + \varepsilon \end{aligned} \qquad (3.1.1.9)$$

A small orthogonally randomized Draper-Lin compositional experiment plan was created to study the effect of 7 factors in 40 experiments in a single block (including 2 central points per block) with 4 degrees of freedom for error.

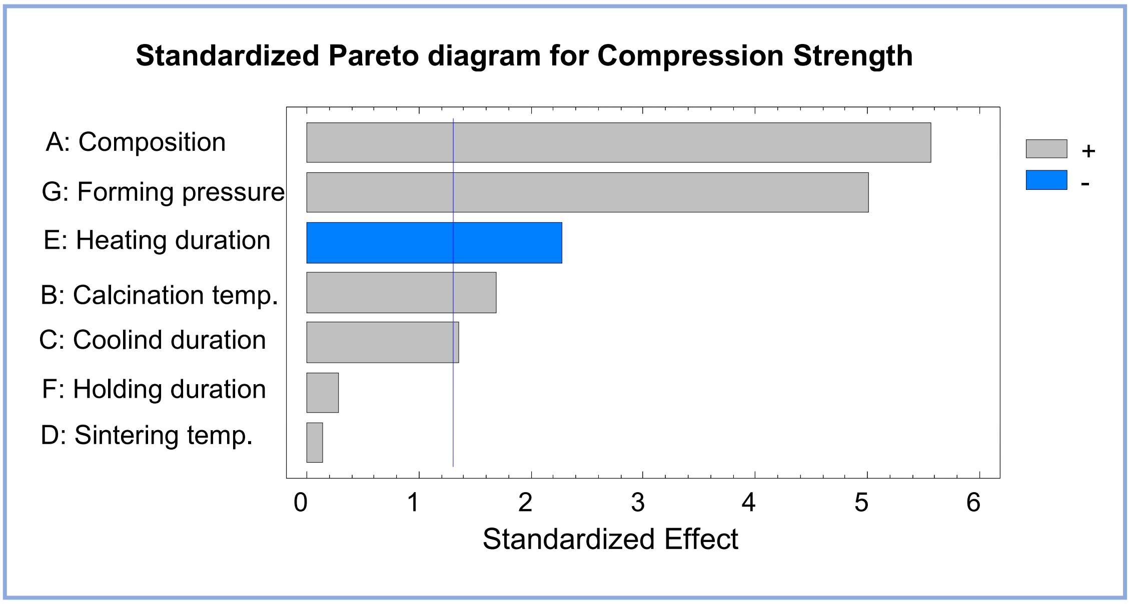


Fig. 3.1.1.23 Standardized Pareto chart for factor effects (excluding interactions)

Table 3.1.1.15 presents a Comparison between the order of importance of the factors for the Taguchi method and the RSM method (Draper-Lin).

Tab. 3.1.1.15 Comparison between the order of importance of the factors for the Taguchi method and the RSM method (Draper-Lin)

Importance order	Taguchi L_8	Draper-Lin (with interactions)	Draper-Lin (without interactions)
1	**Composition**	**Composition**	**Composition**
2	**Forming pressure**	**Forming pressure**	**Forming pressure**
3	Calcination temp.	Sintering temp.	Heating duration
4	Heating duration	Holding duration	Calcination temp.
5	Sintering temp.	Cooling duration	Cooling duration
6	Holding duration	Calcination temp.	Holding duration
7	Cooling duration	Heating duration	Sintering temp.

It is observed that the Composition and Forming Pressure factors are considered as the main factors (in this order) in both approaches.

In relation (3.1.1.10) is presented the regression equation, according to the second-order model in relation (3.1.1.9), and in which the values of the variables are specified in the original units of measurement.

$$S_{Compression}[daN/cm^2] = -22677.0 - 209.835 \cdot Composition[\%TiO_2] -$$
$$29.7447 \cdot Temperature_{Calcination}[C] - 974{,}391 \cdot Duration_{Cooling}[h] + 53.9696 \cdot Temperature_{Sintering}[C] +$$
$$728.616 \cdot Duration_{Heating}[h] - 9842.04 \cdot Duration_{Holding}[h] + 10.6282 \cdot Pressure_{Forming}[daN/cm^2] +$$
$$26.7581 \cdot (Composition[\%TiO_2])^2 - 0.474826 \cdot (Composition[\%TiO_2]) \cdot (Temperature_{Calcination}[C]) +$$
$$50.6041 \cdot (Composition[\%TiO_2]) \cdot \left(Duration_{Cooling}[h]\right) - 0.453093 \cdot (Composition[\%TiO_2]) \cdot \left(Temperature_{Sintering}[C]\right) +$$
$$37.8929 \cdot (Composition[\%TiO_2]) \cdot \left(Duration_{Heating}[h]\right) + 301.675 \cdot (Composition[\%TiO_2]) \cdot \left(Duration_{Holding}[h]\right) +$$
$$0.114627 \cdot (Composition[\%TiO_2]) \cdot \left(Pressure_{Forming}[daN/cm^2]\right) + 0.041667 \cdot (Temperature_{Calcination}[C])^2 +$$
$$0.629255 \cdot (Temperature_{Calcination}[C]) \cdot \left(Duration_{Cooling}[h]\right) - 0.0397362 \cdot (Temperature_{Calcination}[C]) \cdot \left(Temperature_{Sintering}[C]\right) -$$
$$1.08744 \cdot (Temperature_{Calcination}[C]) \cdot \left(Duration_{Heating}[h]\right) + 8.96291 \cdot (Temperature_{Calcination}[C]) \cdot \left(Duration_{Holding}[h]\right) -$$
$$0.00519131 \cdot (Temperature_{Calcination}[C]) \cdot \left(Pressure_{Forming}[daN/cm^2]\right) + 17.0235 \cdot \left(Duration_{Cooling}[h]\right)^2 -$$
$$2.40026 \cdot \left(Duration_{Cooling}[h]\right) \cdot \left(Temperature_{Sintering}[C]\right) + 20.5743 \cdot \left(Duration_{Cooling}[h]\right) \cdot \left(Duration_{Heating}[h]\right) +$$
$$389.692 \cdot \left(Duration_{Cooling}[h]\right) \cdot \left(Duration_{Holding}[h]\right) +$$
$$0.0564768 \cdot \left(Duration_{Cooling}[h]\right) \cdot \left(Pressure_{Forming}[daN/cm^2]\right) +$$

$0.000107587 \cdot (\text{Temperature}_{\text{Sintering}}[\text{C}])^2 + 0.263014 \cdot (\text{Temperature}_{\text{Sintering}}[\text{C}]) \cdot (\text{Duration}_{\text{Heating}}[\text{h}]) -$
$0.263014 \cdot (\text{Temperature}_{\text{Sintering}}[\text{C}]) \cdot (\text{Duration}_{\text{Heating}}[\text{h}]) - 0.940357 \cdot (\text{Temperature}_{\text{Sintering}}[\text{C}]) \cdot (\text{Duration}_{\text{Holding}}[\text{h}]) -$
$0.00372683 \cdot (\text{Temperature}_{\text{Sintering}}[°\text{C}]) \cdot (\text{Pressure}_{\text{Forming}}[\text{daN/cm}^2]) +$
$5.27987 \cdot (\text{Duration}_{\text{Heating}}[\text{h}])^2 - 69.3095 \cdot (\text{Duration}_{\text{Heating}}[\text{h}]) \cdot (\text{Duration}_{\text{Holding}}[\text{h}]) -$
$0.0778476 \cdot (\text{Duration}_{\text{Heating}}[\text{h}]) \cdot (\text{Pressure}_{\text{Forming}}[\text{daN/cm}^2]) - 7.15948 \cdot (\text{Duration}_{\text{Holding}}[\text{h}])^2 +$
$0.616217 \cdot (\text{Duration}_{\text{Holding}}[\text{h}]) \cdot (\text{Pressure}_{\text{Forming}}[\text{daN/cm}^2]) - 0.000591358 \cdot$
$(\text{Pressure}_{\text{Forming}}[\text{daN/cm}^2])^2$ (3.1.1.10)

Table 3.1.1.16 compares the calculated values obtained by simulating the full factorial plan (128 experiments), the values expected by applying the Taguchi - $\mathbf{L_8}$ matrix (8 experiments), and the predicted (maximum) values obtained by applying the Draper-Lin plan (40 experiments).

Tab. 3.1.1.16 Comparison between expected (predicted) values of the Taguchi and RSM methods (Draper-Lin plan)

Quality characteristic – Compression strength [daN/cm²]					
Calculated values (simulation - 128)			**Expected values (L_8)**		
Lower limit (-5.38%)	**Calculated optimal value**	Upper limit (+9.73%)	Expected lower limit	**Expected optimal value**	Expected upper limit
1605.124	**1696.389**	1861.144	1616.870	**1669.937**	1724.745
Predicted values (Draper - Lin)			**Predicted values for averages (Draper - Lin)**		
Predicted lower limit	**Predicted maximum value**	Predicted upper limit	Predicted lower limit	**Predicted maximul value**	Predicted upper limit
1286.16	**1597.18**	1908.21	1382.9	**1597.18**	1811.88

Table 3.1.1.17 shows a comparison between the optimal levels of factors according to the Taguchi method and the levels obtained based on the RSM method (Draper - Lin plan) for the maximum expected value.

Tab. 3.1.1.17 Optimal factor levels of factors – comparison Taguchi L_8 and Draper - Lin

Experimental Plan	Factors and Levels						
	A	B	C	D	E	F	G
Taguchi L_8	2	2	2	1(2)	1	1	2
Draper-Lin (maximum)	2	2	2	2	1	2	2

Prediction analysis using the gradient method (the “steepest ascent” method) indicates favorable locations where additional experiments should be performed. The path of the "steepest ascent" starts from the center of the region of the current experiment along with which the estimated response changes the fastest for the smallest change in the values of the experimental factors. Table 3.1.1.18 shows the values of the factors and the predicted value for the compression strength by generating 11 points by changing the composition in 0.1% increments.

Tab. 3.1.1.18 Factor values and predicted value for compressive strength (change in composition in 0.1% increments)

Comp.	Calci. Temp.	Cool. Dur.	Sint. Temp.	Heat. Dur.	Hold. Temp.	Forming Pressure	Comp. Strength (predict.)
[% TiO2]	**[° C]**	**[h]**	**[° C]**	**[h]**	**[h]**	**[daN/cm^2]**	**[daN/cm^2]**
1.0	925.0	4.75	1050.0	9.0	1.25	1750.0	1295.36
1.1	925.277	4.764	1050.47	9.0083	1.2550	1769.55	1311.28
1.2	925.481	4.781	1050.49	9.0179	1.2625	1786.65	1328.05
1.3	925.647	4.802	1050.15	9.0285	1.2719	1801.94	1346.50
1.4	925.799	4.827	1049.51	9.0399	1.2829	1815.89	1367.22
1.5	925.952	4.855	1048.62	9.0519	1.2952	1828.82	1390.69
1.6	926.117	4.885	1047.51	9.0643	1.3085	1840.98	1417.30
1.7	926.301	4.919	1046.21	9.0770	1.322	1852.54	1447.38
1.8	926.500	4.955	1044.74	9.0900	1.3376	1863.64	1481.22
1.9	926.730	4.994	1043.13	9.1031	1.3531	1874.35	1519.07
2.0	**926.990**	**5.034**	**1041.39**	**9.1164**	**1.3693**	**1884.77**	**1561.16**

Table 3.1.1.19 shows the values of the factors and the predicted value for the compression strength by generating 11 points by changing the forming pressure in increments of 25 daN/cm^2.

Tab. 3.1.1.19 Factor values and predicted value for compressive strength (change in forming pressure in increments of 25 daN/cm^2)

Comp.	Calci. Temp.	Cool. Dur.	Sint. Temp.	Heat. Dur.	Hold. Temp.	Forming Pressure	Comp. Strength (predict.)
[% TiO2]	[° C]	[h]	[° C]	[h]	[h]	[daN/cm^2]	[daN/cm^2]
1.0	925.0	4.75	1050.0	9.0	1.25	1750.0	1295.36
1.1305	925.34	4.76	1050.52	9.01115	1.257	1775.0	1316.26
1.2866	925.62	4.79	1050.22	9.02708	1.270	1800.0	1343.93
1.4696	925.90	4.84	1048.92	9.0482	1.291	1825.0	1383.24
1.6774	926.25	4.91	1046.52	9.07414	1.319	1850.0	1440.25
1.9059	926.74	4.99	1043.04	9.10393	1.354	1875.0	1521.38
2.15016	**927.41**	**5.098**	**1038.57**	**9.13638**	**1.3943**	**1900.0**	**1632.69**
2.40579	928.28	5.216	1033.26	9.17039	1.4392	1925.0	1779.32
2.66936	929.33	5.347	1027.23	9.20516	1.4762	1950.0	1965.49
2.93841	930.55	5.489	1020.61	9.24013	1.5388	1975.0	2194.55
3.21123	931.94	5.639	1013.49	9.27493	1.5922	2000.0	2469.19

Table 3.1.1.20 shows the optimal combination of factor levels (taking into account interactions) that maximizes the response (compressive strength) and Table 3.1.1.21 shows the optimal combination of factor levels without interactions.

Tab. 3.1.1.20 The optimal combination of factor levels (with interactions) for the Draper-Lin plan

Factor	Min	Max	Optimum	Optimal Value
Composition	0.0	2.0	1.9915	**2004.26**
Calcination temperature	900.0	950.0	949.999	
Cooling duration	4.0	5.5	5.47818	
Sintering temperature	1000.0	1100.0	1000.0	
Heating duration	8.0	10.0	8.04393	
Holding duration	1.0	1.5	1.5	
Forming pressure	1500.0	2000.0	1947.69	

Tab. 3.1.1.21 The optimal combination of factor levels (without interactions) for the Draper-Lin plan

Factor	Min	Max	Optimum	Optimal Value
Composition	0.0	2.0	1.99993	**1537.19**
Calcination temperature	900.0	950.0	950.0	
Cooling duration	4.0	5.5	5.49936	
Sintering temperature	1000.0	1100.0	1100.0	
Heating duration	8.0	10.0	8.00001	
Holding duration	1.0	1.5	1.5	
Forming pressure	1500.0	2000.0	1999.99	

Table 3.1.1.22 compares the values measured in the confirmation experiments based on the Taguchi L_8 experiment plan, the expected values obtained by simulating a complete factorial plan (128 experiments), the expected values obtained by applying the Taguchi L8 experiment plan, the maximum expected and optimal values predicted by applying the Draper-Lin experiment plan, the measured values obtained in the 40 experiments in the Draper-Lin plan and the values predicted by the gradient method. The levels of the factors for the respective conditions are also presented.

Tab. 3.1.1.22 Comparison between different methods of estimating, measuring, and calculating the value of compression strength

	Factors and Levels							
Method	**Value**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
Maximum mesured value (L_8)	**1700**	2	2	1	2	1	1	2
Optimal calculated value (simulation - 128)	**1696.38**	2	2	1	2	1	1	2
Expected optimal value (L_8)	**1669.93**	2	2	1	2	1	1	2
Measured value (Avg. confirmation experiment 1)	**1742.59**	2	2	1	2	1	1	2
Measured value (Avg. confirmation experiment 1)	**1754.59**	2	2	2	2	1	1	2
Maximum measured value (Draper-Lin)	**1640**	2	2	2	2	1	2	2
Predicted maximul value (Draper - Lin)	**1597.18**	2	2	2	2	1	2	2
Optimal value with interactions (Draper-Lin)	**2004.26**	2	2	2	1	2	1	2
Optimal value without interactions (Draper-Lin)	**1537.19**	2	2	2	2	1	2	2
Predicted value by modifying composition (gradient method)	**1561.16**	2	1.5	1.58	1.48	1.52	1.64	1.61

Figures 3.1.1.24 and 3.1.1.25 show the estimated response area and the contours of the estimated response area, respectively. It should be noted that the surface height represents the predicted values for the compressive strength over a space determined by 2 factors, the remaining 5 factors being maintained at their average values.

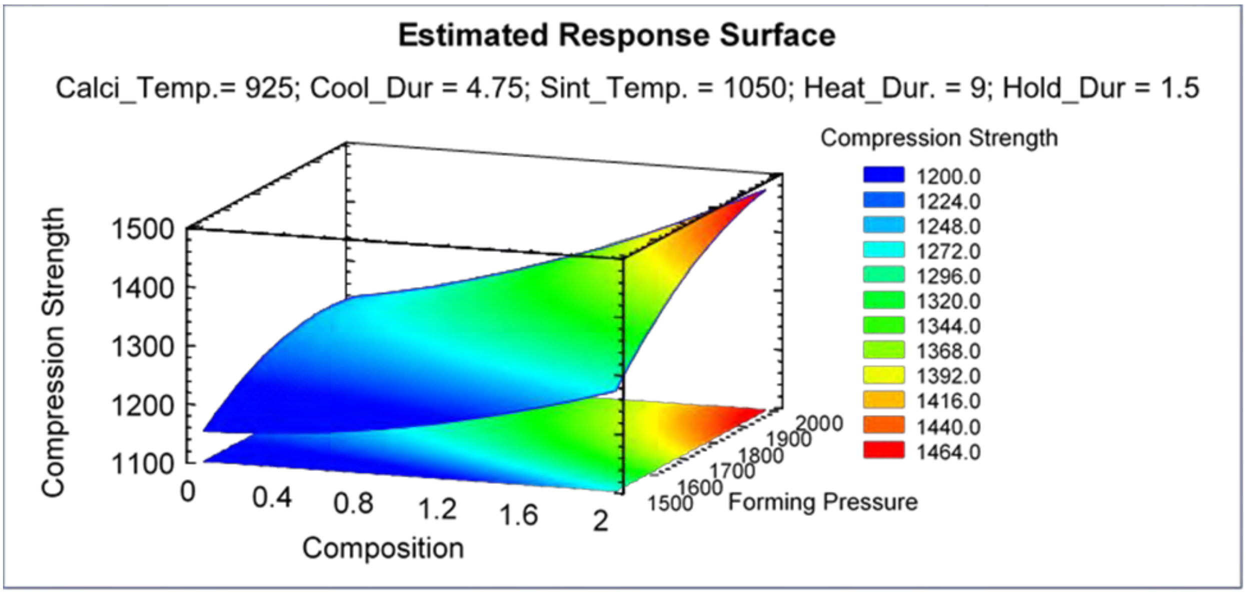


Fig. 3.1.1.24 Estimated Response Surface (Composition – Forming Pressure)

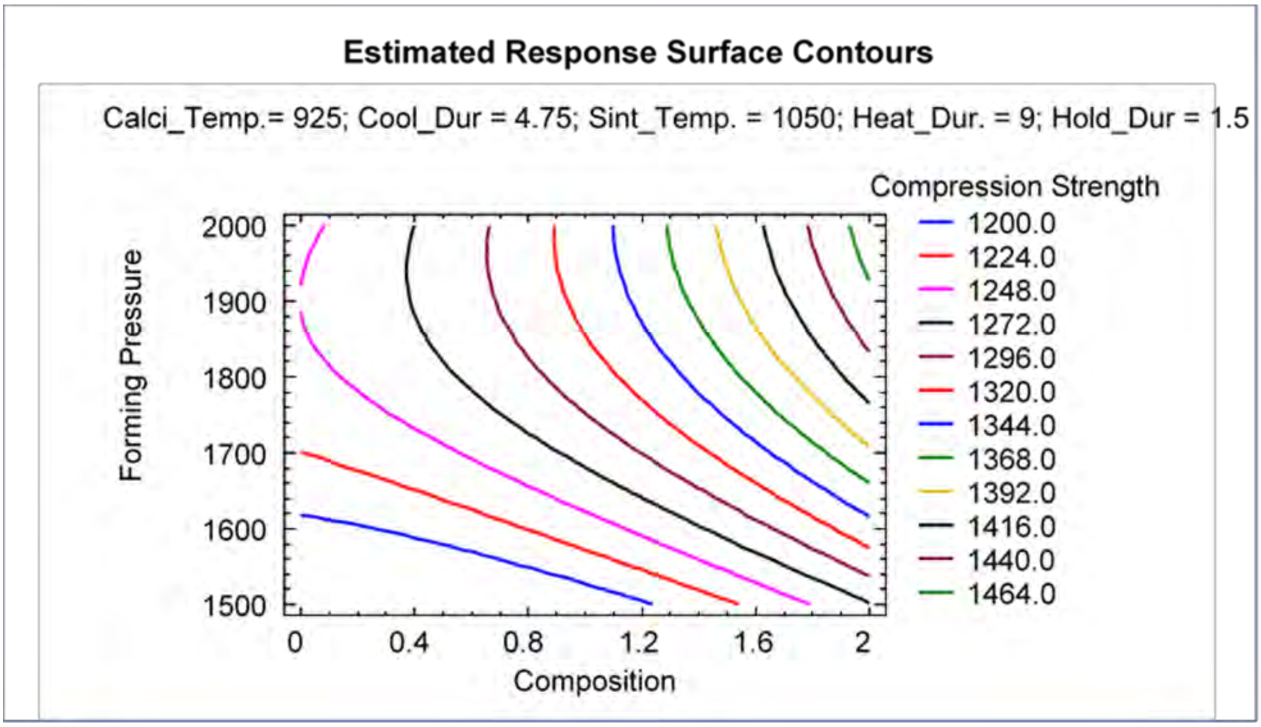
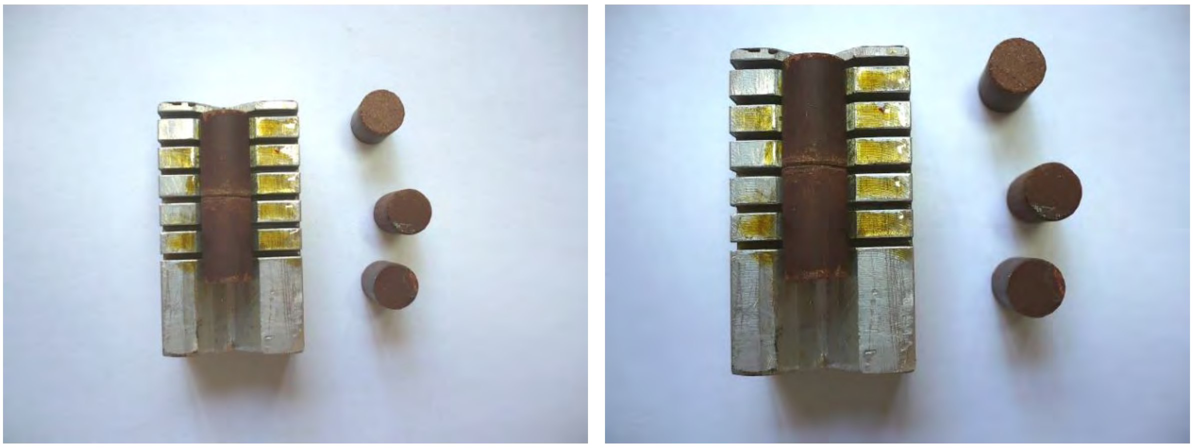


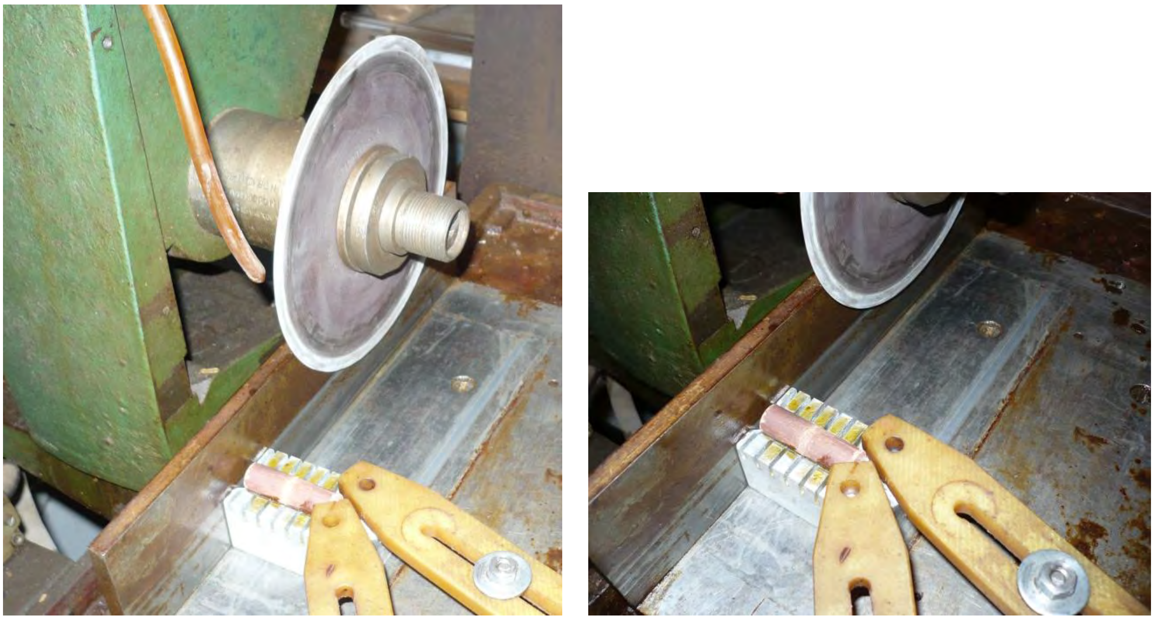
Fig. 3.1.1.25 Estimated Response Surface Contours (Composition – Forming Pressure)

It has been designed a device (Figure 3.1.1.26) for supporting the sintered basalt pieces with a special adhesive which gives in at reasonably high temperatures so that the parts are not affected at the detachment. With the help of a device using a diamond blade (Figure 3.1.1.27), sintered basalt pellets of 4mm thickness were cut.



(a) (b)

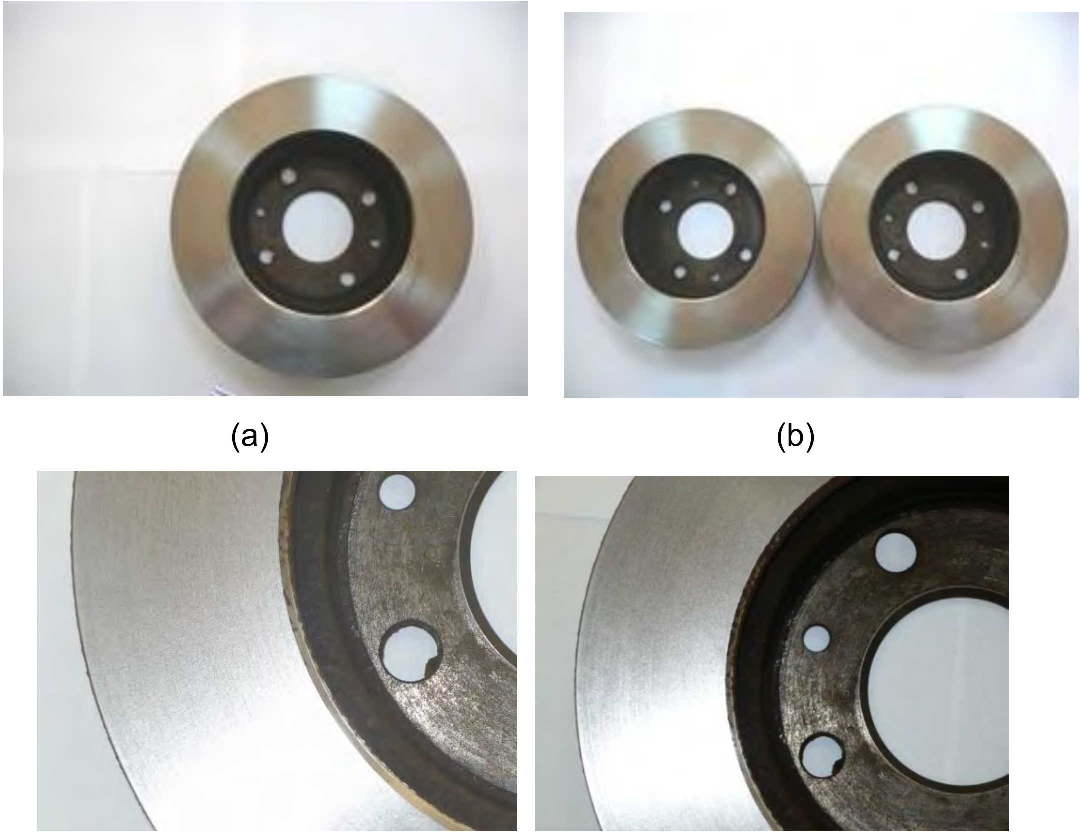
Fig. 3.1.1.26 (a), (b) Device for supporting the sintered basalt pieces



(a) (b)

Fig. 3.1.1.27 (a), (b) Device for cutting sintered basalt pellets

Two braking disks of Dacia Supernova were rectified as in figure 3.1.1.28 (a), (b), (c), (d).



(a) (b)

(c) (d)

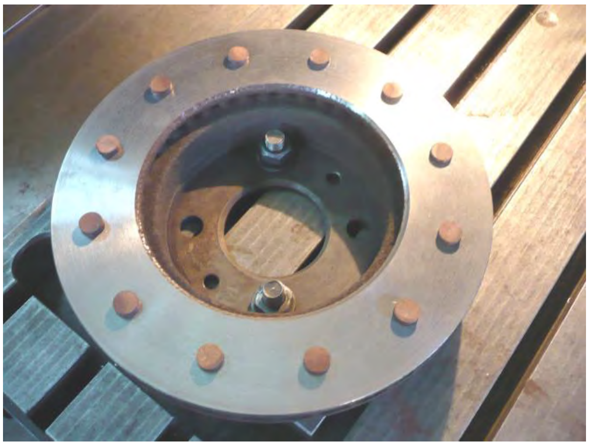
Fig. 3.1.1.28 (a), (b), (c), (d) Rectified braking disks

16 holes (at 30 °) of 2 mm depth were made, as in figure 3.1.1.29 (a), (b)

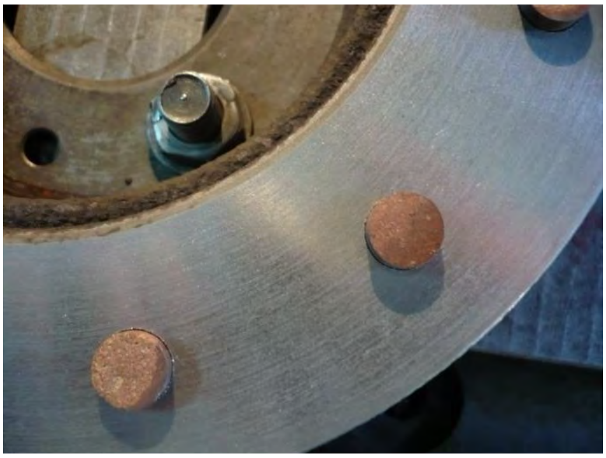
(a) (b)

Fig. 3.1.1.29 (a), (b) Drilling holes in braking disks

The previously cut sintered basalt pellets were inserted into the holes in the brake disks, their fixing being carried out both by shape and by gluing with adhesive as in figure 3.1.1.30 (a), (b).



(a)



(b)

Fig. 3.1.1.30 (a), (b) Inserting and fixing the basalt pellets in the brake disks

By fixing the pellets, their remaining thickness above the braking disk is 2 mm, constituting the maximum wear to which the disk with pellets can be subjected.

To carry out the wear tests of the disk equipped with sintered basalt pellets, we started from the idea of using the braking disk with basalt pellets as a braking device. 3 cases were used for the other disk, if the disk with basalt pellets acts directly on a disk, if the disk with basalt pellets acts on a disk on which 2 ordinary braking pads were fixed (Figure 3.1.1.31) and if the disk with basalt pellets acts on a disk on which 4 ordinary braking pads have been fixed (Figure 3.3.1.32).

Fig. 3.3.1.31 Braking disk with 2 pads

Fig. 3.3.1.32 Braking disk with 4 pads

The tests were performed on a milling machine in which the disk with basalt pellets was fixed on the machine table and the simple disk, respectively those with 2 or 4 pads were fixed instead of the milling cutter (so they are the ones that perform the rotational movement). Figure 33 shows the assembly with the simple disk, figure 34 shows the assembly with 2 braking pads, and in figure 35 the assembly with 4 braking pads.

Fig. 3.3.1.33 Single disk mounting

Fig. 3.3.1.34 Mounting with 2 pads

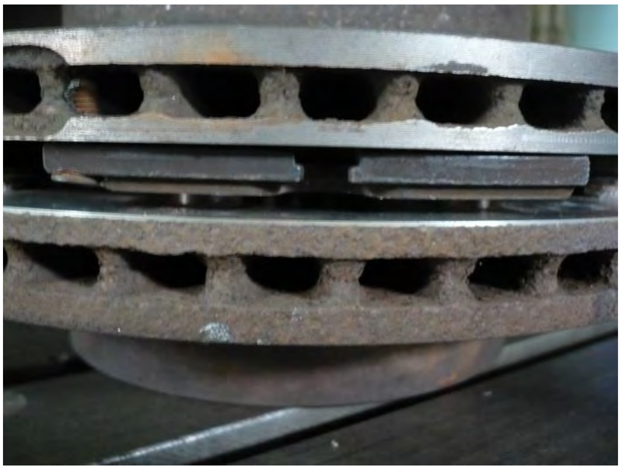


Fig. 3.3.1.35 Mounting with 4 pads

The milling machine ensured the 3 speeds at which the tests were performed: 630 rpm, 800 rpm and 1000 rpm. Taking into account the relation (3.1.1.11), in which the peripheral speed of the vehicle wheel is given and the fact that the radius of the vehicle wheel is r_{wheel} = 0.300 m, it is practically obtained the speeds with which the vehicle travels, corresponding to the speeds at which the tests were performed and which are given in relations (3.1.1.12), (3.1.1.13) and (3.1.1.14).

$$V_p = \frac{2\pi \cdot r \cdot n}{60} \quad (3.1.1.11)$$

$$V_{p1000} = \frac{2\pi \cdot r \cdot n}{60} = 113 \ \frac{km}{h} \quad (3.1.1.12)$$

$$V_{p800} = \frac{2\pi \cdot r \cdot n}{60} = 90{,}4 \ \frac{km}{h} \quad (3.1.1.13)$$

$$V_{p630} = \frac{2\pi \cdot r \cdot n}{60} = 71{,}2 \ \frac{km}{h} \quad (3.1.1.14)$$

All tests were performed over 1 hour, measuring the average wear on the corresponding pills and disks. The operating time was taken into account as the time until the wear of the plates is maximum, ie 2 mm. Another variable taken into account is the working pressure. To determine this pressure, we started from the real data in the case of a braking device for a Dacia type vehicle.

Thus in figure 3.1.1.36 are presented the characteristic elements that appear on a wheel of the Dacia type vehicle and the characteristic elements of the braking system.

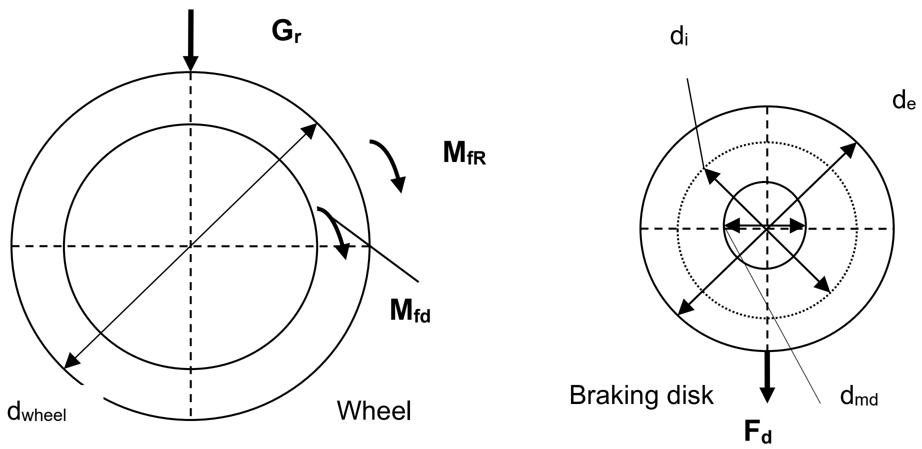


Fig. 3.1.1.36 Characteristic elements of the wheel and the braking disk

Characteristic elements of the wheel:

- Dacia weight, Ga = 960 kg
- wheel radius, r_{wheel} = 0.300 m

- wheel weight (force), FR = GR = (0,75 x Ga) / 2 ≈ 360 daN
- wheel braking torque (disk), MfR = Mfd = FR x wheel ≈ 108 daN
- surface at the braking wheel, Sf = 106.75 cm2

Characteristic elements of the braking disk:
- outer diameter of the braking disk, of = 0.235 m
- inner diameter of the braking disk, di = 0.140 m
- average diameter of the braking disk, dmd = 0.235 m
- braking disk pressure, psl = Mfd / (Sf x rmd) ≈ 10.76 daN / cm2

To achieve the pressure on the disk with sintered basalt pellets, an assembly was made in which the pressure is achieved by means of a torque wrench placed on the working head of the cutter.

The pressure delivery system as well as the corresponding characteristic elements are shown in Figure 3.3.1.37.

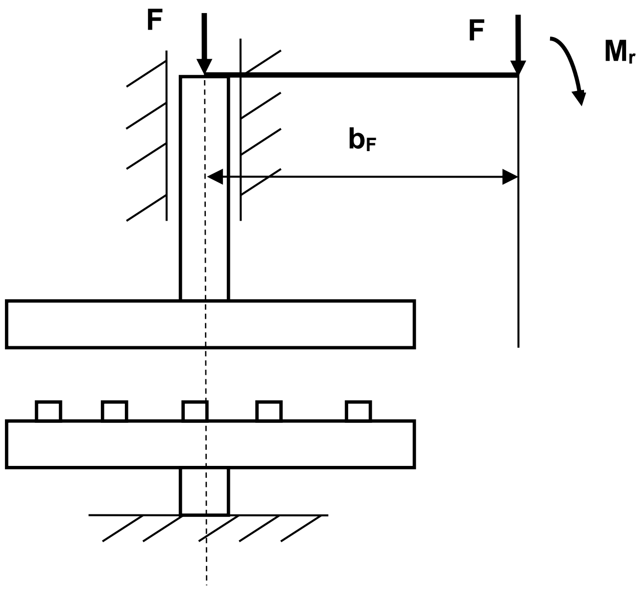


Fig. 3.1.1.37 Characteristic elements of the pressure system

- *Characteristic elements of the pressure system*

- torque wrench arm, b_F = 0.710 m
- torque wrench moment, $M_r = M_{fd} = F \times b_f = p_{sl} \times S_f \times r_{md}$

Case I: p_{sl} = 1 daN / cm²

a) Disk with 2 pads - Braking disk with 2 x 2 basalt pellets,

Sf = 3.79 cm² (surface of 4 pellets with reduced diameter by sintering at 1.1 cm by sintering);

F = 0.5 daN (at the end of the torque wrench).

b) 4-plate disk - Braking disk with 4 x 2 basalt pellets,

S_f = 7.59 cm² (surface of 4 pellets with reduced diameter by sintering to 1.1 cm by sintering);

F = 1.01 daN (at the end of the torque wrench)

b) Single disk - Braking disk with 12 basalt pellets,

S_f = 11.38 cm² (surface of 4 pellets with reduced diameter by sintering to 1.1 cm by sintering);

F = 1.50 daN (at the end of the torque wrench)

Case II: p_{sl} = 10.76 daN / cm²

a) Disk with 2 pads - Braking disk with 2 x 2 basalt pellets,

S_f = 3.79 cm² (surface of 4 pellets with reduced diameter by sintering to 1.1 cm by sintering);

F = 5.38 daN (at the end of the torque wrench)

b) 4-plate disk - Braking disk with 4 x 2 basalt pellets,

S_f = 7.59 cm² (surface of 4 pellets with reduced diameter by sintering to 1.1 cm by sintering);

F = 10.86 daN (at the end of the torque wrench)

b) Single disk - Braking disk with 12 basalt pellets,

S_f = 11.38 cm² (surface of 4 pellets with reduced diameter by sintering to 1.1 cm by sintering);

F = 16.14 daN (at the end of the torque wrench)

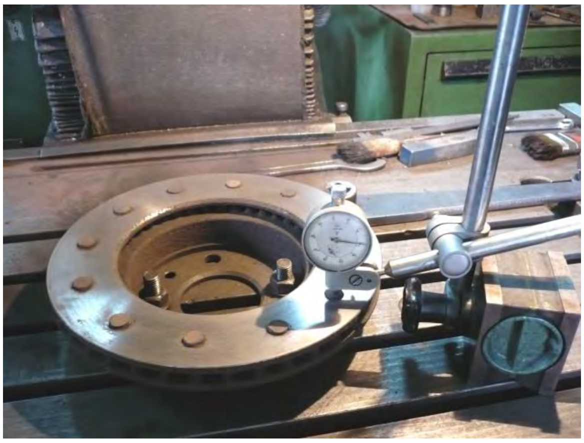
Figure 3.1.1.38 (a), (b), (c), (d) shows the practical realization of the assembly to obtain the required working pressure.


(a) (b)


(c) (d)

Fig. 3.1.1.38 (a), (b), (c), (d) Practical realization of the pressure system

Figure 3.1.1.39 (a), (b) shows the wear resulting from wear tests and the measurement of wear, respectively.



(a)

(b)

Fig. 3.1.1.39 (a), (b) Wear measurement

➢ *Wear analysis of sintered basalt pellets*

Table 3.1.1.23 shows the data obtained from the wear tests to which the sintered basalt pellets mounted on the braking disk and the wear of the abrasion disks were subjected.

Tab. 3.1.1.23 Data obtained from the wear tests

Revs.	Abr. disk	Pressure	Avg. wear	Dur.	Cen.	Disk wear D0	Avg. wear 4 pads D4	Avg .wear 2 pads D2
[rpm]	-	[daN/cm^2]	[μm]	[h]	-	[μm]	[μm]	[μm]
630	D0	1	4.36	458.7	1	7.85		
630	D0	10.76	41.26	48.4	0	74.27		
630	D4	1	3.58	558.6	1		21.73	
630	D4	10.76	36.43	59.8	0		221.13	
630	D2	1	1.68	1190.4	1			5.99
630	D2	10.76	17.36	115.2	1			61.97
800	D0	1	5.38	371.7	1	9.42		
800	D0	10.76	49.51	40.3	0	91.59		
800	D4	1	4.43	451.4	1		27.07	
800	D4	10.76	44.45	44.9	0		269.81	
800	D2	1	2.13	938.9	1			7.61
800	D2	10.76	21.77	91.8	1			77.72
1000	D0	1	7.03	284.4	1	11.95		
1000	D0	10.76	61.87	32.3	0	117.5		
1000	D4	1	5.89	339.5	1		35.75	
1000	D4	10.76	59.32	33.7	0		360.07	
1000	D2	1	2.76	724.6	1			9.85
1000	D2	10.76	28.86	69.3	1			10.21

Note that in the durations column it was estimated (according to the corresponding average wear) the duration in hours required for the basalt pellets to wear out completely (2 mm).

- *The general linear model associated with average wear*
  - ✓ Number of dependent variables: 1 (average wear);
  - ✓ Number of absolute factors: 1 (A - Abrasion disk)
  - ✓ Number of quantitative factors: 2 (B - Pressure, C - Speed)
  - ✓ Box-Cox transformation applied: power = 0.0403159; displacement = 0.0

Table 3.1.1.24 presents the analysis of variance for average wear

Tab. 3.1.1.24 ANOVA for average wear

Source	Sum of squares	DOF	Square mean	F - Ratio	P - value
Model	3751.64	4	937.909	9143.03	0.0000
Rezidual	1.33356	13	0.102582		
Total (Revised)	3752.97	17			

From table 3.1.1.24 it is observed that because the P - value for the average wear is less than 0.05, there is a statistically significant relationship between the average wear and the 3 predictive variables with a probability of 95%. Table 3.1.1.25 shows the sum of the third-order squares.

Tab. 3.1.1.25 Sum of the third-order squares

Source	Sum of squares	DOF	Square mean	F - Ratio	P - value
Abrasion Disk	367.514	2	183.757	1791.32	0.0000
Pressure	3287.7	1	3287.7	32049.49	0.0000
revs	96.4251	1	96.4251	939.98	0.0000
Rezidual	1.33356	13	0.102582		
Total (revised)	3752.97	17			

R^2 = 99.9645%

R_{adj}^2 = 99.9535%

Estimation Standard Error = 0.320284

Absolute Average Error = 0.223012

Durbin-Watson statistics = 2.21211 (P = 0.5852)

Table 3.1.1.25 tests the statistical significance of each factor, as introduced in the model. Because the P-values are less than 0.05, all factors are statistically significant, with a probability of 95%. In this case, all factors must be kept in the model. The R-square statistic indicates that the model explains 99.9645% of the variability in average wear. The R-square statistic (adjusted for gdl), which is more suitable for comparing models with different numbers of independent variables is 99.9535%. The standard error of the estimate is 0.320284, this value can be used to build prediction limits for new observations. The absolute average error of value 0.223012 represents the average value of the residual errors. The Durbin-Watson statistic tests for residual errors to determine if there are significant correlations based on how they appear in the data file. Because the value of the statistic is greater than 0.05, there are no suspicions of serial autocorrelation in the residual errors.

The equation of the associated general linear model is given in relation (3.1.1.15):

$$\mathrm{BoxCox(average\ wear)} = 0.446041 + 3.98476 \cdot \mathrm{Q}(1) - 6.31875 \cdot \mathrm{Q}(2) + 2.76943 \cdot \mathrm{Pressure} + 0.0153058 \cdot \mathrm{revs} \quad (3.1.1.15)$$

where:

$$\mathrm{BoxCox(average\ wear)} = 1 + \frac{\mathrm{average\ wear}^{0.0403159} - 1}{0.0403159 \cdot 11.8155^{-0.959684}} \quad (3.1.1.16)$$

Q (1) = 1 if Abrasion Disk = D0; Q (1) = - 1 if Abrasion Disk = D4; Q (1) = 0 if Abrasion Disk = D2; Q (2) = 1 if Abrasion Disk = D2; Q (2) = - 1 if Abrasion Disk = D4; Q (1) = 0 if Abrasion Disk = D0.

Figure 3.1.1.40 shows the estimated (optimized) response surface for the average wear of the basalt pellets and for the abrasion disk D0

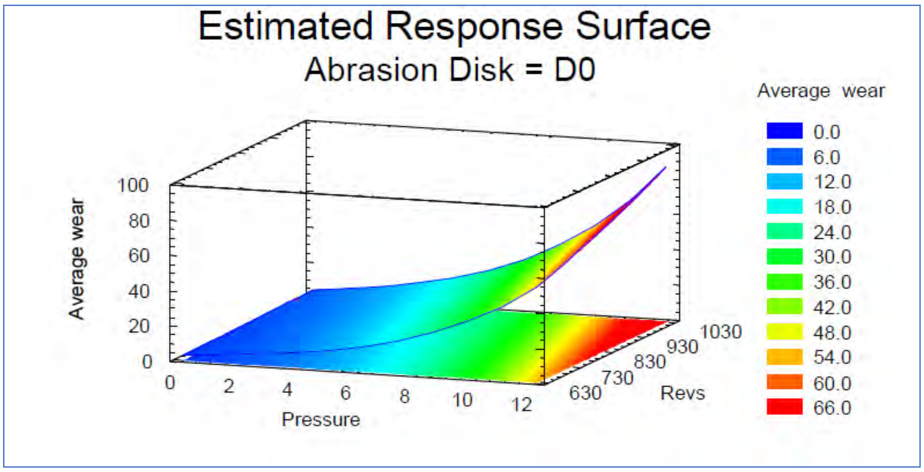


Fig. 3.1.1.40 Estimated (optimized) response surface for the average wear of the basalt pellets, abrasion disk D0

Figure 3.1.1.41 shows the estimated (optimized) response surface for the average wear of basalt pellets and the D4 abrasion disk.

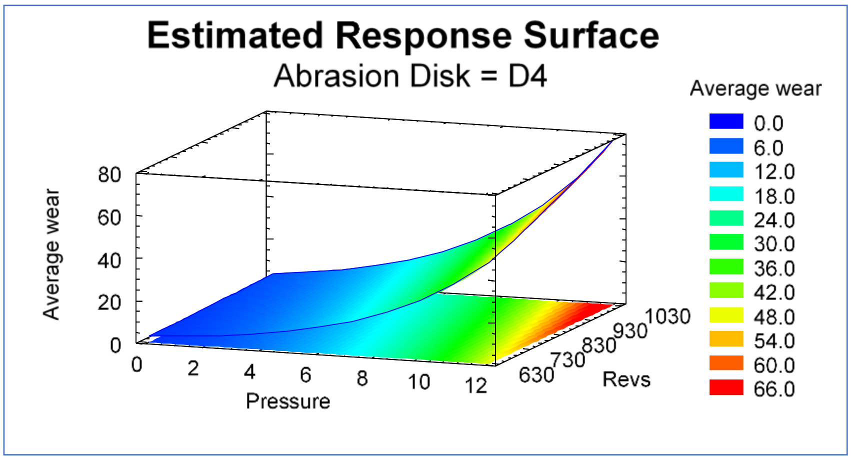


Fig. 3.1.1.41 Estimated (optimized) response surface for the average wear of basalt pellets, abrasion disk D4

Figure 3.1.1.42 shows the estimated (optimized) response surface for the average wear of basalt pellets and the D2 abrasion disk.

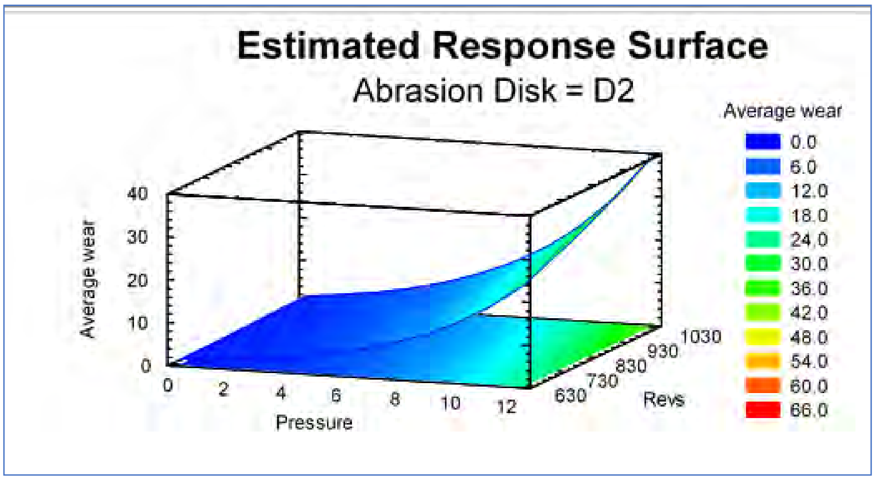


Fig. 3.1.1.42 Estimated (optimized) response surface for the average wear of basalt pellets, abrasion disk D2

➢ *The model associated with the lifetime pattern of sintered basalt pellets*

The distributions that can model the service life of sintered basalt pellets are given in table 3.1.1.26 (specifying the corresponding parameters of the assigned model).

Tab. 3.1.1.26 Distributions that can model the service life of sintered basalt pellets

Birnbaum-Saunders	Exponential	Weibull
shape = 1.33361	average = 325.271	shape = 0.919819
scale = 172.771		scale = 312.298

Figure 3.1.1.43 shows the histogram for the service life of sintered basalt pellets as well as the assigned distributions.

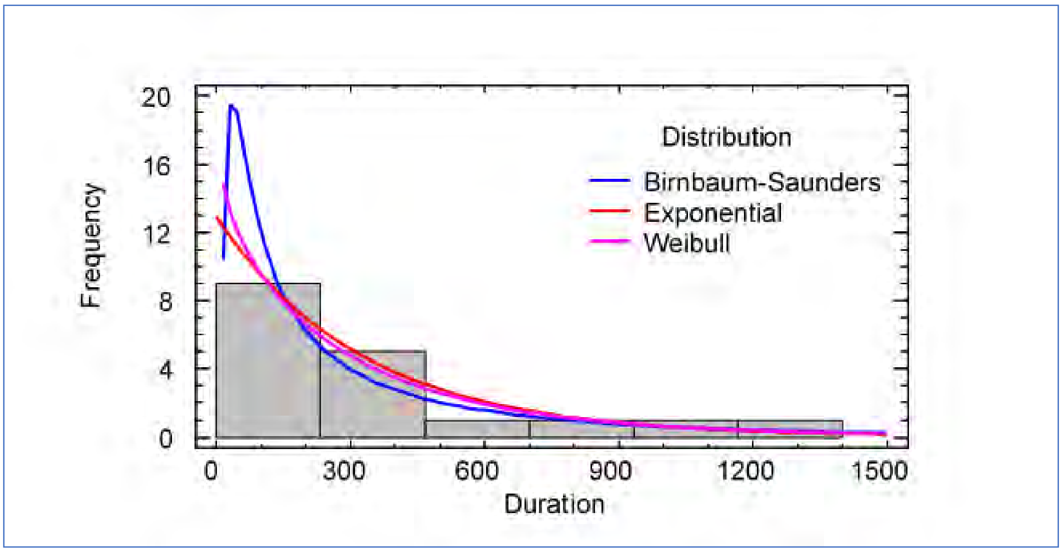


Fig. 3.1.1.43 Histogram for the service life of sintered basalt pellets and the assigned distributions

Table 3.1.1.27 presents 2 tests to verify the normality of the data corresponding to the service life of the sintered basalt pellets. The χ^2 test divides the duration domain into 12 likely equal classes and compares the number of observations in each class with the expected number. The Shapiro-Wilk test is based on comparing the assigned distribution quantiles with the data quantiles.

Since the - P values of the two tests are less than 0.05, then the idea that the “duration” comes from a normal distribution with a probability of 95% can be rejected.

Tab. 3.1.1.27 Tests to verify the normality of the data

Test	**Statistics value**	**P - -value**
χ^2 (Chi-square)	35.3333	0.0000520319
Shapiro-Wilk (W)	0.826154	0.00291285

Tables 3.1.1.28 - 3.1.1.30 present 3 tests to verify whether the analyzed data can be modeled with the assigned distributions.

Tab. 3.1.1.28 Kolmogorov - Smirnov test for the adequacy of the assigned distributions

	Birnbaum-Saunders	**Exponențial**	**Weibull**
DPLUS	0.149749	0.201737	0.170576
DMINUS	0.147235	0.0946141	0.116769
DN	0.149749	0.201737	0.170576
P - value	0.814343	0.464949	0.671519

Tab. 3.1.1.29 Cramer – Von Mises test for the adequacy of the assigned distributions

	Birnbaum-Saunders	**Exponential**	**Weibull**
W^2	0.106434	0.147527	0.112805
Modified shape	0.0908454	0.134221	0.0975702
P - value	≥ 0.10	≥ 0.10	≥ 0.10

Tab. 3.1.1.30 Watson test for the adequacy of the assigned distributions

	Birnbaum-Saunders	**Exponential**	**Weibull**
U^2	0.105968	0.135329	0.110517
Modified shape	0.105197	0.135864	0.109949
P - value	≥ 0.10	≥ 0.10	≥ 0.10

P-values less than 0.05 would indicate that the data does not come from the assigned distributions, which is not the case. Table 3.1.1.31 presents the Anderson - Darling test for ranking assigned distributions.

Tab. 3.1.1.31 Anderson – Darling test for ranking assigned distributions

Distribution	**Estimated parameters**	$\mathbf{A^2}$
Birnbaum-Saunders	2	0.601474
Weibull	2	0.664277
Exponential	1	0.868175

According to the $\mathbf{A^2}$ statistic of the Anderson - Darling test, the most suitable distribution would be Birnbaum - Saunders. But the Birnbaum - Saunders distribution describes a pattern of life distribution that derives from a fatigue process in which the growth of cracks causes the fall assuming a bell shape, more or less flattened. Therefore the most probable model is the bi-parametric Weibull model given in the relation (3.1.1.17).

$$F(x) = \frac{\gamma}{\alpha}\frac{x}{\alpha}^{(\gamma-1)} \exp\left(-\left(\frac{x^{\gamma}}{\alpha}\right)\right) \quad (3.1.1.17)$$

where γ = 0.919819 is the shape parameter și α = 312.298 is the scale parameter

The procedure for determining the regression of the lifetime is designed to assign a statistical parametric model through which to relate the life to one or more predictive factors (quantitative and absolute). First-order models (without interactions) and second-order models (with interactions) can be assigned. Considering as a dependent variable "duration" (duration until complete wear of basalt pellets) as independent variables (quantitative) revs and pressures, respectively and as an attributive variable, the abrasion disk, in the relation (3.1.1.18) is presented a Weibull first-order regression model and in relations (3.1.1.19) and (3.1.1.20) are presented 2 Weibull second-order, regression models.

The estimated values of the corresponding parameters and the tests of the likelihood ratio are presented in tables 3.1.1.32 - 3.1.1.38.

$$Duration = \exp(7.38273 - 0.231998 \cdot Pressure - 0.00130825 \cdot Revs - 0.144968 \cdot Abrasion\ Disk\ D0 + 0.728483 \cdot Abrasion\ disk\ D2) \quad (3.1.1.18)$$

Tab. 3.1.1.32 Parameters estimation for the Weibull first order regression model

Parameter	Estimation	Standard deviation	Lower limit P = 95%	Upper limit P = 95%
Constant	7.38273	0.0453026	7.29394	7.47152
Pressure	-0.231998	0.00203073	-0.235978	-0.228018
Revs	-0.00130825	0.0000554602	-0.00141695	-0.00119955
Abrasion Disk D0	-0.144968	0.0229361	-0.189922	-0.100014
Abrasion Disk D2	0.728483	0.0201764	0.688938	0.768028
Sigma	0.0316088	0.00581135	0.0220451	0.0453214

Tab. 3.1.1.33 Likelihood ratio tests for the factors of the Weibull first order regression model

Factor	χ^2	DOF	P - value
Pressure	124.383	1	0.0000
Revs	62.7153	1	0.0000
Abrasion Disk	89.09	2	0.0000

Because all P-values are less than 0.05, all factors are significant and must be maintained in the model.

$$Duration = \exp(7.52384 - 0.232136 \cdot Pressure - 0.00146929 \cdot Revs - 0.448281 \cdot Abrasion\ disk\ D0 + 0.640649 \cdot Abrasion\ disk\ D2 - 0.00000257828 \cdot Pressure \cdot Turații + 0.00690963 \cdot Presiune \cdot Abrasion\ disk\ D0 - 0.00510723 \cdot Pressure \cdot Abrasion\ disk\ D2 + 0.000312182 \cdot Revs \cdot Abrasion\ disk\ D0 + 0.00012755 \cdot Revs \cdot Abrasion\ disk\ D2) \quad (3.1.1.19)$$

Tab. 3.1.1.34 Parameters estimation for the Weibull second order regression model

Parameter	Estimation	Standard deviation	Lower limit P = 95%	Upper limit P = 95%
Constant	7.52384	0.0477802	7.43019	7.61749
Pressure	-0.232136	0.00389997	-0.23978	-0.224492
Revs	-0.00146929	0.0000496436	-0.00156659	-0.00137199
Abrasion disk D0	-0.448281	0.0505299	-0.547318	-0.349244
Abrasion disk D2	0.640649	0.046794	0.548934	0.732363
Pressure ·Turații	-0.00000257	0.000004348	-0.000011100	0.0000059443
Pressure · Abrasion disk D0	0.00690963	0.00214464	0.0027062	0.0111131
Pressure · Abrasion disk D2	-0.00510723	0.00161245	-0.00826759	-0.00194687
Revs · Abrasion disk D0	0.000312182	0.0000625813	0.000189525	0.00043484
Revs · Abrasion disk D2	0.00012755	0.0000491533	0.0000312112	0.000223889
Sigma	0.0102952	0.00208846	0.00691765	0.0153217

Tab. 3.1.1.35 Likelihood ratio tests for the factors of the Weibull second-order regression model

Factor	χ^2	DOF	P - value
Pressure	98.971	1	0.0000
Revs	73.2395	1	0.0000
Disc abraziune	66.931	2	0.0000
Pressure · Revs	0.342125	1	**0.5586**
Pressure · Abrasion disk	25.5648	2	0.0000
Revs · Abrasion disk	16.2719	2	0.0003

Because the P-value for the Pressure · Revs interaction is greater than 0.05, it is not significant and must be removed from the model.

Duration = exp (7.54023 – 0.234297 · Pressure – 0.00148698 · Revs – 0.452078 · Abrasion disk D0 + 0.634088 · Abrasion disk D2 + 0.00707316 · Pressure Abrasion disk D0 – 0.00501944 · Pressure · Abrasion disk D2 + 0.000311479· Revs · Abrasion disk D0 + 0.000133329 · Revs · Abrasion disk D2) (3.1.1.20)

Tab. 3.1.1.36 Parameters estimation for the Weibull second-order regression model (modified)

Parameter	Estimation	Standard deviation	Lower limit P = 95%	Upper limit P = 95%
Constant	7.54023	0.0436413	7.45469	7.62576
Pressure	-0.234297	0.00154478	-0.237325	-0.231269
Revs	-0.00148698	0.0000438595	-0.00157294	-0.00140101
Abrasion disk D0	-0.452078	0.0531763	-0.556302	-0.347855
Abrasion disk D2	0.634088	0.0505692	0.534974	0.733202
Pressure · Abrasion disk D0	0.00707316	0.00214263	0.00287368	0.0112726
Pressure · Abrasion disk D2	-0.00501944	0.00178679	-0.00852148	-0.00151739
Revs · Abrasion disk D0	0.000311479	0.000063158	0.000187692	0.000435267
Revs · Abrasion disk D2	0.000133329	0.0000525517	0.0000303295	0.000236329
SIGMA	0.0104458	0.00210808	0.00703331	0.015514

Tab. 3.1.1.37 Likelihood ratio tests for the factors of the Weibull second-order regression model (modified)

Factor	χ^2	DOF	P - value
Pressure	134.452	1	0.0000
Revs	77.463	1	0.0000
Abrasion Disk	67.0675	2	0.0000
Presiune· Abrasion Disk	26.5194	2	0.0000
Revs· Abrasion Disk	16.1991	2	0.0003

Because all - P values are less than 0.05, all factors are significant and must be maintained in the model. Figures 3.1.1.44 - 3.1.1.49 show the first-order Weibull model for abrasion disks, keeping speed and pressure constant in turn.

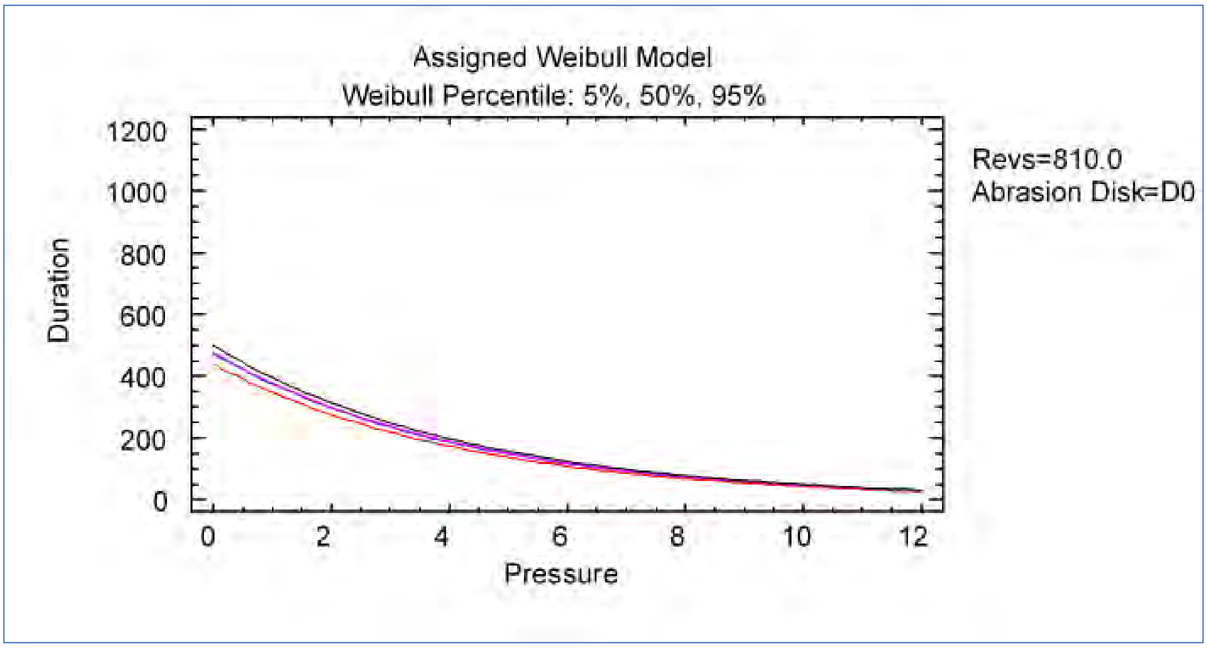


Fig. 3.1.1.44 Weibull first order model assigned for the D0 abrasion disk (Revs maintained at 810 rpm)

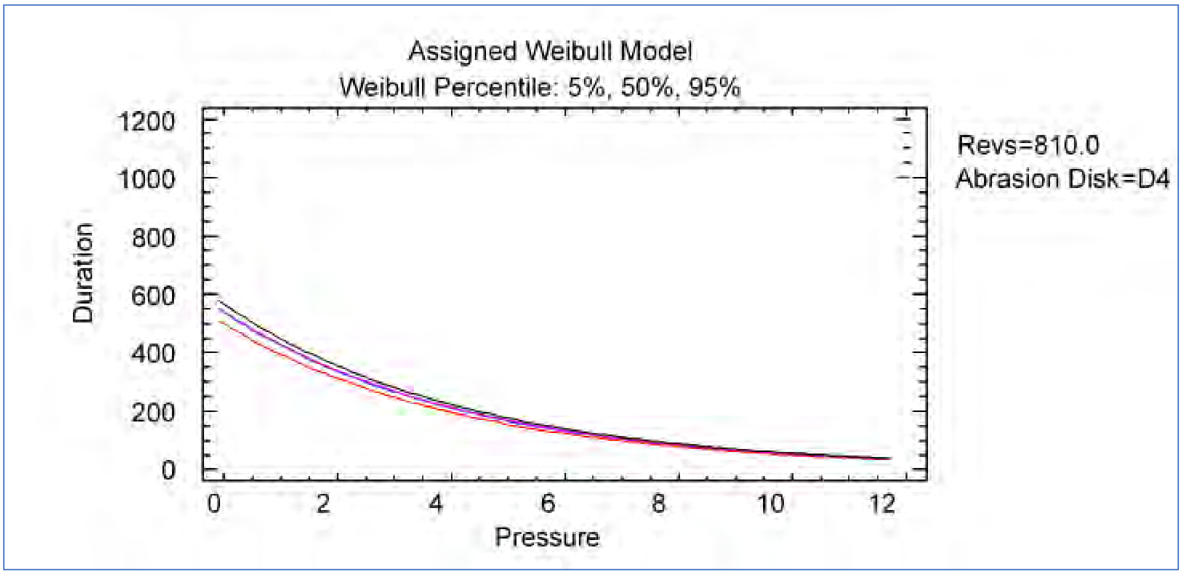


Fig. 3.1.1.45 Weibull first order model assigned for the D4 abrasion disk (Revs maintained at 810 rpm)

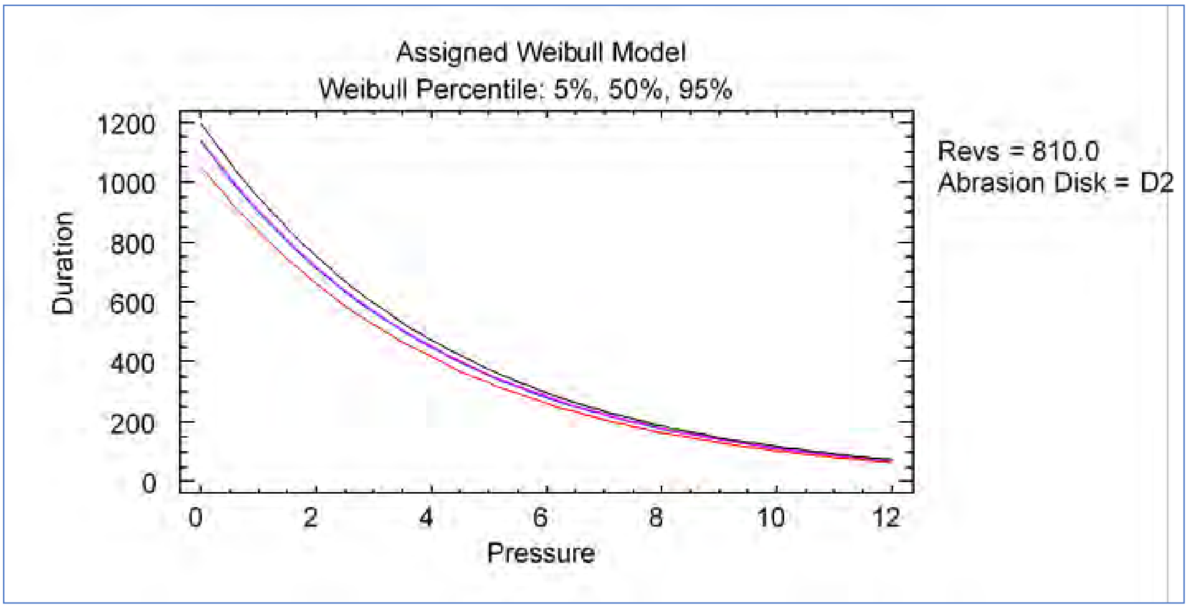


Fig. 3.1.1.46 Weibull first-order model assigned for the D2 abrasion disk (Revs maintained at 810 rpm)

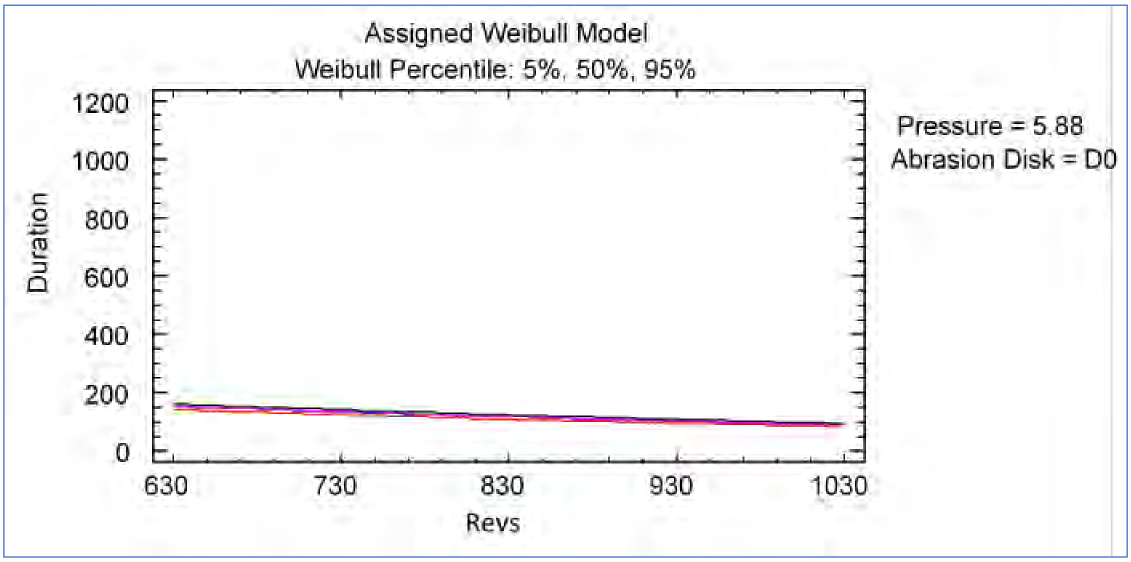


Fig. 3.1.1.47 Weibull first-order model assigned for the D0 abrasion disk (pressure maintained at 5.88 daN/cm^2)

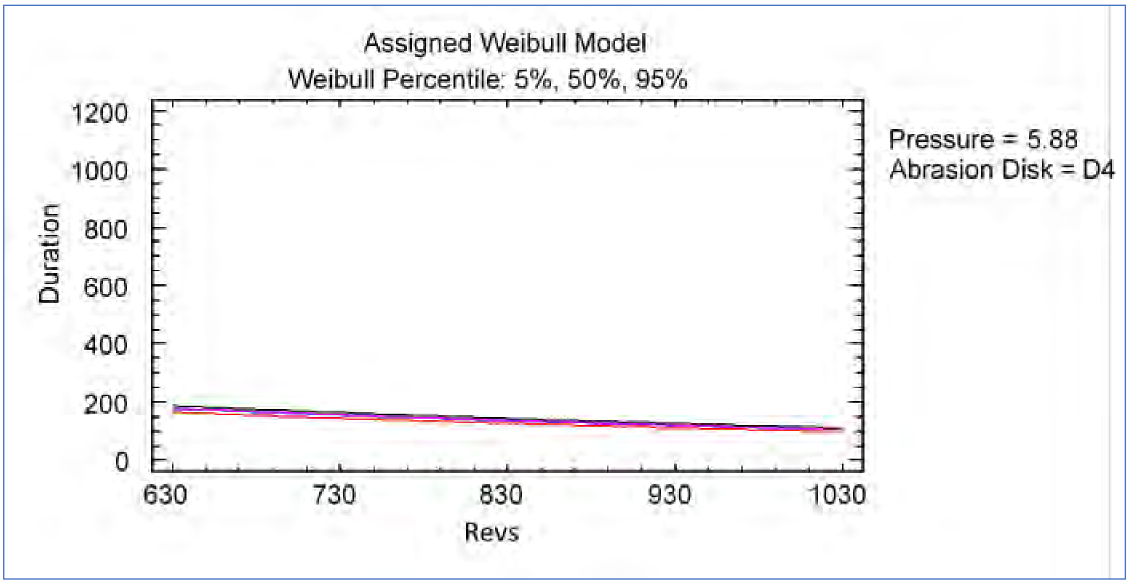


Fig. 3.1.1.48 Weibull first-order model assigned for the D4 abrasion disk (pressure maintained at 5.88 daN/cm^2)

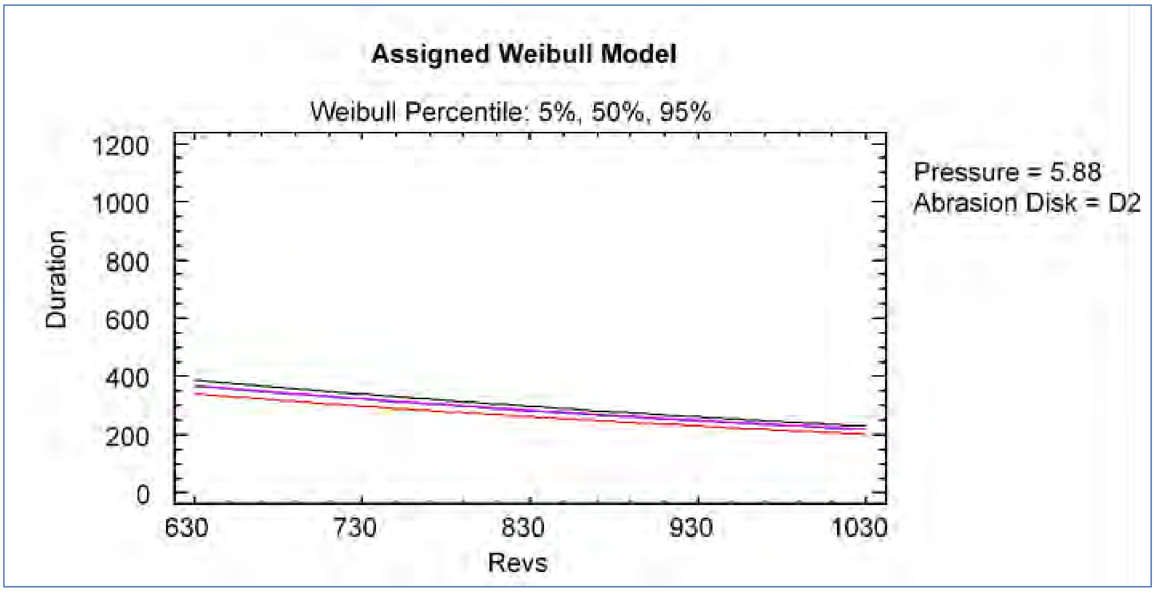


Fig. 3.1.1.49 Weibull first-order model assigned for the D2 abrasion disk (pressure maintained at 5.88 daN/cm^2)

3.1.2 Applying Experimental Design to Ag-doped TiO_2 Doped Nanoparticles

Based on earlier researches, (Pugna, 2005), (Pugna, Mocan, Negru - Străuţi, Giuca., 2011), (Giuca, Grozescu., 2011), (Giuca, Nicoara, Grozescu., 2012), (Tărbăț, 2012), Giuca and Pugna (2013) presented a method for improving dimensional stability of Ag doped TiO_2 nanoparticles through experimental design.

Titanium dioxide (TiO_2) has been intensively used as a photocatalyst (see an overview and prospects of TiO_2 photocatalysis in Sadarna et al., 2009). It also has many applications for environmental protection, such as atmospheric pollution control, sewerage treatment, etc. (See a review in Lăzău et al., 2011). Nowadays special interest is paid to the elaboration of adequate techniques of synthesis, for instance, the microwave-hydrothermal (M-H) and fast hydrothermal methods (Lăzău et al, 2009 and Lăzău et al, 2001), to facilitate a strict control of nanoparticles dimensions. Compared with other antimicrobial agents, TiO_2 nanoparticles, used in microbiology and medicine, attracted much attention because of their adequate stability but also because they are environmentally benign, safe, cheap, nontoxic, bioactive, etc. Also, TiO_2 has great catalytic potential, serving as an active redox agent for water and air purification. To be efficient, Ag-doped TiO2 nanoparticles must have certain features such as high purity and unitary chemical composition; besides, their dimensions must enroll in a uniform, narrow and controllable distribution, form, and morphology. In addition to obtaining nanocrystals by such methods as sol-gel, spray-pyrolysis, precipitation, solvothermal, electrochemical, combustion, etc., there is another method that has many advantages, namely, the hydrothermal method. The main advantages of this method are as follows: due to high pressures it allows syntheses at lower temperatures than at room temperature, crystallization duration is relatively low, synthesis conditions can be easily replicated, energy consumption is low, etc. However, it has certain drawbacks, such as low crystallization speed and the absence of an effective agitation of the solution to deliver germ of crystallization with fresh nutrients from the solution. Then, thermal inertia is high because heating and cooling processes take place through autoclave steel walls As the heating gradient is low some unwanted transitory processes may appear, such as premature crystallizations and dimensional stability of nanoparticles, which cannot be controlled rigorously. Some of those drawbacks can be eliminated by using a microwave field as the heating method. While manufacturing the autoclave permeable to microwaves (usually electromagnetic radiation with approximately 2.45 GHz) from materials like Pyrex glass or quartz, conductive solvents from the solution will absorb energy and therefore will be quickly heated from inside. Moreover, heating becomes more uniform if the autoclave is rotated in the microwave Owen. Thus, stationary processes are eliminated due to fast heating and working temperature can be achieved in minutes and maintained constant by controlling the magnetron emission power. Thermal agitation and chemical activation induced by electromagnetic radiation increase the reaction speed, nucleation centers numbers are higher and convection currents efficiently replenishes nuclei with fresh nutrient. In this way, nanoparticles will be produced having low dimensional dispersion due to the high speed of recrystallization, a large number of nanoparticles growing simultaneously and very fast.

- *Method of Obtaining Ag-doped TiO_2 Nanoparticles synthesized through M-H (Lăzău et al., 2008)*

Into a Berzelius glass, 40 ml of ethyl alcohol were added, on top of which 10 ml of titanium isopropoxide under continuous stirring were dropped. After a few minutes of continuous stirring, 45 ml of double-distilled water were added. The initial pH of the solution was 5.5 and the adjustment to the final pH (according to the experimental design) was obtained with nitric acid. Then a nutrient, silver nitrate, was added. When titanium isopropoxide is added on ethyl acid, a solid white precipitate is obtained. Before thermal treatment, the precipitate was washed with distilled water, filtered, and dried at 600°C for 10 hours. There were performed preliminary experiments, synthesized Ag-doped TiO_2 probes, and controlled factors are presented in table 3.1.2.1.

Tab. 3.1.2.1 Parameters of Ag-doped TiO2 probe synthesized through M-H method

Samples	Ag concent-ration [%]	Auto-claving dura-tion [min]	Autocla-ving tempera-ture [^{0}C]	Micro-wave owen power [W]
$P1_{M-H}$(15-150-800)	2	15	150	800
$P2_{M-H}$ (30-150-800)	2	30		
$P3_{M-H}$(15-200-1000)	2	15	200	1000
$P4_{M-H}$ (30-200-1000)	2	30		
$P5_{M-H}$ (15-150-800)	3	15	150	800
$P6_{M-H}$ (30-150-800)	3	30		
$P7_{M-H}$ (15-200-1000)	3	15	200	1000
$P8_{M-H}$ (30-200-1000)	3	30		

After autoclaving, the obtained material was filtered and washed with distilled water to remove secondary reaction compounds. The filtered and washed material was dried at 60°C for 6 hours. Verification of the presence of Ag ions in the washing solution has been done by using calcium chloride. No AgCl precipitate has been observed, thus meaning that all Ag quantity has been consumed in the reaction. X-ray diffraction (XRD) spectra for Ag-doped TiO2, autoclaved at temperatures of 150°C or 200°C for 15 and 30 minutes, synthesized through the M-H method, are presented in figures 3.1.2.1 and 3.1.2.2.

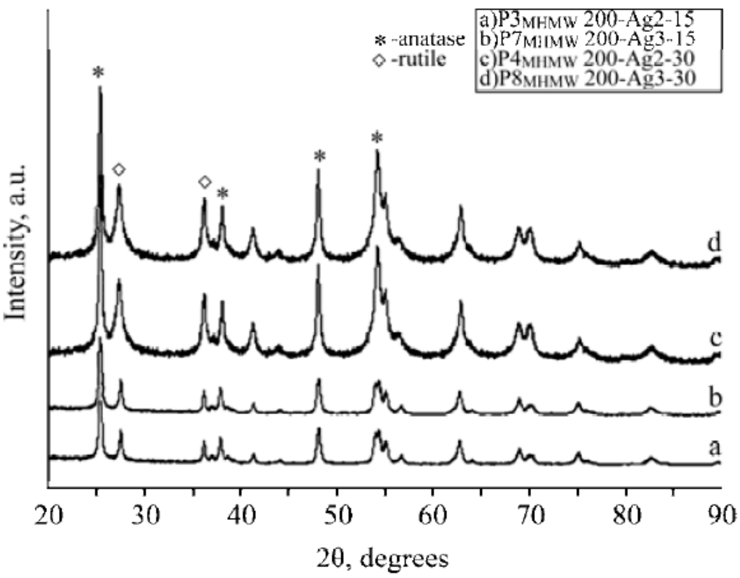


Fig. 3.1.2.1 XRD spectra for P3M-H 200-Ag2-15 (a), P7M-H200-Ag3-15 (b), P4M-H 200-Ag2-30 (c) and P8M-H200-Ag3-30 (d), synthesized through the M-H method

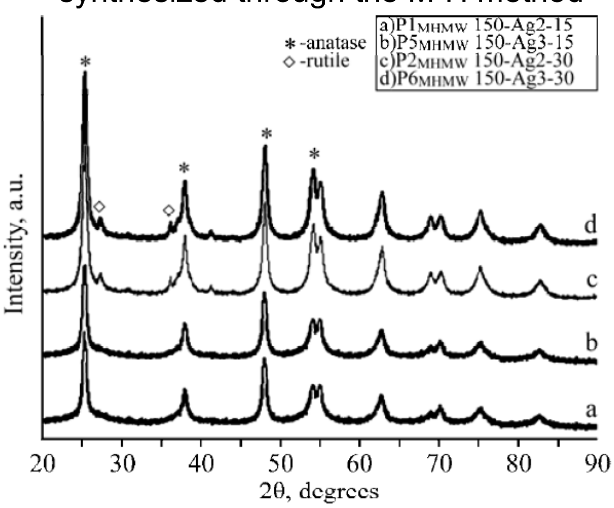


Fig. 3.1.2.2 XRD spectra for P1M-H 150-Ag2-15 (a), P5M-H 150-Ag3-15 (b), P2M-H 150-Ag2-30 (c) and P6M-H150-Ag3-30 (d), synthesized through the M-H method

In autoclaving at 200°C for 15 minutes, a phase transition is taking place for TiO_2 doped both with 2% Ag (Fig. 3.2.1.1a) and with 3% Ag (Fig. 3.2.1.1b), resulting in a mixture of anatase and rutile phases. When autoclaving duration increases up to 30 minutes, anatase becomes more unstable and phase transition is more pronounced (Figures 3.1.2.1c and 3.1.2.1d). In autoclaving at 150°C for 15 minutes, for both TiO_2 doped with 2% Ag (Fig. 3.1.2.2a) and with 3% Ag (Fig. 3.1.2.2b), a single crystalline phase is obtained, namely, anatase. After autoclaving for 30 minutes, at the same temperature of 150°C, anatase phase passes progressively into rutile one (Fig. 3.1.2.2c and 3.1.2.2d). With the spectral analysis, it is noted that there are no significant changes in the crystalline phases irrespective of the amount of a dopant.

The conclusion drawn from these results is that the structure and crystalline form of Ag-doped TiO_2 nanoparticles synthesized through M-H metho is, in the first case, influenced by the dopant quantity, thermal treatment, and autoclaving parameters. In table 3.1.2.2 the average dimensions of nanoparticles are presented, calculated with the Debye-Scherrer equation (relation 3.1.2.1):

$$D = \frac{K \cdot \lambda}{\beta \cdot \cos\theta} \qquad (3.1.2.1)$$

where: λ – the wavelength of the X-ray radiation (λ = 0.15406 nm); K – the Scherrer constant (K = 0.89); θ – the diffraction angle; β – the line width at half maximum height for different peaks from diffractogram

Tab. 3.1.2.2 Average dimensions of Ag-doped TiO2 nanoparticles synthesized through M-H method

Material type	Nanoparticles dimension (nm)
$P4_{M\text{-}H}$ (30-200-1000)	10.1
$P8_{M\text{-}H}$ (30-200-1000)	9.9

Figure 3.1.2.3 presents the SEM image and EDAX spectrum for TiO2 doped with 2% Ag synthesized through the M-H method.

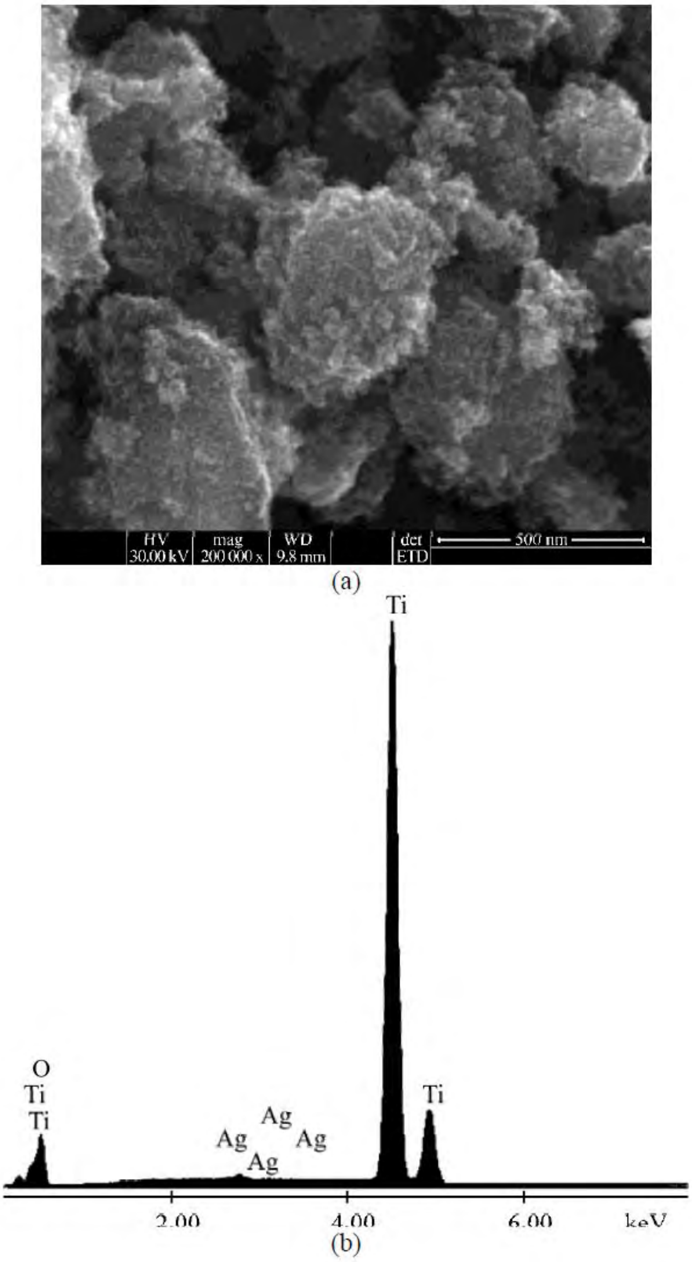


Fig. 3.1.2.3 SEM surface morphology (a); EDAX spectrum (b) for P4M-H (30-200-1000)

- *Applying Taguchi Robust Design for Dimensional Stability of Ag-doped Tio2 Nanoparticles (M-H method)*

The Design of Experiments usually consists of performing a fixed aprioristic number of experiments to determine, with minimum attempts and maximum precision, possible influences of different factors on the optimization of system performance (Alexis, 1999). Based on the initial results, it has been decided to use the Taguchi **L_8** experimental design, consisting of an orthogonal fractional factorial design. An orthogonal fractional factorial design consists of much fewer experiments than a full factorial design but its drawback is offering a smaller amount of information. Thus, besides the four control factors determined initially: dopant (Ag) concentration, autoclaving duration, autoclaving temperature, and microwave oven power, three more factors were added: nutrient quantity, pH of the solution, and autoclave filling degree. The actual design consisted of 8 experiments on which 7 factors were studied at 2 levels, the system response (to be improved) considering nanoparticle dimensions, as shown in table 3.1.2.3.

Tab. 3.1.2.3 Control factors and levels

No.	Description of factor	Level 1	Level 2
1	Dopant (Ag) concentration	2%	3%
2	Autoclaving duration	15 min	30 min
3	Autoclaving temperature	150°C	200°C
4	Microwave owen power	800 W	1000 W
5	Nutrient quantity	10 g	20 g
6	Solution pH	2.5	2.8
7	Autoclave filling degree	50%	60%

The objective of these 8 experiments was to determine the best combination of factors to achieve dimensional stability of Ag-doped TiO_2 nanoparticles, according to the target value of 10 ± 0.2 nm. Using Qualitek-4 statistical package experimental conditions were randomly established. The experiments were performed, results (nanoparticles dimension) obtained in 8 experiments. Actual values were: General mean = 9.987 nm, Standard deviation = 0.132, Average S/N ratio 17.806 dB. By analyzing the average effects of the factors on the S/N ratio and their interactions, the optimal condition was determined, as shown in table 3.1.2.4.

Tab. 3.1.2.4 Optimal condition based on average effects of factors

Factors	Level
Dopant (Ag) concentration	2
Autoclaving duration	2
Autoclaving temperature	1
Microwave owen power	2
Nutrient quantity	2
Solution PH	2
Autoclave filling degree	2

To determine the influences of significant factors, variance analysis was performed, namely ANOVA. Under analysis were optimal and performance conditions, with the due account of the comparison of parameters of current and improved conditions. It was also established that the factor "Solution pH" is not statistically significant and therefore can be eliminated from the model (actually it can have any of the two levels). The factors' importance order and corresponding percentage are presented in table 3.1.2.5.

Tab. 3.1.2.5 Factors importance order

Order of importance	Factors	Percentage [%]
1	Autoclave temperature	26.869
2	Autoclave filling degree	24.368
3	Microwave owen power	20.096
4	Dopant (Ag) concentration	20.020
5	Autoclaving duration	5.687
6	Nutrient quantity	2.901
7	Error/other	0.391
		TOTAL = 100%

Also, two confirmation experiments (with factor's levels as previously determined) were also performed, thus presenting the statistical parameters of experiments and their capability indices. The calculated values are those for optimum condition, are consistent with those calculated in average effects and interactions of factors. Factors total contribution is 3.12; performance current general average for S/N ratio = 17.806 dB; an expected result at optimum conditions for S/N ratio = 20.927 dB. For a confidence degree of P = 95% (significance level α = 1 - P = 5%), confidence interval Δ is calculated according to relation (3.1.2.2):

$$\Delta = \pm\sqrt{\frac{F(n_1,n_2)\cdot V_3}{N_e}} \quad (3.1.2.2)$$

where: $F(n_1, n_2)$ = 1.6 (calculated value), n_1 = 1 (error degree of freedom), n_2 = 1, V_e = 0.00816 (error variance), N_e = 1.14 (replications number), factors degree of freedom (DOF = 6) as included in estimation.

The value of Δ = ± 0.107 resulted in a confidence interval and therefore an expected value for S/N ratio at an optimum of 20.927 ± 0.107, meaning a confidence interval of [20.820; 21.034]. Thus, the expected value expressed in quality characteristics (nanoparticles dimension) units, based on S/N ratio of 21.034 (optimum value), is $Y_{expected}$ = 10 ± 0.089 nm, meaning a confidence interval of [9.911; 10.089] nm.

Another way of showing performance improvement is to present modifications which occur in the normal distribution. Thus, an improved S/N ratio at the optimum condition corresponds to a reduction in the standard deviation. Figure 3.1.2.4 presents the normal distribution for current and improved conditions assuming that the optimum performance is a target; control limits are at ± 3σ at improved condition, the standard deviation is directly proportional to the S/N ratio modification.

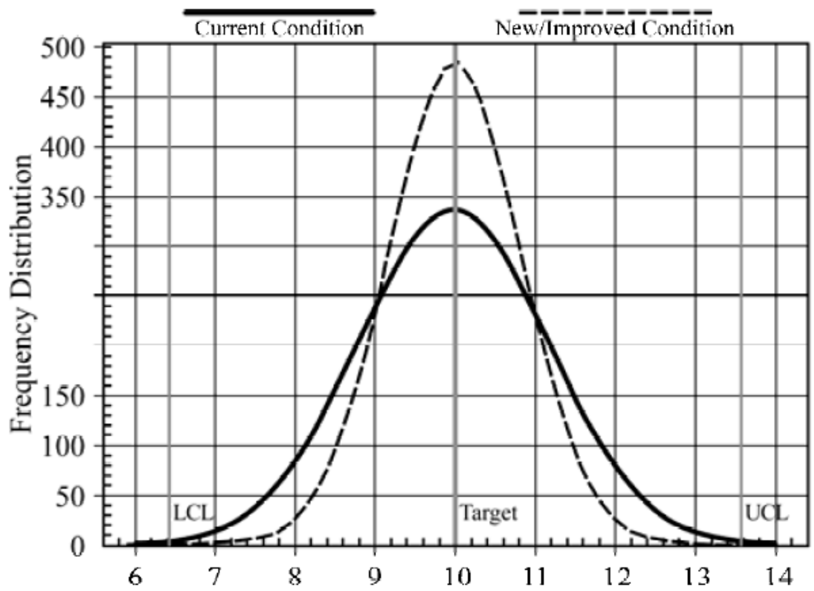


Fig. 3.1.2.4 Variation reduction plot for improved conditions based on normal distribution

Table 3.1.2.6 presents, by comparison, the parameters situation at current and improved conditions

Tab. 3.1.2.6 Parameters values at improved versus current conditions

Initial experiment	Current conditions	Predicted conditions
S/N ratio	17.806	20.927
Mean	9.987	10
Standard deviation	1.19	0.83
Cp	1	1.432
Cpk	0.996	1.432
Savings	–	51.2 cents/1$ loss

- *Applying Full Factorial Simulation for Dimensional Stability of Ag-Doped Tio2 Nanoparticles (M-H method)*

To determine whether the error was made in fractioning the experimental design (8 experiments), a full factorial simulation (2^7 = 128 experiments) was performed. There is a possibility to work with predefined equations that can be solved in complete factorial conditions (all possibilities). The following notations were used: Y – Nanoparticles dimension; A – Dopant concentration; B – Autoclaving duration; D – Autoclaving temperature; E – Microwave oven power; F – Nutrient quantity; G – Solution pH; F – Autoclave filling degree.

Assuming that the characteristic equation represents the system behavior, the maximum value obtained from the full factorial experiment combinations may be considered as an exact solution with which the solution obtained from the **L_8** experimental plan can be compared. Also, performance at optimum conditions can be compared with an exact solution to determine the **L_8** experimental plan prediction correctness. More than 2500 simulations were performed and the obtained linear characteristic equation is presented in relation (3.1.2.3).

$$Y = 0.425 \cdot A + 0.025 \cdot B + 0.001 \cdot C + 0.00225 \cdot D + 0.045 \cdot E + 0.485 \cdot F + 0.004575 \cdot G \qquad (3.1.2.3)$$

Table 3.1.2.7 visualizes a comparison between the calculated values obtained from the full factorial experiment simulation and the values obtained from the $\mathbf{L_8}$ experiment. One can notice that the maximum relative error is - 3.87%

Tab. 3.1.2.7 Values comparisons between full factorial experiment simulation and $\mathbf{L_8}$

Full factorial simulation experiment number	L_8 experi-ment number	Calculated value (simula-tion)	Average value calculated (L_8)	Relative error [%]
1	1	9.48	9.862	- 3.87
16	2	9.98	10.030	- 0.49
52	3	9.95	9.846	1.05
61	4	10.25	10.150	0.98
86	5	10.31	10.074	2.34
91	6	10.00	9.878	1.23
103	7	9.87	9.996	-1.26
106	8	10.18	10.040	1.39

- *Applying Response Surface Methodology Design for Dimensional Stability of Ag-doped TiO_2 Nanoparticles (M-H method)*

The Response Surface Methodology (RSM) was applied by using a Draper-Lin small compositional design (40 experiments) in a single block (including two central points per block) with four degrees of freedom for error. The regression equation of the first-order model (relation 3.1.2.4) was determined, the results being estimated accordingly.

$$Y = 0.966292 + 0.000378769 \cdot A + 0.00006648469 \cdot B + 0.00108788 \cdot C + 0.00020 \cdot D + 0.00130976 \cdot E + 0.0354602 \cdot F + 0.0463939 \cdot G \quad (3.1.2.4)$$

The main effects of factors were estimated as well as the standard deviation for each effect (which is measuring the sampling error). Table 3.1.2.8 presents, by comparison, the order of importance of factors, obtained through Taguchi ($\mathbf{L_8}$) and

RSM (Draper- Lin) designs. One can see that the first 3 factors are considered as main factors (in that order) for both designs. Under analysis were predictions with the gradient method (steepest ascent method) and an optimized combination of factors levels for the Draper-Lin design.

Tab. 3.1.2.8 Factors importance order obtained through Taguchi and RSM designs

Order of importance	Taguchi L_8	Draper-Lin
1	Autoclaving temperature	Autoclaving temperature
2	Autoclave filling degree	Autoclave filling degree
3	Microwave owen power	Microwave owen power
4	Dopant (Ag) concentration	Nutrient quantity
5	Autoclaving duration	Solution pH
6	Nutrient quantity	Autoclaving duration
7	Solution pH	Dopant (Ag) concentration

Figure 3.1.2.5 is showing the Estimated Response Surface for Ag-doped TiO_2 nanoparticles dimension as a function of the Autoclaving temperature and Autoclave filling degree, the rest of the factors being kept at their average value.

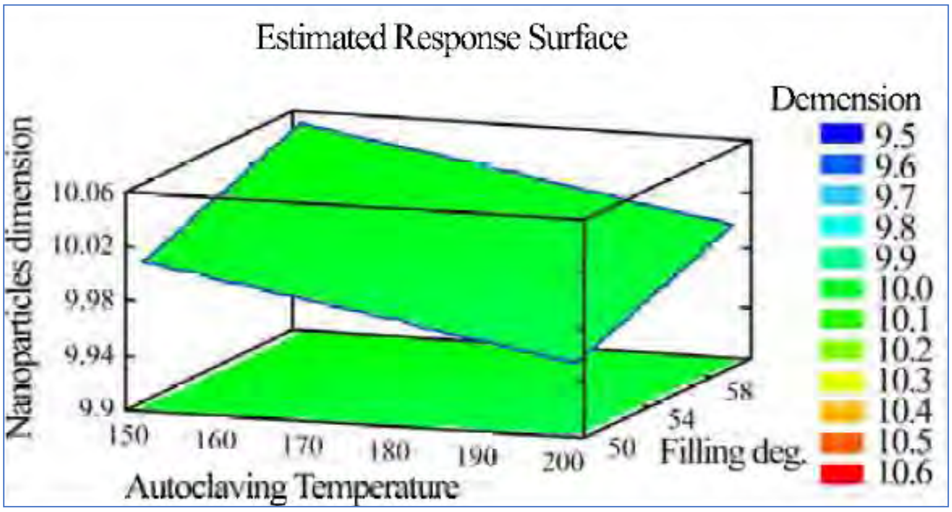


Fig. 3.1.2.5 Estimated Response Surface for Ag-doped TiO2 nanoparticles dimensions – RSM (Draper-Lin) design

The M-H method used to synthesize Ag-doped TiO_2 nanoparticles eliminates some of the major drawbacks of other methods of synthesis. To achieve dimensional stability (one of the most important features of Ag-doped TiO_2 nanoparticles), certain initial experiments were performed showing that four controllable factors are very important. Moreover, it was established that there are three more factors with a major influence on dimensional stability. To determine the order of the factors of influence upon dimensional stability of Ag-doped TiO_2 nanoparticles, two different designs of experimentation were used: the Taguchi **L_8** fractional factorial design (8 experiments) and the RSM (Draper-Lin small compositional design) in 40 experiments. It has been demonstrated that the error made by using a fractional design (**L_8**) instead of full factorial design (27 = 128 experiments) is relatively small. Moreover, the 40 experiments of Draper-Lin design demonstrated the same importance and order of factors as **L_8** design.

- *Method of Obtaining Ag-doped TiO_2 Nanoparticles synthesized through Fast Hydrothermal Method (F-H method)*

Into a Berzelius glass, there were added 44 ml of ethyl alcohol, on top of which have been dropped 6 ml of titanium isopropoxide under continuous stirring. Silver nitrate has been added as a dopant solution. Dopant has been added after adjusting pH with a nitric acid solution. The thermal treatment has been carried out in the thermostatic chamber filled with silicone oil at a temperature of 150°C for 15 and at a temperature of 200°C for 30 minutes. It should be pointed out that before the autoclave introduction into the oil from the thermostatically controlled chamber; the oil has been pre-heated at a temperature of 150°C, respectively 200°C. Obtained materials have been filtered, washed extensively with distilled water to help remove the secondary reaction breakdown products. Drying filtrate has been carried out in the oven for 6 hours at a temperature of 60°C. Checking for the presence of silver ions in the washing solution was carried out with calcium chloride. It was not noticed the AgCl precipitate formation, which means that the entire quantity of Ag has reacted. There were performed preliminary experiments, synthesized Ag-doped TiO2 probes, and controlled factors are presented in table 3.1.2.9. After autoclaving, the obtained material was filtered and washed with distilled water to remove secondary reaction compounds. Verification of Ag ions presence into the washing solution has been done by using calcium chloride. It has not been observed any AgCl precipitate, meaning that all Ag quantity has been consumed in the reaction. The conclusion drawn from these results is that structure and crystalline form of Ag-doped TiO_2 nanoparticles synthesized through F-H are, in the first instance, influenced by dopant quantity and thermal treatment.

Tab. 3.1.2.9 Parameters of Ag-doped TiO_2 samples, synthesized through F-H method

Samples	Ag. Conc. [%]	Autoclaving duration [min.]	Autoclaving temperature [^{0}C]
P1FH (15-150)	2	15	150
P2FH (30-150)	2	30	
P3FH (15-200)	2	15	200
P4FH (30-200)	2	30	
P5FH (15-150)	3	15	150
P6FH (30-150)	3	30	
P7FH (15-200)	3	15	200
P8FH (30-200)	3	30	

In table 3.1.2.10 are presented the average dimensions of nanoparticles, calculated with Debye - Scherrer equation (relation 3.1.2.1).

Tab. 3.1.2.10 Average dimensions of Ag-doped TiO_2 nanoparticles synthesized through F-H method

Material type	Nanoparticles dimension [nm]
P4FH (30-200)	5.1
P8FH (30-200)	4.8

- *Applying Taguchi's robust design for dimensional stability of Ag-doped TiO_2 nanoparticles (F-H method)*

Based on the initial results, it has been decided to use a Taguchi's $\mathbf{L_9}$ experimental design, consisting of an orthogonal fractional factorial design. An orthogonal fractional factorial design consists of much lesser experiments than a full factorial design but by the drawback of offering a smaller amount of information. Thus, besides the 3 control factors determined initially, dopant (Ag) concentration (A), autoclaving time (B), and autoclaving temperature (C), there was added 1 more factor, microwave oven power (D). The actual design consists of 9 experiments on which the 4 factors were studied at 3 levels, system response (to be improved) being considered the nanoparticle dimension, as shown in table 3.1.2.11.

Tab. 3.1.2.11 Factor levels and experimental results under standard Taguchi $\mathbf{L_9}$ matrix

Sample	A [%]	B [min]	C [ºC]	D [W]	Dimension [nm]
1	2	15	150	800	4.82
2	2	30	200	1000	4.9
3	2	45	250	1200	5.13
4	3	15	200	1200	5.01
5	3	30	250	800	4.88
6	3	45	150	1000	4.81
7	4	15	250	1000	5.02
8	4	30	150	1200	5.04
9	4	45	200	800	5.04

The objective of these 9 experiments is to determine the best factors combination to achieve dimensional stability of Ag-doped TiO_2 nanoparticles, according to a target value of 5 ± 0.2 nm. Using StatGraphics statistical package there were randomly established experimental conditions. To determine the influences of significant factors, variance analysis was performed, namely ANOVA (Fig. 3.1.2.6).

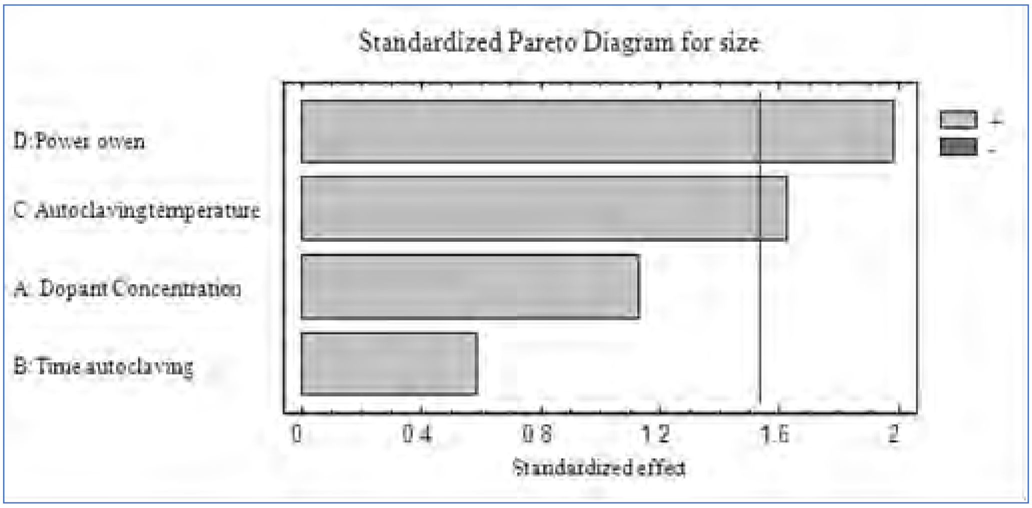


Fig. 3.1.2.6 Standardized Pareto Diagram for factors effect

The obtained linear characteristic equation is presented in relation (3.1.2.5):

$$\mathrm{Size_{nanoparticles}}[\mathrm{nm}] = 4.18611 + 0.41667 \cdot \mathrm{Concentration_{dopant}}[\%] + 0.00144444 \cdot \mathrm{Time_{autoclaving}}[\mathrm{min}] + 0.0012 \cdot \mathrm{Temperature_{autoclaving}}[C] + 0.000366667 \cdot \mathrm{Power_{oven}}[\mathrm{W}] \quad (3.1.2.5)$$

Table 3.1.2.12 presents pieces of information on the size of nanoparticles generated by the order I model associated with experimental plan **L_9**, measured values, their predicted values, and their limits with a probability of 95%.

Tab. 3.1.2.12 Measured values, predicted values and their limits associated with **L_9**

No.	Measured values	Predicted values	Predicted lower limit P = 95%	Predicted upper limit P = 95%
1	4.82	4.76444	4.54275	4.98614
2	4.9	4.91944	4.78696	5.05193
3	5.13	5.07444	4.85275	5.29614
4	5.01	5.01278	4.84519	5.18036
5	4.88	4.94778	4.78019	5.11536
6	4.81	4.92278	4.75519	5.09036
7	5.02	5.04111	4.8446	5.23762
8	5.04	5.01611	4.8196	5.21262
9	5.04	4.95111	4.7546	5.14762

Optimum conditions (Table 3.1.2.13) represent the predictive equation for performance at the optimal conditions and any other possible condition. The calculated values presented in the table are those for optimal conditions. It can be observed that the levels of factors at optimum condition are consistent with ones presented in average effects and interactions of factors previously presented.

Tab. 3.1.2.13 Optimized combination of factors levels for **L_9**

Factor	Min	Max	Optimum	Optimal value
Dopant concentration	2.0	4.0	2.96591	5
Autoclaving time	15.0	45.0	30.0915	
Autoclaving temperature	150.0	250.0	212.838	
Oven power	800.0	1200.0	1067.56	

- *Applying Response Surface Methodology Design for Dimensional Stability of Ag-doped TiO_2 Nanoparticles (F-H method)*

Response Surface Methodology was applied using a Box-Behnken experimental plan, running 27 experiments in 3 blocks, including a central point on each block. Box-Behnken experimental plan is completely randomized, the number of freedom degrees for error is equal to 10. In relation (3.1.2.6), the second-order regression equation is presented, according to Box-Behnken experimental plan.

$$\begin{aligned}
&\mathrm{Size}_{\mathrm{nanoparticles}}[\mathrm{nm}] = 4{,}72958 - 0{,}326667 \cdot \mathrm{Concentration}_{\mathrm{dopant}}[\%] + \\
&+ 0{,}0290556 \cdot \mathrm{Time}_{\mathrm{autoclaving}}[\mathrm{min}] - 0{,}00748333 \cdot \mathrm{Temperature}_{\mathrm{autoclaving}}[^{\circ}\mathrm{C}] + \\
&+ 0{,}00138333 \cdot \mathrm{Power}_{\mathrm{oven}}[\mathrm{W}] + 0{,}04125(\mathrm{Concentration}_{\mathrm{dopant}}[\%])^2 - \\
&- 0{,}00883333 \cdot \mathrm{Concentration}_{\mathrm{dopant}}[\%] \cdot \mathrm{Time}_{\mathrm{autoclaving}}[\mathrm{min}] + \\
&+ 0{,}0007 \cdot \mathrm{Concentration}_{\mathrm{dopant}}[\%] \cdot \mathrm{Temperature}_{\mathrm{autoclaving}}[^{\circ}\mathrm{C}] + \\
&+ 0{,}0002125 \cdot \mathrm{Concentration}_{\mathrm{dopant}}[\%] \cdot \mathrm{Power}_{\mathrm{oven}}[\mathrm{W}] + \\
&+ 0{,}000111111 \cdot (\mathrm{Time}_{\mathrm{autoclaving}}[\mathrm{min}])^2 - \\
&- 0{,}00000333333 \cdot \mathrm{Time}_{\mathrm{autoclaving}}[\mathrm{min}] \cdot \mathrm{Temperature}_{\mathrm{autoclaving}}[^{\circ}\mathrm{C}] - \\
&- 0{,}0000075 \cdot \mathrm{Time}_{\mathrm{autoclaving}}[\mathrm{min}] \cdot \mathrm{Power}_{\mathrm{oven}}[\mathrm{W}] + \\
&+ 0{,}00003235 \cdot (\mathrm{Temperature}_{\mathrm{autoclaving}}[^{\circ}\mathrm{C}])^2 - \\
&- 0{,}00000675 \cdot \mathrm{Temperature}_{\mathrm{autoclaving}}[^{\circ}\mathrm{C}] \cdot \mathrm{Power}_{\mathrm{oven}}[\mathrm{W}] + \\
&+ 0{,}0 \cdot (\mathrm{Power}_{\mathrm{oven}}[\mathrm{W}])^2
\end{aligned} \tag{3.1.2.6}$$

There were determined the estimations of factor's main effects and also the standard deviation for each effect. Table 3.1.2.14 presents, by comparison, the order of factors importance, obtained through Taguchi (**L_9**) and RSM (Box-Behnken) designs. One can see that the first 2 factors are considered as main factors (in that order) for both designs.

Tab. 3.1.2.14 Order of factors importance obtained through **L_9** (Taguchi) and Box – Behnken (RSM) experimental plans designs

Order of importance	Taguchi L_9	Box-Behnken
1	**Oven power**	**Oven power**
2	**Autoclaving temperature**	**Autoclaving temperature**
3	Dopant concentration	Autoclaving time
4	Autoclaving time	Dopant concentration

There were presented the estimated response surfaces and contours (Figures 3.1.2.7 and 3.1.2.8) for Ag-doped TiO_2 nanoparticles dimension as a function of dopant concentration and autoclaving time, the rest of the factors being kept on their average value.

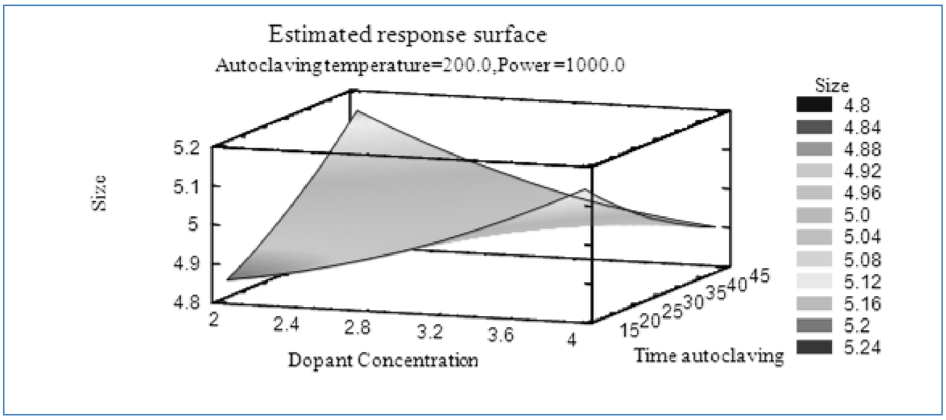


Fig. 3.1.2.7 Estimated Response Surface (dopant concentration - time autoclaving)

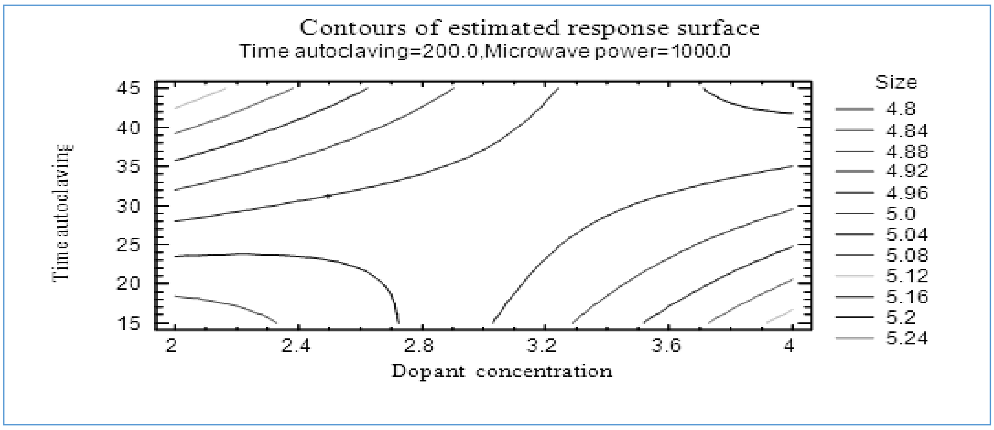


Fig. 3.1.2.8 Contours of Estimated Response Surface (dopant concentration – autoclaving temperature)

For the synthesis of TiO_2 nanocrystals doped with Ag by fast hydrothermal method (F - H), Taguchi's Robust Design Method Taguchi (using an **L_9** experimental plan – 9 experiments) and Response Surface Methodology (using a Box - Behnken experimental plan - 27 experiments) were applied. It was determined that there are 2 factors with major influence on dimensional stability, in the same order for both methodologies. For accurate modeling of the system, there were taken into account the interactions also, second-order model associated with Box-Behnken experimental plan explaining 80.5926% of the variability in the size of nanoparticles, with the drawback of more experiments needed.

C. Achievements. Development perspectives

According to the METHODOLOGY for obtaining the habilitation certificate at the Politehnica University of Timisoara - according to National Education Law, MECTS Order no. 5664/2012, Order no. 6560/2012 and Order no.3121/2015, respectively to UPT Senate Decision no. 152/16.07.2015. Achievements and proposals to develop the academic career addresses two issues: teaching and professional activity and research activity. The career development proposal is based on the candidate's achievements materialized until now and continue with the description of which will be the focus for future work.

C.1 Teaching directions

- ***Achievements until now***

I graduated from the “Traian Vuia” Polytechnic Institute in Timișoara, Faculty of Mechanics, Precision Mechanics Section, as head of promotion in 1985. After graduation, I was assigned to IAEM Timișoara as a trainee engineer.

In 1987, by the decision of the Executive Bureau of the Senate of the Polytechnic Institute "Traian Vuia" from Timisoara, I was hired for teaching in the position of associate assistant, position 44, in the State of Functions of the Department of Machine Parts and Mechanisms at the Faculty of Mechanics and I carried out the following activities: General Metrology laboratory with the 5th year Precision Mechanics, day courses and the 6th year Precision Mechanics evening courses, project of Mechanisms and Machine Parts with the 3rd year Electrotechnical Engineering, day courses.

On September 15, 1990, I was hired as an assistant professor in the disciplines of General Metrology and Applied Metrology. Until 1992 I delegated the following courses: General Metrology with 5th year Precision Mechanics, day courses and 6th year Precision Mechanics evening courses, Applied Metrology with 3rd year Precision Mechanics evening courses (Bachelor), and 4th Precision Mechanics evening courses (Bachelor). During this period I contributed to the development of the laboratories of General and Applied Metrology, Mechanisms of Precision Mechanics and Constructive Elements of Fine Mechanics, respectively within the Department of

Machine Parts and Mechanisms, Faculty of Mechanics. On 04.03 1992 I was hired by competition as a lecturer for the disciplines of General and Applied Metrology, an activity I carried out until 1994. During this period I was co-author of 5 patented innovations. From 1994 to 1999 I worked in Canada and the USA in the Automotive Industry as a Quality Engineer at Salga Associates, Blow Injection Molding Parts Manufacturer, Senior Quality Engineer at Polyrim Green Lane / Decoma Exterior Systems / Magna International, Reaction Injection Molding Parts Manufacturer, and Project Engineering Coordinator at Rollstamp Mfg. During this period I was Program Manager for CK Truck - GM, SSE Bonneville - GM, Corvette - GM, FN 145 - Ford, responsible for all sample submission via the PPAP system for new products, engineering, and process changes, performed engineering studies for surface quality improvement, molding and trimming, actively participated in all APQP activities, monitored product runs and defined PFMEA, responsible for supplier audits, analyzed internal, customer rejects and PPM reduction, maintained PR / R system, wrote specific procedures for implementing QS 9000. Also in this period, I attended the following courses: Auto CAD specialist, Caddgroup Education Services, GD&T, Quality Management Services Inc., Team Oriented Problem Solving, Magna Engineering R&D, Management Methods of Dr. W. Edwards Deming, Process Improvement Inc. From December 2002 to 2003 I was employed as a stand-in lecturer at the Faculty of Management in Production and Transport and from 2003 to 2006 I was an assistant at the same faculty. Since October 2006, I have been employed as a lecturer. During this period I taught the following courses: Legislation and Techniques of Domestic and International Trade, Quality Engineering, Quality Assurance, Management, Ethics, Behavior, and Negotiation in Business, Engineering of Assimilation of New Products, Work Organization and Standardization in Chemical Enterprises, with students from the Faculty of Management in Production and Transportation, I taught courses of Management, Marketing and Industrial Engineering for students from the Faculty of Mechanics and I taught courses in Comparative Management for students from the Faculty of Chemistry. Also during this period, I supported practical work activities in the disciplines of Quality Engineering and Ergonomics, seminar activities, and project activities in the disciplines of Value Engineering and Value Management, Engineering of the Assimilation of New products, and Logistics with students from the Faculty of Management in Production and Transportation. By decision 250/112/C from 22.01.2009, I was appointed to the position of Associate Professor. During this period, I contributed to the development of a new laboratory within the Management Department - "Integrated Business IT Solutions Laboratory" - in which ERP-SAP and Microsoft Dynamic Nav. solutions were integrated, I also contributed to the endowment and development of Quality Engineering and Ergonomics laboratories. In 2010, I participated at Windersheim University Zwolle in Holland in the Erasmus LLP program as a lecturer. I changed during the past years the curricula for the disciplines I teach to be as relevant as possible in the current context. Thus, for Quality Engineering and Management, the most important methods, methodologies, and tools are presented at the undergraduate studies. Next, in the master studies, elements of Total Quality Management are presented and then fundamental elements of the Six Sigma Methodology are also presented. Regarding Value Engineering, I introduced the study of the FAST methodology. Also, all the courses I teach are based on Statistical Thinking and the statistical-mathematical approach to problem-solving and process improvement. All the bachelor's and dissertation papers that I have conducted were based on real problems in the industry and whose purpose is to solve problems and improve processes.The entire teaching and professional activity were supported by the publication of several specialized books, manuals, courses, guidance for practical activities as sole author or co-author. The most important companies I have collaborated with are Continental Automotive Romania SRL, Leman Industry SRL Timisoara, AEM-Luxten Timisoara, Hella Romania SRL, ELBA SA Timisoara, ETA- 2u Timisoara, Green Forest Timisoara, Lasting System Timisoara, Trident Timisoara, Colterm Timisoara, etc. During this period I won the Third Prize in the contest "Technical Book 2009" awarded by AGIR Timiș branch to the team of authors Adrian Pavel Pugna and Ioan Grozescu for the book "Robust Taguchi Design. Comparisons, Opportunities, Applications in hydrothermal technique" and the "Diploma of Excellence" at the "Technical Book 2009" competition awarded by AGIR, Timiș branch to the group of authors C.D. Dumitrescu, Adrian Pavel Pugna, C. Militaru for the book "Quality, reliability, maintenance of complex systems". Over time I have been a member of several domestic and international organizations, as follows ARR-ROMSIR founding member since 1990, SRM member since 1991, ASQ member 1995 -1996, AGIR member since 2006, SAMRO since 2016.

➢ ***Proposals for the development of teaching career***

For the rest of my teaching career, I want to improve my teaching style, under the new situations and requirements and I also want to pass on all the teaching information I have accumulated over time to younger collaborators.

C.2 Research directions

➢ ***The results of the research activity until now***

I started the research activity since my student days, when I participated together with the late professors Dan Perju, Francisc Kovacs, Nicolae Gheorghiu, Marcu Balekics as well as with professors Gerhard Puri, Ioan Nicoara, Voicu Mesaros in various research contracts in progress at the Department of Machine Parts and Mechanisms from the Faculty of Mechanics of the "Traian Vuia" Polytechnic Institute from Timisoara. As a young teacher, I participated in several research contracts whose purpose was the realization of the first industrial robot in Romania, REMT-1, the realization of a synchronous manipulator at IMMUM Baia mare, etc. I also mention the participation in the scientific and technical collaboration with the Institute of Condensed Matter from Timisoara, which was the premise for the realization in 2005 of the doctoral thesis. In 2005 I defended my doctoral thesis in the field of mechanical engineering entitled: “Researches regarding Taguchi’s Robust Design of growing alfa-quartz monocrystals through the hydrothermal method”. It was the first time that robust Taguchi design was used in the field of alpha-quartz crystal growth, the book resulting from the publication of the results being awarded, as mentioned above. The collaboration with 2 Ph.D. students led to the realization of unique studies on the sintering process of basalt and the evaluation of Ag-doped TiO_2 nanocrystals by using various experimental and simulation plans. The researches were also carried out through research contracts, in 2 of them being Project manager and in the others being a member of the research team. The most important research contracts are the following:

1. Introduction of a unitary problem-solving system and improvement of thermal galvanizing processes. BC 7 / 30.01.2020. Continental Automotive Romania SRL. **Project Manager.**

2. Diagnostic analysis of the necessary training in the field of Lean 6 Sigma. BC 25/11.03.2015. Berg Banat SRL. **Project Manager.**
3. Comparative study regarding the training needs for the development of entrepreneurial competencies in the context of E.U. post-integration. Contract 451CB/11.10.2010. **Quality expert.**
4. Updating the development plan of Timisoara International Airport Traian Vuia SA. BC 59/2012. Aeroportul International Traian Vuia SA Timisoara. **Quality expert.**
5. Profitability analysis project for 2008, 2009, 2010, and profitability forecasts for 2011. BC 48/2011. Aeroportul International Traian Vuia SA Timisoara. **Quality expert.**
6. Introduction of the 5 S system to Leman Industrie SRL Timişoara. 31/10.03.2008. Leman Industrie SRL. **Quality expert.**

The research results were shared through the publication (author or co-author) as follows 4 papers published in journals indexed in the Web of Science database (Clarivate Analytics); 29 papers published at international conferences indexed in the Web of Science database (Clarivate Analytics); 13 papers published in journals and volumes indexed in other international databases (BDI); 71 published in journals or volumes not indexed in BDI; co-author of 1 book at an international publishing house, co-author of 5 chapters in books at international publishing houses, author and co-author of 9 books at recognized national publishing houses and author and co-author of 8 teaching materials including in electronic format - course support /guidance. The most important ones are as follows:

Studies:

1. **Pugna, A**., Grozescu, I. (2008). *Robust Taguchi Design. Comparisons, Opportunities, Applications in hydrothermal technique* – in Romanian. Editura EUROBIT Timisoara. ISBN 978-973-620-441-8.
2. **Pugna, A**., Buciuman, C., Pavlov, D., Negru-Strauti, G., Tăucean, I.M., Tămăşilă, M., Todorova, M., Enimaneva, S., Ruskova, S., Gedinach, V. (2012). *Comparative study regarding the training needs for the development of entrepreneurial competencies in the context of EU post-integration.* Primax Ltd. Publishing House. Ruse. Bulgaria. ISBN 978-954-8675-30-7.
3. **Pugna, A**., Potra, S., Negrea, R., Mocan, M. (2018). Chapter 2 - DMAIC Six Sigma for improving complex processes. In: Understanding Six Sigma, Ed. Seifedine Kadry. Nova Science Publishers Inc. 26-65.

Articles:

1. **Pugna, A.P**., Potra, S.A. and Negrea, R. (2020). A strategic decision making tool for new product and service design. Management Decision. ISSN: 0025-1747. Publication date: 14 April 2020. Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/MD-01-2019-0110. **(Quartile Q2 in Management, Quartile Q2 in Business – yellow zone, indexed WOS Clarivate Analytics).**

2. Miclea, S., **Pugna, A.,** Negrea, R. Potra, S. (2018). Using a refined attractive quality model for assessing students' requirements for a new university online application. Proceedings of the 12th International Technology, Education and Development Conference. Valencia. Spain. 5153-5161. **(indexed WOS Clarivate Analytics).**

3. Potra, S.A, Izvercian, M., **Pugna, A.P**., Dahlgaard, J.J. (2017). The HWWP, a refined IVA-Kano model for designing new delightful products or services. Total Quality Management & Business Excellence. Vol. 28 .No. 1-2. 104-117. **(indexed WOS Clarivate Analytics).**

4. Dahlgaard, J.J., **Pugna, A**., Potra, S., Negrea, R., Mocan, M. (2016). A greenhouse approach for value cultivation. Total Quality Management & Business Excellence. Vol. 27. No.7-8. 836-852. **(indexed WOS Clarivate Analytics).**

5. **Pugna, A**., Negrea, R., Miclea, S. (2016). Using Six Sigma Methodology to Improve the Assembly Process in an Automotive Company. SIM 2015 / 13th International Symposium in Management. Procedia - Social and Behavioral Sciences 221. ISSN 1877-0428, 308 – 316. **(indexed WOS Clarivate Analytics).**

6. **Pugna, A**., Potra, S., Negrea, R., Miclea, S., Mocan, M. (2016). A Refined Quality Attribute Classification Model for New Product and Service Strategic Design. Information Technology and Quantitative Management (ITQM 2016). Procedia Computer Science 91. 296-305. **(indexed WOS Clarivate Analytics).**

7. Potra, S., **Pugna, A.** (2015). DFSS in marketing: designing an innovative value co-creation campaign. International Journal of Six Sigma and Competitive Advantage. Vol. 9. No.1. 21-36. **(indexed Scopus).**

8.Giuca, O., **Pugna, A.P**. (2013). Improving Dimensional Stability of Ag doped TiO2 Nanoparticles through Experimental Design. Surface Engineering and Applied Electrochemistry. ISSN 1068-3755. 450-456. **(indexed Scopus).**

9. Mocan, M., **Pugna, A. P**., Negru Străuți, G. (2011). Robust Design of Sintered Basalt Brake Disks. Proceedings of the 7th International Management Conference of Technological Changes MTC 2011. ISBN 978-99486-1-6. Alexandroupolis. Greece. 573-576. **(indexed WOS Clarivate Analytics).**

10. **Pugna, A. P**., Mocan, M. L.., Negru - Străuţi, G., Giuca, M. G. O**.** (2011). Using doe to improve sintered basalt mechanical properties. Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium. ISBN 978-3-901509-83-4. ISSN 1726-9679. 0295-0296. **(indexed Scopus).**

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- ***Proposals for future***

I want to involve younger collaborators more intensely in the real research activity and also to attract students, master students, and Ph.D. students to this activity. I want to continue the research activity in the field of Attractive Quality Theory by developing a general and universal model, easy to understand and apply by managers, valid for evaluating products and services in the design phase. I also want to extend the models we have developed so far to the functional stage of products and services. I want to continue the application of Six Sigma in other fields, not only in the technical one, by integrating the latest methodologies and tools. I want to continue the collaboration with the industry and the services, to be able to carry out quality studies and researches that can be effectively applied and that will lead to the improvement of their activity. I want to apply the Six Sigma methodology in medicine and other branches in which this methodology is currently either not known or not applied. A good opportunity is the statistical processing of data and the scientific design of experiments. I want to continue the activity and to develop new directions for joint research with colleagues from the Universities from the country and abroad. I will continue the activity of participating in scientific conferences as well as that of a reviewer.

C.3 Administrative responsibilities

I was 5 years member of the Board of the Management Department, acting as a member of the Bureau of the Department Council as well as the coordinator of the commission for evaluation and quality assurance and also I was 12 years member of the Faculty Council of FMPT, where I served as coordinator of the commission for evaluation and quality assurance. Over the years I have participated as a coordinator and / or member in many accreditation commissions for undergraduate and master's studies. I am also Quality Auditor at University level quality in which I participated in several complex audits. I am currently the chairman of the Board of the master's degree in Engineering and Competitiveness Management as well as a member of the boards of the masters of Engineering and Management of Quality and Competitiveness (English), Logistics Systems Management, and Engineering in Business Administration. will continue to support the administrative activity at the department, faculty, and university level.

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Appendix – 10 Papers considered by the candidate to be the most relevant

1. **Pugna, A.P**., Potra, S.A. and Negrea, R. (2020). A strategic decision making tool for new product and service design. Management Decision. ISSN: 0025-1747. Publication date: 14 April 2020. Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/MD-01-2019-0110. (**Quartile Q2 in Management, Quartile Q2 in Business – yellow zone, indexed WOS Clarivate Analytics**).

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