POLITECNICO DI MILANO

Department of Management, Economics and Industrial Engineering

M.Sc. in Management Engineering

THE USE OF APQP AND CPM IN QUALITY MANAGEMENT

REPORT: WHIRLPOOL CORPORATION

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ABBREVIATIONS

APQP: Advanced product quality planning

CC: Critical characteristic

CPM: Critical parameter management

CTQ: Critical to quality

DFT: Design for test

DoE: Design of experiment

EoL: End of line

FMEA: Failure mode and effect analysis

HIC: High impact characteristic

HoQ: House of Quality

MIC: Medium impact characteristic

MSE: Measurement system evaluation

NPI: New Product Introduction

QFD: Quality function deployment

RPN: Risk priority number

SPC: Statistical process check

TGR: Things gone right

TGW: Things gone wrong

VoC: Voice of the customer

VoE: Voice of engineering

WPD: Whirlpool product development process

WPS: Whirlpool production system

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ABSTRACT

This report covers quality management activities of an NPI project of new induction hobs being developed by Whirlpool called i100. The report touches upon the theoretical information from literature and the information created by Whirlpool. This document can be divided into two: theoretical part and real-life applications.

The project has been conducted by using advanced product quality planning and critical parameter management. These approaches reduce the complexity of the project and increase the collaboration among teams. Within APQP scope, tasks are assigned to teams and each team reports to the APQP master who is responsible for project management. As the quality control department, we were responsible for the tasks assigned to our team. This document focuses on the activities performed by the quality control department within the scope of APQP. The activities this report contains are:

- APQP activities
- Critical Parameter Management implementation
- Process characterization
- Process capability
- Process mapping
- Measurement system evaluation
- Design of experiment
- Failure mode and effect analysis

Keywords: *APQP, CPM, Quality control, MSE, DOE, Process map, FMEA, Process capability, Process Characterization*

1. Introduction

As mass-production concept started getting popular after the industrial revolution, the manufactured products became more and more complicated and eventually, jobs had to become more specialized. This situation introduced the need for an inspection of the quality of finished products back in 1920-1930s. In these years the focus was mostly on profits and production quotas. In the 1940s the concept of statistical sampling and in 1960s statistical process control (SPC) has been introduced. All those concepts are considered as old concepts of quality. The new concept of quality begins with the change of focus from profits into organizational quality which includes improved product designs. Currently, the focus is evolved into customer-driven quality. In today's quality approach, design and manufacturing are integrated which means quality is being built into the manufacturing processes [1]. The advantage of this system is that it assures the identification and correction of root causes of quality problems. By embedding preventive and corrective actions into the process, it became possible to mitigate the costs and other problems caused by quality problems while in old quality concept defected products were being identified only after production.

Today's dynamic, fast-paced and overcrowded marketplace increases the consumer demands for differentiated and advanced technology products. For the players of the household appliances industry, it became essential to follow the current trends and to improve the old technologies in such a dynamic market [2]. Increasing consumer power is one of the main trends in the global market for household appliances. Ease of access to information gave rise to a higher number of well-informed customers and this situation leads to growing consumer power [3]. As a result, customer needs grow and become more sophisticated day by day.

The competition among companies has increased the importance of customer satisfaction and Operations Excellence departments edgewise. Quality Control is a department under Operations Excellence which is focused directly to deliver customer satisfaction. The starting point of each activity and project performed by the quality control department is always customer needs and expectations.

2. Objectives

General objective is to conduct a comprehensive overview on the principles of quality control processes in Whirlpool way. Quality tools, projects and methods are evaluated in detail by

touching upon both theoretical information and the way how they are being implemented in Whirlpool.

Main objectives are to give insights about;

- The role and use of CPM in Quality Control processes
- The use of specific quality tools in real-world applications
- The embedment of APQP into Quality Control project plans

3. The Company

Whirlpool Corporation is the leading manufacturer of major home appliances in the world based on most recently available publicly reported annual revenues. The company is found with the name of WHR in New York Stock Exchange. By the end of 2018, the company had approximately $21 billion in annual sales with 92,000 employees and 65 manufacturing and technology research centers all over the world. Whirlpool has the best brand portfolio in the industry, consisting 6 brands with more than $1 billion in revenue with the aim of positioning these desirable brands across many consumer segments. Sales are led by the global brands Whirlpool and KitchenAid. Strong regional and local brands Maytag, Brastemp, Consul, Hotpoint, Indesit and Bauknecht enables the corporation to provide products which are tailored to needs and preferences of local consumers. Whirlpool Corporation owns 12 brands which is shown in Figure 1.

Strategic architecture of the company is divided into 4 bullets:

- Vision: The best branded consumer products.. in every home around the world. The way to achieve this vision has been defined by achieving product leadership, brand leadership, operating excellence and people excellence
- Mission: Create demand and earn trust every day
- Strategy: Product leadership, brand leadership, operating excellence, people excellence

- Values: Respect, Integrity, Diversity & Inclusion, Teamwork, Spirit of Winning

Figure 1. Whirlpool Corporation Brands [4]

4. Advanced Product Quality Planning

4.1. Definition and structure

APQP is a structured process that comprise the definition, execution, and management of the very complex product quality planning actions to ensure that a product satisfies the customer. There are too many activities that need to be conducted simultaneously by different departments of the organization within the scope of product quality planning and it is necessary to synchronize these activities in cases of timeliness and coordination while ensuring satisfying levels of cost and quality. The main activities and different organizations involving in the APQP process are illustrated in Figure 2.

Figure 2. The integration of communication and team effort in the APQP process

APQP establishes common expectations for both internal and external suppliers by creating a standardized status reporting system and it uses common process metrics for all parties. Some of the benefits of Advanced Product Quality Planning are:

- Promoting early identification of change
- Enables intentional changes to increase the value creation for the customers
- Avoiding post-release changes, which is very costly, by anticipating failures and preventing. FMEA study is a good example of this bullet
- Produce on-time, high-quality product at the lowest cost possible
- Improved collaboration between design and production processes
- Definition of roles and responsibilities for the Advanced Product Quality Planning process
- Development of a standardized APQP process for both internal and external suppliers

In Whirlpool all milestones and progress of the processes are tracked by percentages in a dashboard separately for each department. Typical roles in an APQP process involves program management (APQP Masters), quality and reliability, team leaders, engineers, suppliers and program team. In Whirlpool cross-functional teams contains many members. A typical cross-functional team in Whirlpool contains the following members:

- Planning
- Brand / Marketing
- GCD
- Technology [Advanced Development]
- Platform Engineering GSS
- Manufacturing [Ind. Eng. / Process Eng.]
- Logistics
- Consumer Care
- Project Management
- APQP Lead
- CFQL
- Quality Engineer
- Supplier Quality Engineer
- Supplier Development Engineer
- Global Electronic Quality

As mentioned before, APQP includes many phases of product development embedded in each other. The process can be summarized under 6 phases as indicated in Figure 3.

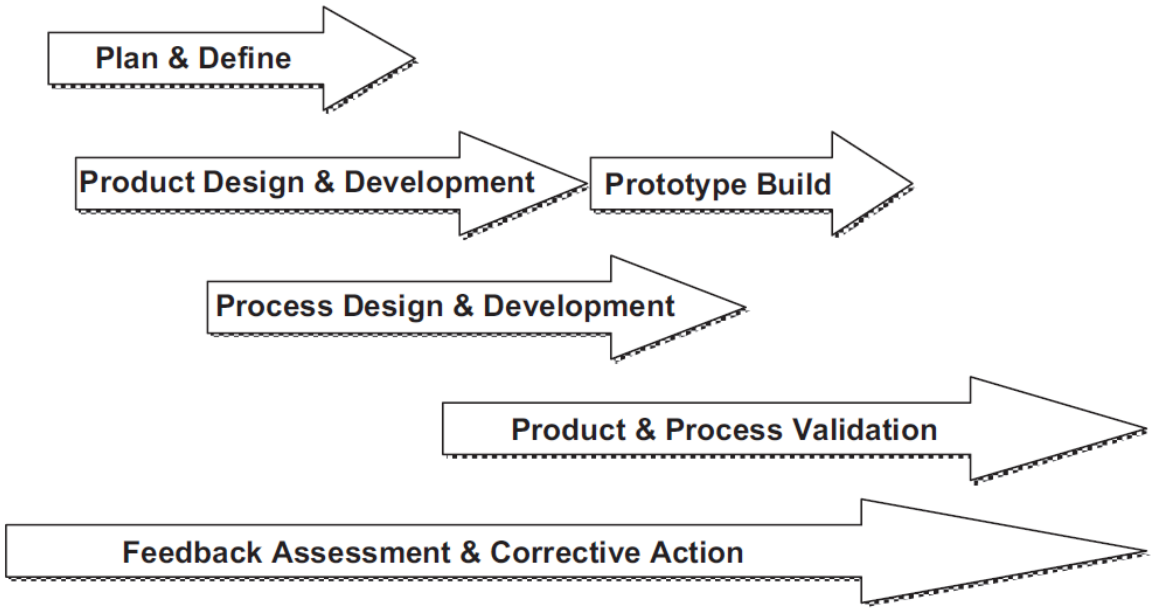


Figure 3. Typical model of APQP implementation [5]

4.2. Phases of APQP used in Whirlpool:

1. Planning

Preliminary planning is necessary for new product introductions or when there are significant changes in the previous products. Brand&Marketing, planning executives and APQP masters are mainly involved in this phase. The main goal of the planning phase is to define customer requirements. The first thing to do while identifying the requirements is data collection. Some of the data collected for VOC identification are: TGR/TGW, Product Health, 5 Star, competitive benchmarks (product & process benchmark data), etc. The quality program could be defined after the identification of requirements. Outputs of this phase includes deign goals, reliability and quality goal, preliminary bill of material, preliminary CPM inputs, etc. Main activities done in this phase are:

- VOC identification by using relevant data
- Project Charter preparation
- "VOC translation into VOE by using QFD
- Preliminary Process Flow Chart

- Preliminary Identification of Special Product and Process Characteristics (linked to CPM activities)
- System-Level DFMEA creation
- Risk assessment & manufacturing review
- Competitive benchmark analysis

2. Product design and development

According to the design goals identified in the first phase, the product design is done in this phase. Design FMEA activity needs to be performed to identify the potential failures of the product as well as verification and review of the design. Technical engineering drawings of the product could be done in the light of previous data. Special product and process characteristics would be identified after this phase. Those characteristics are mainly used in CPM. Product capability studies are a part of the collaborative study of APQP and CPM.

3. Process design and development

The manufacturing process is planned for the new product in this phase. Production efficiency must match with customer demand in quality, quantity, and cost. The main goal of this phase is to satisfy these requirements. The main actor in this phase is the Manufacturing Quality department. The activities I took part during my work in Whirlpool mainly focuses on phase 3 and phase 4. Deliverables of this phase comprise the following items:

- The design production process, equipment, tooling, gages, packaging, and facility
- Process FMEA (section 6.5)
- Start tool and simulation design
- DFT [Design for Test / Test Coverage]
- Special Characteristics (CPM process, section 5)
- Pre-launch control plan
- Process instructions
- Preliminary process capability study plan

4. Product and process validation

This phase comprises a trial run of production to validate the manufacturing using the planned resources for the process. The aim is to align the product and process characteristics in the best way possible. In light of these characteristics, a control plan should be developed to be able to check the defined characteristics of the product. Identified characteristics need to be tested if

the production is able to satisfy the required capability. The study to validate that conformance is called process capability. Cpk and Ppk are the metrics used to measure the capability. A real -life example of this study has been shown in section 7.3. One of the special characteristics of the i100 product was not within the desired limits for customer satisfaction and improvement activities are done during my trainee period in which I intensely involved in. In the last step of this phase production validation tests must be performed to see if the process meets engineering specifications.

5. Feedback assessment & corrective actions

As mentioned previously, APQP constantly seeks for improvements in the process. What to improve could be understood by feedback assessments and some other quality tools such as design of experiments, cause-effect diagrams, fault tree analysis, pareto diagrams etc. Those tools are very supportive since they show where to focus to be able to improve the process. After the identification of improvement points, corrective actions take place. The first thing comes to one's mind when said corrective action in Whirlpool is 8D method. This is a standardized method with 8 steps for the improvement of a detected issue. Steps of the 8D investigation worksheet used in Whirlpool contains following steps:

- Team definition
- Define the Problem
- Take Short Term Action (Containment)
- Determine and Rank Potential Causes (Root Cause) (prevent, protect, predict)
- Develop and Verify Solution (Corrective Action)
- Implement Corrective Actions (Validation/Verification)
- Prevent Problem Recurrence (Prevent Reoccurrence)
- Problem Closure

Deliverables of the feedback assessment & corrective actions phase includes following items in Whirlpool:

- 8D
- Safe Launch
- GSIR / Reliability
- Long-Term Capability
- Design of Experiments

- Cause-Effect Diagram
- Fault Tree Analysis
- Pareto Diagram
- Histogram
- Scatter Diagram
- Flow Chart

4.3. APQP Dashboard

In Whirlpool, a dashboard which defines the tasks and steps assigned to several teams and shows the maturity levels of each single task given is being used as a living document during all product quality planning process. The dashboard allows everyone to be aware of where the process currently is and what needs to be done next. It consists of 4 main phases and 14 milestones under those phases. Main phases of the dashboard are illustrated in Table 1.

Global Platform Planning Customer Needs Identification "Whats / Hows"	**WPD "KICK-OFF" From Customer Needs to Product**	**WPD "DEVELOPMENT" Product & Process Development / Product Design Optimization**	**WPD "EXECUTION" Process Optimization and Capability Verification**

Table 1. Main phases of APQP dashboard

Project deliverables are placed at the first column and each one belongs to certain phases of the dashboard. According to current status which is being updated instantaneously by each team who owns that specific task. Cells of each task are colored by different colors to make it easier to detect the current status. The color map used in dashboard has been shown in Table 2.

DELIVERABLE STATUS	NOT DUE YET	COMPLETE	IN PROCESS	LATE	TEAM NEEDS ASSISTANCE	NO INFORMATION	BUSINESS DECISION

Table 2. Deliverable status color map used in APQP dashboard

Levels of each deliverable are categorized in 6 different levels by using a legend. Each number corresponds to a different category as shown in Table 3. Each cell has a distinct color indicating the current status, and numbers which categorize their level.

DELIVERABLE LEVEL	5 GOOD	4 ADEQUATE	3 REQUIRES IMPROVEMENT	2 REQUIRES SIGNIFICANT IMPROVEMENT	1 INADEQUATE	0 NOT AVAILABLE

Table 3. Legend for the levels of deliverables used in APQP dashboard

Each deliverable is assigned to several members. Roles are defined by using a participant/leader table. An illustration of this table can be seen in Table 4.

Cross-Functional "L" Leader / "P" Participant															
Planning	Brand / Marketing	GCD	Technology [Advanced Development]	Platform Engineering	GSS	Manufacturing [Ind. Eng. / Process Eng.]	Logistics	Consumer Care	Project Management	APQP Lead	CFQL	Quality Engineer	Supplier Quality Engineer	Supplier Development Engineer	Global Electronic Quality
P	L	P		P				P		P	P				
			L	L		L									
L	P	P	P	P				P	P	P	P				
				L											

Table 4. Leader/Participant chart in APQP Dashboard

5. Critical Parameter Management

5.1. Definition and structure

CPM is an engineering approach which aims the maximization of robustness and reliability of production system through detailed design and manufacturing [6]. Critical parameters may be optimized for a single specific product. But in such a dynamic high-tech market, new technologies are coming into field every day. This situation gives rise to the need of faster development and delivery of new products with high quality standards. As products are being updated quickly, critical parameters for each product change as well. Robustness of the system has to be maintained by a solid management system. CPM is a part of the system to satisfy this need efficiently. It ensures the consistent quality by managing the parameters which impacts customers the most.

In Whirlpool Production System (WPS), CPM approach is defined using 3 bullets:

1. KNOW - Critical parameters (also known as Special Characteristics or Dimensions of Interest) are those entities that must be managed to ensure product Safety, Performance,

Reliability and Robustness. Disciplined execution of critical parameter management is required for make and buy parts.

2. BELIEVE - Critical parameters are measurable requirements that must be met for customer satisfaction.
3. DO - Support tracking of critical parameters throughout the development process from drawing release through the manufacturing process

CPM is an important part of a rigorous, systems engineering-driven product development process. Critical Parameter Management is a disciplined strategic methodology for developing, managing, analyzing, and communicating technical product performance and determining critical-to-customer requirements linking controlled design and manufacturing parameters. The phases of the CPM are illustrated in Figure 4.

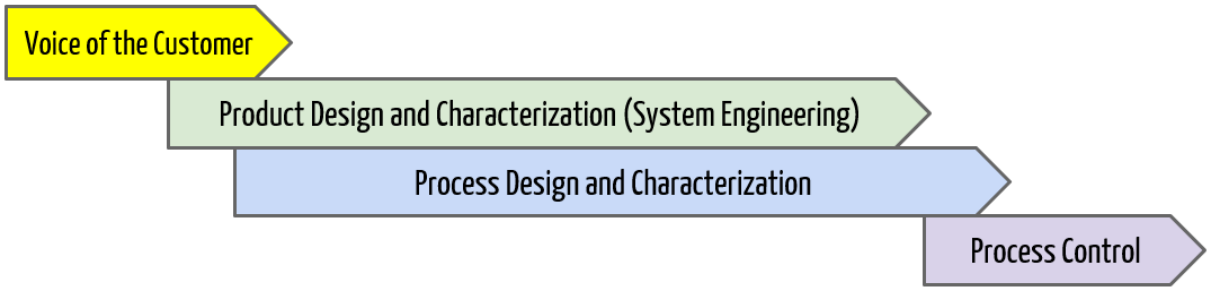


Figure 5. Phases of critical parameter management

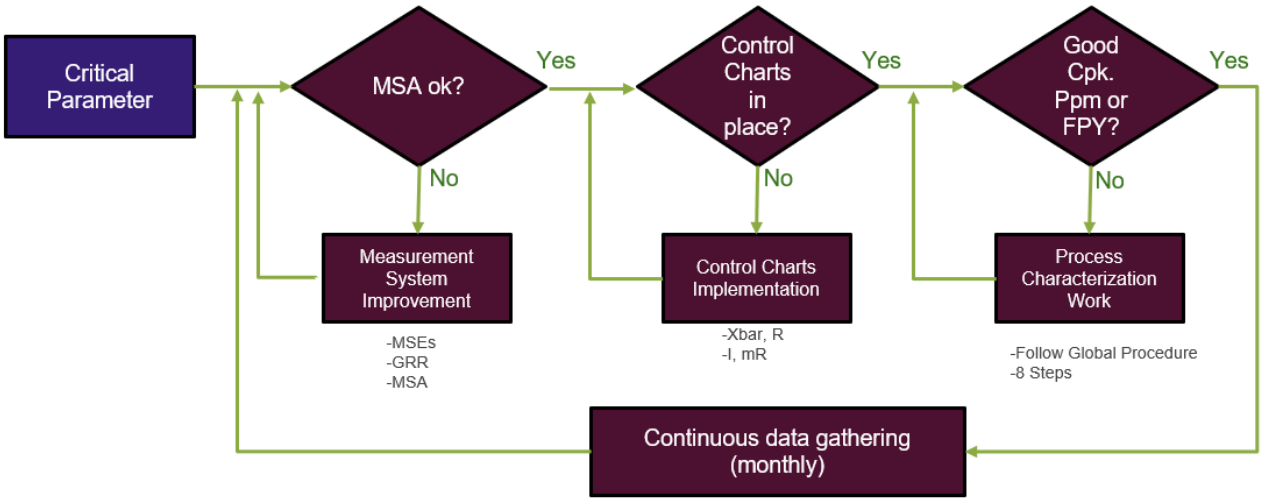


Figure 4. Critical parameter management workflow

Parameters are divided into two; design and process parameters. A critical design parameter is defined as: A functional output or dimension that directly or indirectly impacts the safety or function of a product, subsystem or component as identified by a design failure mode and effect analysis (DFMEA) and tested using design validation plan (DVP). A critical design parameter is defined as: A quantitative process parameter that should be monitored and controlled to

ensure all critical design parameters are met. Once a critical parameter is defined using described methods, the workflow takes place as shown in Figure 5.

Methodologies used within CPM scope:

1. Voice of the customer (VOC)

   Understanding the customer helps the firm to understand of what customers want. This is the key to product leadership. Firms needs to listen the customers and understand the competition. The aim is to utilize & prioritize purchase drivers, predict competitive moves and shifts, react and communicate priorities. Metrics used on evaluation of VOC are: five-star ratings, power ratings and social media.
2. Quality Function Deployment (QFD) / House of Quality (HoQ)

   QFD is a tool to translate VOC into prioritized purchase drivers that link/interact with product leadership. Aim is to define brand priorities, demonstrated knowledge of attributes/interactions. Methodologies used in QFD are as follows:

   - Define gaps between competitors
   - Define the key attributes/parameters
   - Refine interactions & prioritize
   - Prioritize/Optimize the system
3. Systems Engineering

   Outputs of systems engineering are designs that meet expectations, capability & knowledge reuse (across platforms, subsystems, etc.) It aims to create robust designs capable of providing critical parameters and achieving targets. Methodologies used in systems engineering are as follows:

   - Reuse like models/CAD/documents
   - Leverage current Voice of the Process (VOP) in system modelling
   - Create the linkages between product, process and parameters
   - Develop a roadmap to demonstrate capability including all required stack-ups
   - Resist progressing before capable

   Metrics used for the systems engineering are: CETOL (6σ Tolerance Analysis Software), SEP & System Models Capability, Lab Testing.
4. Process Characterization

It is a methodology that drives project approach towards process capability & improvements. The aim of this methodology is to understand & deep-dive the processes, improve with data and to focus on weaknesses/gaps in the process.

Select processes critical to success. Methodologies for process characterization are as follows:

- Study gaps & opportunities (SIR, FPY)
- Improve through Operations Excellence focused work
- Control & implement process capability, error proofing & cadence of reviews

Metrics used for process characterization are: product capability, test coverage, process capability.

5. Partner

This step includes a partner that provides information & data early to influence the design. Aim is to be bold and participate in the development process to ensure capable designs. Test coverage and capability metrics are being used as data. Methodologies used in this step are as follows:

- Support efforts toward capable designs through ongoing data collection on critical parameters
- Actively participate in design
- Sustain product & process capability through test, inspect & analyze

5.2. Terms used within CPM scope

Before deep-diving into CPM process it is necessary to define frequently used terms in the process. Definitions are better explained by using real examples used in washing machines.

- Y's

Product-level characteristics which is critical to deliver the key customer needs, resulting from the VOC to VOE (Voice of Engineering) translation and documented in the product-level House of Quality.

Example:

Customer needs (VOC): "I want my washing machine to clean the dirt on clothes very well.", "I want my machine to be nature friendly and economic"

Translated into VOE: Cycle Cleaning Performance, Cycle Water Consumption

- y’s

Characteristics critical to deliver the Y’s that can be measured only at product-level. Example: heating energy [kwh], water quantity / washing [lt]

- X’s

Special characteristics of components or assemblies that are critical to deliver either the "Y’s" or the "y’s"

Example: X1 = Hook Door Hinge Distance, X2 = Consol Width, X3 = Consol Height, X4 = Heater tolerances, X5 = Bellow thickness

- Xp’s

Process parameters critical to deliver the "X’s" documented in the production control plan Example: Molding process parameters, Welding process parameter

- Critical Parameter Management (CPM)

A product development process which seeks to translates the Y’s into y’s, into Xs, into Xp’s and by identifying the cause/effect relationships among them.

- Product Capability

Ability of the product to deliver the key customer needs. Measured using Y’s and y’s.

- Process Capability

Ability of the manufacturing process to deliver the design intent. Measured using X’s and Xp’s. Cpk is used as a metric to evaluate the capability.

Criticality of the characteristics are evaluated using FMEA’s. They can be classified as either Critical, High Impact or Medium Impact according to their Severity points defined in FMEA.

5.3. Special Characteristics

- Critical characteristic (CC)

A product or process FMEA line item is assigned as CC for which reasonably anticipated variation could potentially affect a product’s safety, compliance with regulatory requirements, or DOE standards.

Severity: 9

Expected Cpk: 2

- High Impact Characteristic (HIC)

A product or process FMEA line item is assigned as HIC for which reasonably anticipated variation could potentially affect customer satisfaction with a product.

Severity: 5-7

Expected Cpk: 1,67

- Medium Impact Characteristic (MIC)

A characteristic (usually a dimension) which is a part of a variation chain (stack-up). If the dimensional variation exceeds the defined capability, there can be a negative impact on fit, function, durability. Customer satisfaction (including internal customers), assembly or manufacturability.

Expected Cpk: 1,00

The flow of special characteristics in documentation is illustrated in Figure 6.

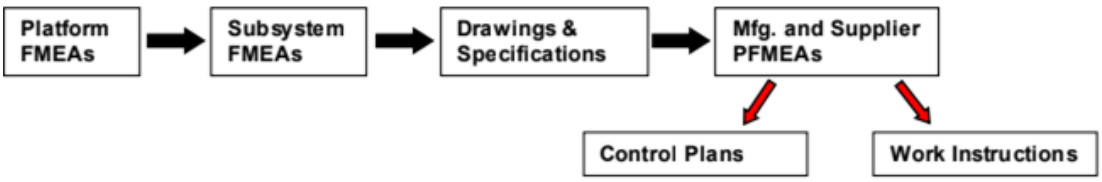


Figure 6. Special characteristics flow in documentation

5.4. Steps of Critical Parameter Management

1. Understand customer requirements

   Just as in all quality studies, CPM starts with understanding the needs of customers. The data comes from House of quality, FMEA's (Safety, Product) and field data. Customer requirements are defined as product attributes in documentation. Some of the examples of these attributes from washing machines are: core performance, energy, noise, craftsmanship, aesthetics etc.
2. Translate VOC into system requirements (Y identification and prioritization)

   Subtopics of this step are product level characteristics (big "Y"), target including variation and measurement methods. Data of these subtopics come from HoQ, FMEA's,

codes & regulation. Some examples of product level characteristics (Y's) are: cleaning performance, washing noise etc.

3. Determine intermediate y's for contributing subsystems/module sets
   Data of the y's comes from product maps, process maps, block diagrams, and function diagrams. For each 'y', a target including variation and a measurement method need to be defined. Some examples for subsystem level (little y's) are: temperature regulation, cycle time, water quantity etc.
4. Determine low level characteristics (X's) and optimize the design
   This step includes all the items which design team is developing, evaluating and has finalized. The data of x's comes from FMEA's and the data validated via: coefficients of variation studies (COV), design of experiments (DOE), tolerance stack-up, simulation and reliability
5. Determine process characteristics (Xp's) and optimize the design
   To determine the Xp's, the data from Statistical Process Control, Components of Variation Studies (COV) and Design of Experiments (DoE's) can be used. After this step the process parameters are optimized to sustain the quality and Quality Assurance methods need to be applied to keep those parameters under control. Again at this step the target including variation and a measurement method need to be defined. Examples of the Xp's can be glue temperature, glue quantity, height of the jigs etc.

5.5. CPM Decomposition and Capabilities KPI

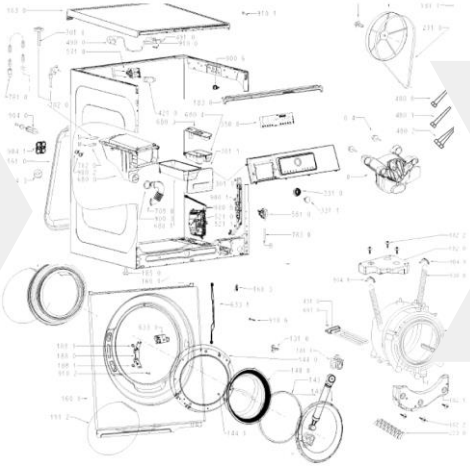
Decomposition of CPM includes 4 different stages as the terms described in chapter 4.2. The decomposition goes on respectively like this: Y's, y's, X's, Xp's. Those stages begin with the identification of product requirements (Y's). Y's are identified by translation of voice of the customer into voice of engineering by using House of Quality etc. VOC represent the perceived value for the customers. Y's generally consists of performances, rates etc. and they are not being controlled by metrics and numbers. The decomposition begins by finding the metrics to deliver expected Y's. Second step is the product-level characteristics which are critical to deliver Y's. They are usually composed of physical metrics such as kwh, liters, minutes etc. To deliver a product requirement (Y) it is possible to define several product-level characteristics (y1, y2,y3…). In the end Y's branch out into several y's. Y's and y's are the *Product Capability* specific to a single product/model.

Next step is the identification of special characteristics which are defined in section 5.3. Special characteristics are usually distances, width, thickness, tolerances etc. Identification of special characteristics can be defined as an equation y = f(X). This equation means that the delivery of y's depends on the identified special characteristics (X's). Naturally in real life the correlation between y and X is not defined. This equation may even be something like y = 3x+5. To better understand the correlation between them, it is necessary to conduct Y=f(X) Modeling & Simulation by using quality tools such as DOE's, Stack-up analysis, D-FMEA's etc. As described in section 5.3. X's are classified as CC, HIC, or MIC. Each one needs to be kept under control with a metric and that's where *Process Capability* comes into play. An example of process capability study can be found in section 7.3. Insufficient capability, if not solved, may even result in 'buy' decision instead of 'make'. A very basic capability study could be conducted by measuring the desired characteristic X times and checking the success rate. The very basic definition of success rate is the ratio between measurements which falls within defined minimum & maximum tolerances and total measurements. Calculation of process capability has been defined in section 7.3. Process capability of special characteristics are kept under control with Cpk metrics. The last step is the identification of critical process parameters (Xp's) to deliver desired Cpk's for special characteristics (X's). Machine capability is very important to deliver reliable and consistent results. The parameters have to be optimized for the production of each single product. For the identification of Xp's it is necessary to find out the correlation between Xp's and X's. The question is: "How a slight change in a process parameter affects a special characteristic?". The answers can be found by conducting process characterization which is defined in detail in section 6. The aim of the process characterization is to identify critical Xp's to deliver X's by using quality tools such as COV's, DOE's, -FMEA's etc. Decomposition of Critical Parameter Management is summarized by using examples in Table 4. Arrows are used as an example to show the branching. Branching shows the correlation between those four stages of CPM flow. The characteristics are picked randomly just to simulate the decomposition process. Planning of the critical parameter management is a very important issue.

Even though it seems like the processes are done one after another, in real life the departments work simultaneously in collaboration during all project. The project plan is standardized by Whirlpool. Upper part of the figure represents the checkpoints of APQP planning used by Whirlpool in projects. The standard planning chart of CPM has been shown in Figure. 7.

Y=f(X) MODELING & SIMULATION

IDENTIFY CRITICAL X's TO DELIVER THE Y's, y's THROUGH SBD/DOEs, STACKUPS. D-FMEAs



PROCESS CHARACTERIZATION

IDENTIFY CRITICAL Xp's TO DELIVER THE X's THROUGH COVs, DOE's, P-FMEA's…

PRODUCT REQUIREMENTS VOC to VOE/HOQ (Y's)

STD Cycle_Cleaning

Performance

STD Cycle_WaterConsumption

STD Cycle_EnergyConsumption

CTI_Perfomances

Fault rate [defects/n appl.]

Craftsmanship related Y's

NVH related Y's

…

PRODUCT-LEVEL CHARACTERISTICS (y's)

y1 = mech. energy [kwh]

y2 = heating energy [kwh]

y4 = Water quantity / washing [lt]

y5 = Water quantity / Rise [lt]

y6 = temperature regulation [°C]

y7 = cycle time [min]

y8 = Table top and consol alignment H

SPECIAL CHARACTERISTICS (CC, HIC, MIC) X's

X1 = Hook Door hinge distance

X2 = Consol Width

X3 = Consol Height

X4 = Heater tolerances

X5 = Bellow thickness

X6 = Tube diameter

CRITICAL PROCESS PARAMETERS (Xp's)

Xp1 = Molding pressure

Xp2 = Molding temperature

Xp3 = Welding current

Xp4 = Mold holder height

Xp5 = ...

Xp6 = …

PRODUCT CAPABILITY

PROCESS CAPABILITY

MACHINE CAPABILITY

Table 4. Decomposition of critical parameters

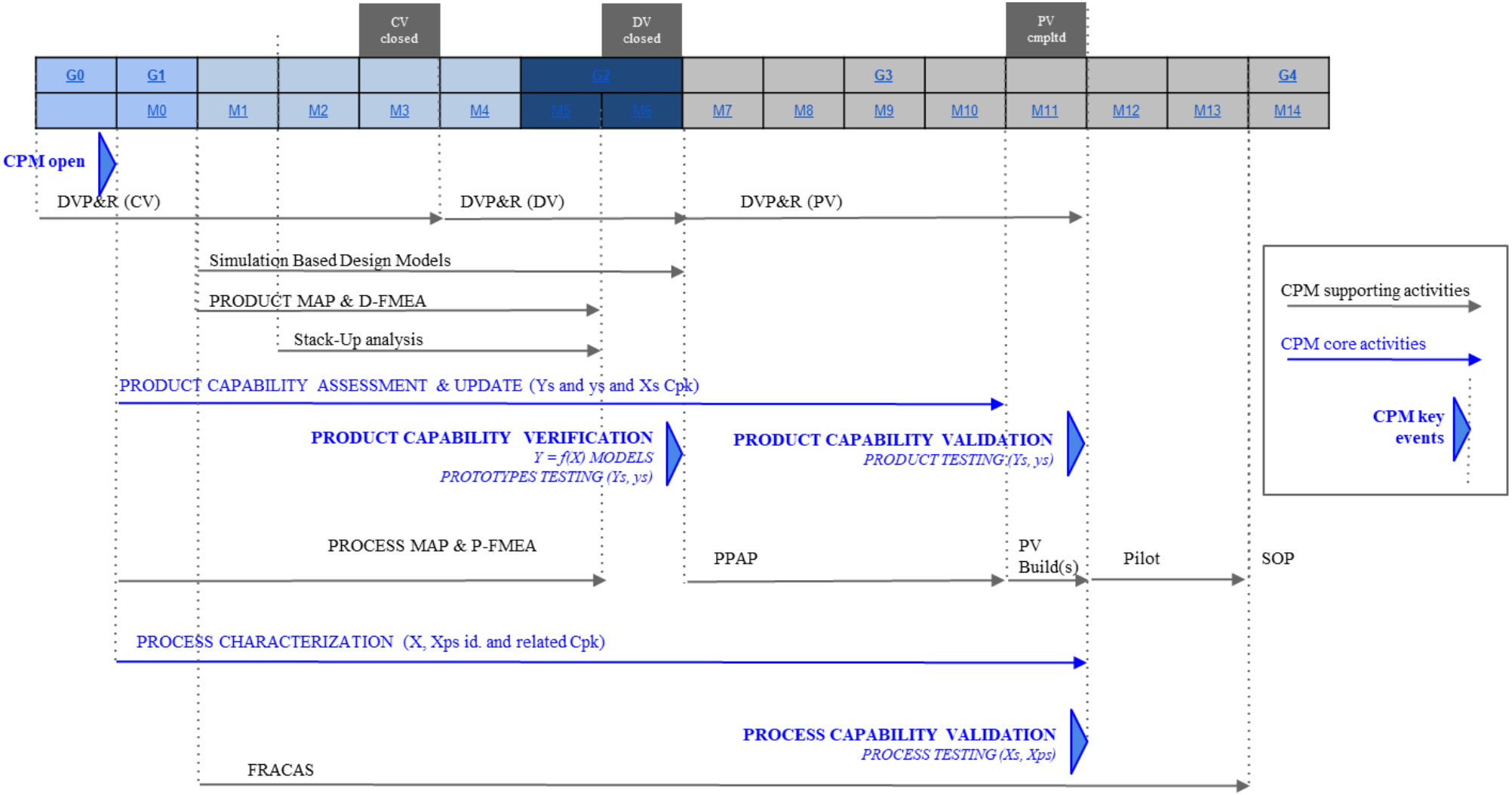


Figure 7. Critical parameters management planning

6. Process Characterization

6.1. Definition

Process characterization is an activity which includes following exercises:

- Identification of input and outputs of a process step or overall process
- Data collection of as-is state of a process
- Estimation of the steady state behavior at optimized operation conditions
- Building models describing the parameter correlations within an operation range

Main goal of this activity is monitoring and improvement of a process. The activity consists of 3 steps but not all steps have to be conducted in every situation.

1. Screening
   In this step all possible inputs and outputs should be identified, and some experiments need to be conducted to filter them down to key inputs and outputs.
2. Mapping
   This step includes creation of process maps which show the flow and behavior of key inputs and outputs. To map the process, it is necessary to divide the process into its' sub-steps to better spot the failures by investigating the small pieces instead of a huge process.
3. Passive step
   In this step the process is allowed to run at nominal conditions and estimations are made if the process is stable, centered and capable. [7]

Within the scope of Critical Parameter Management, the processes must be stable, centered and capable. Being stable means there are no unplanned shifts or drifts in key metrics. In Figure 8, the stability of a process is shown by using graphs.

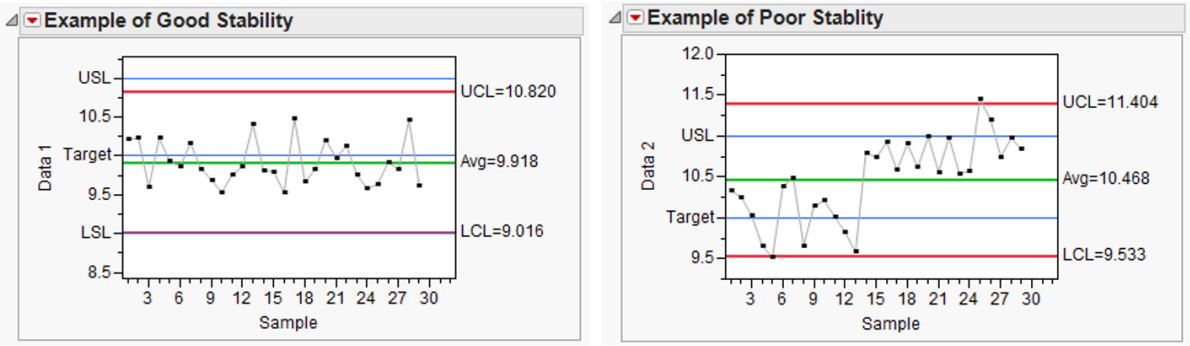


Figure 8. Good and bad stability graphs of a metric

A metric is considered to be centered when the difference between the process average and target is low. An example of centered and non-centered metric is shown in Figure 9.

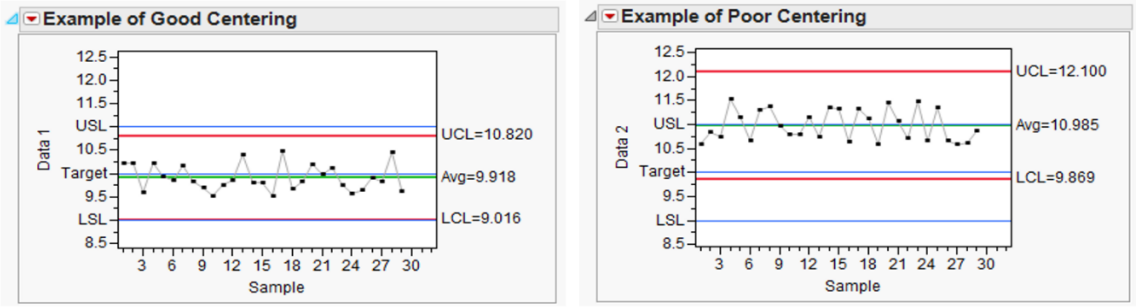


Figure 9. Centered and non-centered graphs of a metric

Capability of a process is measured by using a metric called Cpk. The min. required Cpk is different for each process as it is stated in CPM section. A capable process means Cpk being higher than min required value. Figure 10 explains how graph of a capable process should look like.

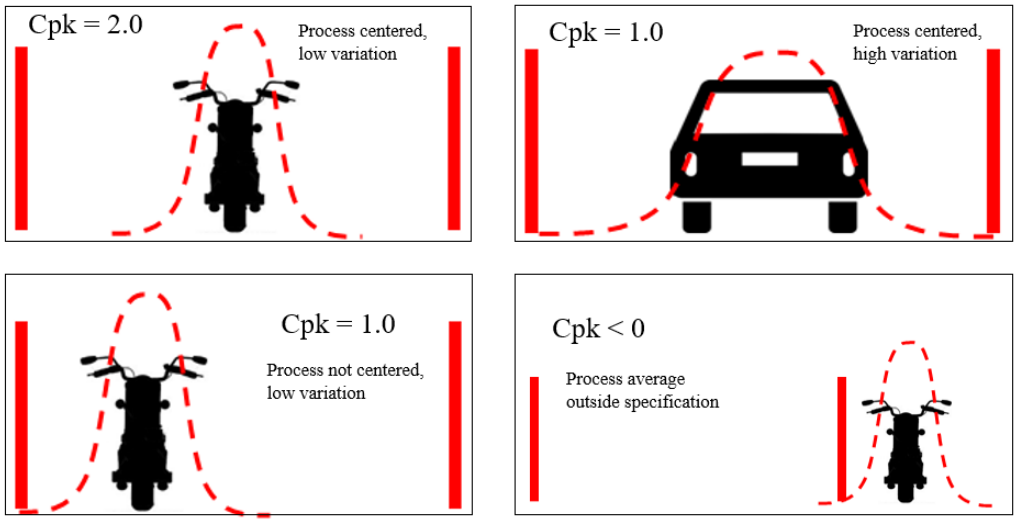


Figure 10. Graphs for different capability values

6.2. Process Maturity & Accuracy Curve

Process maturity curve and accuracy curve is a very useful tool used in embedment of process characterization into CPM. It consists 5 steps starting with the identification of critical product characteristics and mapping the process. A typical process maturity & accuracy curve has been shown in Figure 11.

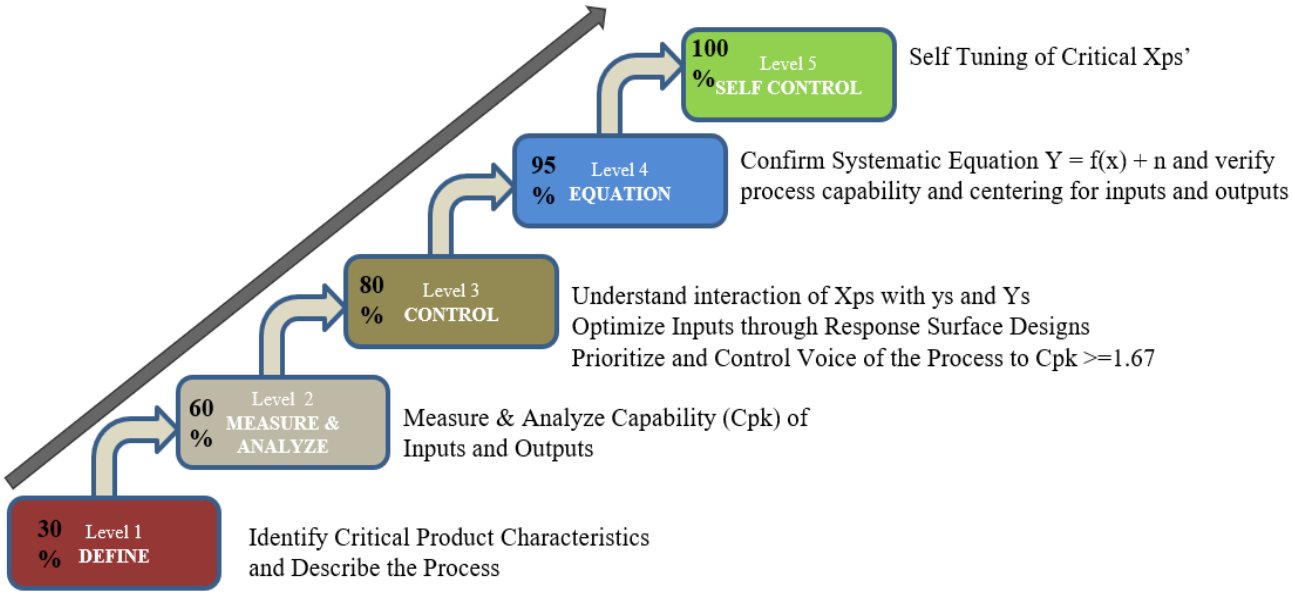


Figure 11. Levels of process maturity & accuracy curve

Descriptions of each maturity level in the curve has been shown below.

Process Level	Maturity Curve Description	Accuracy of the Mean (%)
0	*COMPLETE IGNORANCE* – The existence of the phenomenon is unknown, or even if the existence is known, there is no clue that it may be relevant to the process.	0 – It is not known where and how to act. Actions are completely random.
1	*DEFINE* – The existence of the phenomenon and the possibility that it may be relevant to the process is understood. There is still no way to use	30 – The team start acting towards the right side. This corresponds to the state of existence of a past experience or benchmark work is done.

	the parameter in the process, but the investigation may begin in order to proceed to the next level.	
2	*MEASURE AND ANALYZE* – The Cpk of the parameters can be measured and analyzed accurately. This requires development and installation of a specific instrumentation.	60 – The team has a sense of general direction. This corresponds to the state of preliminary XYZ equations established, preliminary DOEs (if necessary) conducted and early simulation-based analysis ability acquired.
3	*CONTROL* – The team knows how to control the parameters with accuracy and precision. The correlation between parameter and the result is also known. The process is stable, predictable, and controlled with a Cpk of 1,33 or greater.	80 – Through the use of screening designs of experiments, the team has an idea of the general area they should approach. The identification of the critical factors allows team to reach a targeted mean and/or reduce variation in the process.
4	*DEVELOP EQUATION* –A scientific model of the process has been developed and it's known how it operates over a broad region, including nonlinear and interaction effects of this parameter with other parameters.	95 – Through the use of high-resolution DOE's, the team is approaching to the target solution. Simulation-based analysis is capable of setting boundaries around the solution. This corresponds to the state of solution demonstrated through physical prototyping.
5	*SELF CONTROL* – The complete functional form and parameter values that determine the result is known, Y, as a function of all the inputs. The parameters are self-tuned within the process.	100 – The target solution has been achieved as all defined critical Xp's are controlled on a continuous basis.

6.3. Steps of Process Characterization

Process characterization is standardized in Whirlpool. The activity is being conducted with a workflow shown in Figure. 12.

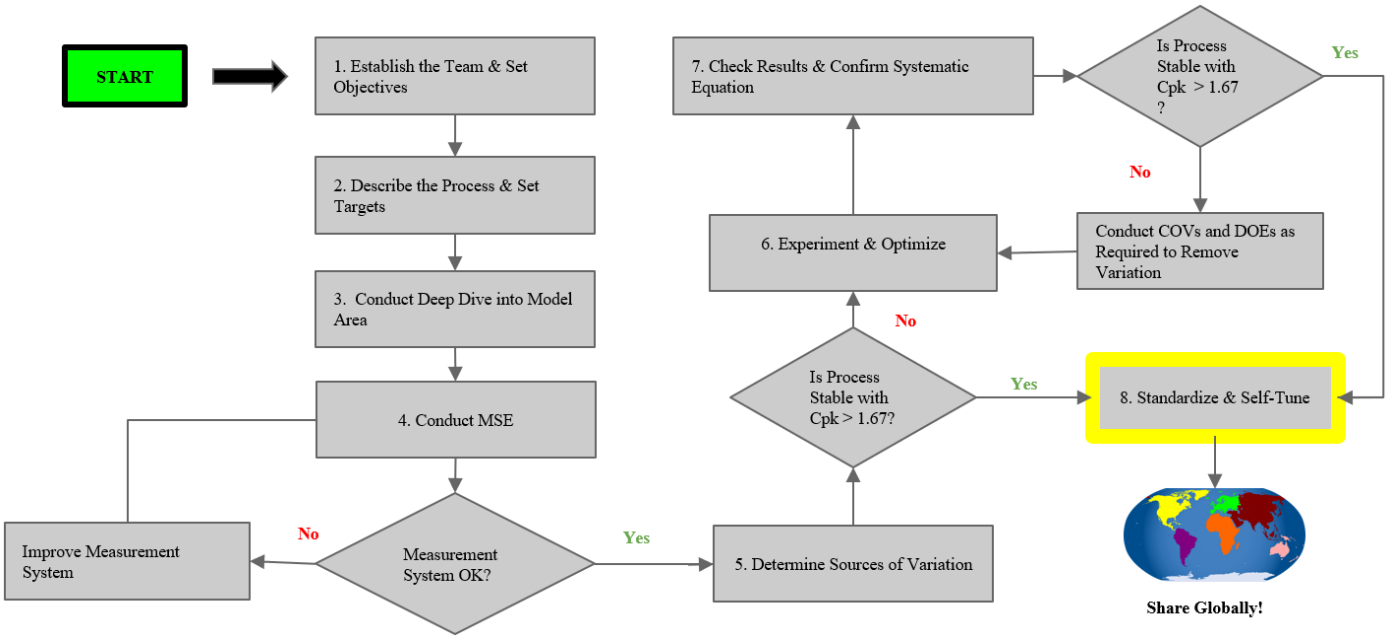


Figure 12. Process characterization steps

1. Establish team and set objectives

   At the first step the team needs to be established. A standard team for process characterization activity is built up by following members:

   - Team sponsor - to whom will the team report progress? Has resources?
   - Process owner - who will make sure the discipline is in place and remains in place?
   - Team leader (often SME or process owner)
   - Team master black belt or black belt
   - Other team members - process engineer, technician, operator, or subject matter expert

   Objectives should be listed and documented to start loading information about the activity. At the beginning expected savings and benefits need to be filled.

2. Describe the process and set targets

   Target mean and variation should be identified. Then the availability of tolerance stack-up needs to be checked.

Detailed process map (for each station) and product map should be created. Y's, y's, and x's should be identified by studying the process very well. Inputs must be labeled whether they are controlled or noise.

Potential competing response variables have to be identified in order not to harm an important response while correcting another.

Product attributes should be evaluated whether they are boated on appropriate drawings.

Stability of the critical outputs in the initial assessment need to be checked.

Critical outputs are required to have a Cpk >1.67 in initial assessment.

3. Deep dive into model area

   Gathering existing data as it is relevant to outputs and process parameters.

   Evaluate to appreciate historic behavior. They should be classified whether they are a mean or variation problem or both.

   Conduct audit of process maps against bill-of-process if it exists.

   Conduct audit of standard work and control plans.

   Create / update PFMEA.

4. Perform MSE (measurement system evaluation)

   Conduct measurement system evaluation. Evaluate repeatability, reproducibility, discrimination, and measurement error against the tolerance window in addition to process variation. Verify accuracy against a known standard.

5. Determine sources of variation

   Create and utilize rate of change information to create COV (coefficient of variant) sampling plans.

   Conduct COV studies to quantify the magnitude of the variation for different components. Determine the direction of work.

   Update the PFMEA

6. Experiment and optimize

   Based on information gathered from COV's, construct Factor Relationship Diagrams (FRD), conduct screening Design of Experiments (DOE), and analyze. Repeat sequential screening DOE's to identify critical factors.

   As appropriate consider mapping experiments such as high resolution DOE's, multiple level, center points, central composite, and etc.

   Conduct boundary condition evaluation (design and noise inference space) with process parameters at high and low level settings for each. Also include critical noise factors that are not planned to have active compensation.

Implement process changes including mistake-proofing the process against defects, and monitor the response variables. Achieve a Cpk > 1.67.

Visual factory management of critical factors and process changes implemented.

Update the PFMEA with achieved situation.

7. Check results & confirm systematic equation

   A checklist is used to confirm each of following questions:

   Are the critical outputs that are stable?

   Do the critical outputs have a Cpk > 1.67?

   Are the critical inputs stable?

   Do the critical inputs have a Cpk > 1.67?

   With the active factors identified, can the targeted mean and variation be achieved? If not, loop back to more COV or DOE work as required.

   Confirm the systematic equation $y = f(x) + n$. Calculate the process mean, effects, and coefficients. In theory $y = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + \varepsilon$. This model can provide assistance in prediction and future investigations.

   Control plan updated for all process and product parameters with reaction plan and help chain established. Operators are trained to understand the critical parameters and the relationship between the inputs and outputs.

   Update the PFMEA.

8. Standardize and self-tune

   Update process maps, product maps, PFMEA's, control plans, standard work and additional floor communication documents.

   Drawings: any newly identified critical parameters are communicated to the appropriate design engineer in order to have them boated on drawings. Tolerance stack-up updated with key learnings.

   Complete all required documents in the process characterization workbook and share.

   Identify system self-tuning enablers such as equipment and technologies and define a self-tuning implementation plan if applicable.

   Implement automatic data analysis and correction by equipment.

6.4. Process Mapping

Before defining how to map a process it is necessary to understand what process is. A process is defined as a structured set of activities designed to achieve an objective [8]. A process uses inputs and turns them into desired outputs as shown in Figure 13.

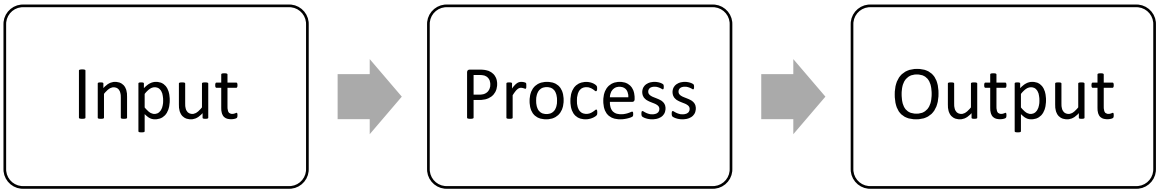


Figure 13. General representation of a process

Process map is a tool that visually represents the activities, connections and flows that are happening to a product, service or information as it moves through a process. The map follows and focuses on the product, not the people. Process is shown with a detailed flow diagram by using colors and symbols. Dividing the overall process into small pieces can be related with divide and conquer strategy. To understand the source of a problem, it is easier to examine smaller pieces of the process rather than looking to overall process. To develop a process map it is necessary to go and see the process by making observations with high attention. It should always be kept in mind that the problem may lie in small details of the process. Goals of mapping a process can be summarized with following bullets:

- Organization of the information which was gathered during direct observation into a visual illustration of the current state of the process. Meaningful improvements will only be possible when it's truly understood how the process really works currently.
- Identification of the opportunities to reduce waste and non-value added activities. As a consequence, reducing the costs.
- To create a more efficient and streamlined process.
- Make processes adaptable to change.
- To identify the gap between the as-is state and ideal state.
- To establish high agreement on how the process currently functions and how it should function.
- Enables learning.

First thing to do while mapping a process is to understand the starting and ending points of the process. It is important while dividing the process into sub-processes. Process mapping is not an individual task, so it's more efficient to work and do brainstorming with operators and/or experts of that specific process. The team directly observes and documents the activities, connections and flows of the process. They identify the scope of the process to be studied and clearly defines boundary points. Focusing on one common flow through the process is important. Process map does not focus on exceptions such as 'sometimes it does this.' Mapping

should go from general into specific; to do so it's necessary to list the names of the sub-activities within process turn by turn according to flow. Next step is to deep-dive into tasks done within each single activity listed. In Whirlpool, inputs, outputs, noises and CTQ's (critical to quality) are identified for each single activity. The legend of process flow has been shown in Table 5. Basic guidelines for each sub-process/operation has been shown in Table 6. Criticalities of each sub-process are defined by using color-coding. Outputs of each workstation are listed on top and the rest of the items such as inputs, noises and CTQ's are listed at the bottom. Process inputs and variables can be classified in two categories: controllable and noise parameters. If a process parameter could be adjusted at a certain value and be maintained within a particular range, it is considered controllable. If it's not possible to control the parameter due to due to constraints such as cost, physical etc., it's considered as a noise. Examples of noise parameters can be ambient temperature for a machining process, relative humidity in a gluing operation etc. [9].

Process Flow Legend	
Y- Output	What should the assembly look like when it leaves the station?
X- Input	What is required in order to achieve this outcome?
N- Noise	What can go wrong to prevent the operator from achieving the desired outcome?
C- CTQ	What is critical to make sure that the design and customer's expectations are met?

Table 4. Process flow legend used in process maps

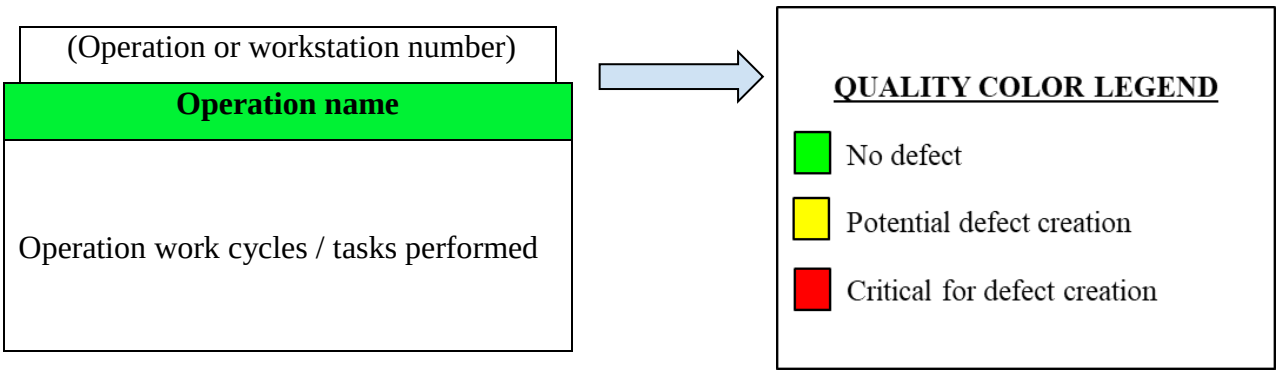


Table 3. Guidelines for process mapping

Analysis of process map is the last step. Opportunities to improve the process need to be understood by analyzing the process map. To do so, following questions can be asked:

- Which activities can be eliminated?
- Which activities do not add value?
- Where does excessive wait, rework, or inspection occur?
- Where can lead times of activities be reduced?
- Which operations can be performed in parallel?
- Where are there redundant activities?

6.5. Failure Mode and Effect Analysis (FMEA)

FMEA is another tool under process characterization which gives insights about the process under examination. Currently it's a very common tool to be used in manufacturing processes and operations excellence. FMEA is being used to identify where problems in processes or products may occur. The tool also identifies potential solutions to minimize the risks of problems and it includes detailed and thorough review of all potential failure modes. FMEA is a useful tool due to following reasons:

- It can be used to identify where problems may occur before a product is launched or a process is implemented which provides the opportunity for a more robust design.
- It informs how to set-up a process control plan.
- Assesses the risk associated with different failure points to determine urgency to correct the problem.
- The constant updating and reflecting of the FMEA promotes a learning organization.

Processes may change in time and needs to be updated so FMEA is a tool which requires active updating. For the preparation of FMEA, a team needs to be established which consists of experts from different expertise areas. FMEA meetings in Whirlpool consists a meeting manager who leads and sets the direction of the meeting, a quality manager and some technical supervisor who knows the process in depth. Workflow of the FMEA preparation is demonstrated in Figure 14.

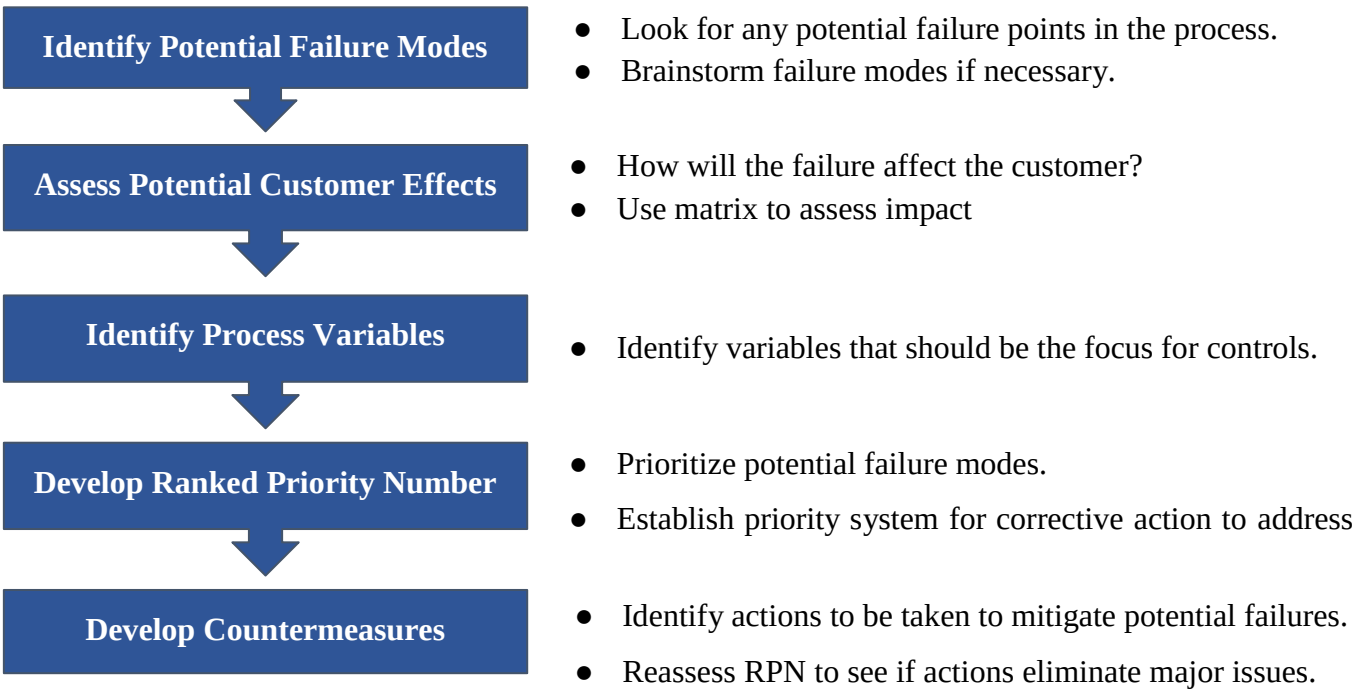


Figure 14. Failure mode and effect analysis workflow

The template used for Process FMEA in projects in Whirlpool is demonstrated in Table 7.

Process	**Function**	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**S e v e r i t y**	**Potential Cause(s) / Mechanism(s) of Failure**	**O c c u r r e n c e**	**Current Design/ Process Control PREVENTION**	**Current Design/ Process Control DETECTIO N**	**D e t e c t i o n**	**RPN**	**Recommended Action(s)**	**Responsibility**	**Target Completion Date**	**Actions Taken**
INDEX and/or Component, System, Process Step or Station Number/Name.	What must this design or process do? What is the purpose of this component, system, process or process step?	What could go wrong? How might the design / process / process step fail to meet the function? *(Also consider potential internal/external customer complaint quotes.)*	How does the failure mode effect customers, trade partners, manufacturing, the next process step, etc? What is their experience and/or reaction?		What in the design (DFMEA) or process (PFMEA) could cause the failure mode? Be specific and focus on causes within your area of influence.		What will be done to prevent the cause / failure mode from occurring? Examples: Design Changes, Analysis, Mistake-Proofing, Definition of Characteristics and/or Quantitative targets	What verification method will be used to detect the Cause or the Failure Mode?			What should be done to reduce the risk? Reduce either severity, occurrence, or detection.	Who is responsible for the recommendation?	When is it going to be done?	What was the result of the recommendation? Can refer to lab reports, print specifications, or PHM, etc.

Identify failure modes and their effects

Identify causes of the failure mode and controls

Determine the actions and assess effectiveness

Table 5. Failure Mode and Effect Analysis functions

Severity is the rating associated with the most serious effects for a given failure mode. It is rated with a five discrete ratings scale: 1,3,5,7,9. '9' is reserved for safety related effects. Higher severity equals a higher rating and a higher priority. The same scale is used for process and design FMEA's. The legend for severity index has been shown in Table 8.

Severity				
Rating	**Severity**	**Customer Description**	**Process Description**	**General Comments**
9	Hazerdous	Safety Failures Safety Faliure may occure with or w/o warning May be life threatening, greivous, Serious or Minor Injury Hazard	Safety Failures Safety Faliure may occure with or w/o warning May be life threatening, greivous, Serious or Minor Injury Hazard	Risk Assessment Required for production to proceed Risk Assessment Required be for product can be used or sold
7	Product Exchange	Extremely Dissatisfied Customer Loss of primary function Does not comply with regulatory requirements Risk of property damage during use, handling or installation	100% of product may have to be scrapped Repair time greater than 1 hour Risk of property damage during use, handling or installation	Major SIR machine repair (>45minutes) Customer may return product Customer may not buy product based on floor demo models
5	Service Call	Dissatisifed Customer Operable but at reduced performance level	Portion of product may have to be scrapped Repair time between 0.5 & 1 hour	May be a service call Customer will tell freiends Customer may not buy another product Customer would like a change to product
3	Minimal	Customer will see and be slightly annoyed Fit, Finish, Squeak, Rattle Noticed by 50% of customers	Minor disruption to production line Portion may have to be reworked	Customer will tell friends Customer would like a change to product
1	None	Has no effect on the customers	No effect	Will not be noticed

Table 6. Severity index for FMEA

Occurrence is an estimate of the likelihood that a Cause will Occur during the design life of a single product. Occurrence is also rated with a five discrete ratings scale: 1,3,5,7,9. The higher the occurrence number of the Cause of Failure, the higher the ratings and the priority. Whenever it's possible, the occurrence should be based on data. The same scale is used for process and design. The legend for occurrence index has been shown in Table 9.

Rating	**Occurrence**	**History**	**PPM**	**Range**	**Percentage**
9	Most certain to occur	No preventiion controls New Technology Little knowledge about factors, effects, noise	>50,000	1 of 20 or more	>5
7	Frequent	No preventiion controls New Technology Little knowledge about factors, effects, noise	5,000 to 50,000	1 of 200 to 1 or 20	0.5 to 5
5	Occasional	Some prevention controls New Technology proven in other industries Some Knowledge of factors, effects, noise	500 to 5,000	1 of 2,000 to 1 of 200	0.05 to 0.50
3	Rare	Strong prevention controls Existing Technology w/ new applictaion Knowledge of many factors, effects, noise	10 to 500	1 of 100,000 to 1 of 2,000	0.001 to 0.050
1	Improbable	Significant, proven controls Implemented design previously Proven predictability	<10	1 of 100,000 or less	< 0.001
0	Reserved for Severity '9' Line Item Closure	The hazard has been mitigated			

Table 7. Occurrence index for FMEA

Detection is a ranking of the ability of the best prevention/detection method listed to detect or prevent the Cause / Failure Mode. Detection is also rated with a five discrete ratings scale: 1,3,5,7,9. The more likely the Prevention/Detection method is to detect the Cause of Failure, the lower the rating. The same scale is used for process and design. The legend for detection index has been shown in Table 10.

Detection	Rating	Criteria	Process example
Very Remote	9	Very remote chance that the control will PREVENT or DETECT the failure mode, effect or cause	Controlled with indirect or random checks only
Low	7	Low chance that the control will PREVENT or DETECT the failure mode, effect or cause	Controlled with visual or double visual inspection only
Moderate	5	Moderate chance that the control will PREVENT or DETECT the failure mode, effect or cause	Controlled with SPC or gaging after parts have left staion 100% go/no go or variable gaging
High	3	High chance that the control will PREVENT or DETECT the failure mode, effect or cause	Error detection in subsequent operations Error detection in station Setup or first piece gaging
Almost Certain	1	Almost chance that the control will PREVENT or DETECT the failure mode, effect or cause	Defective part CANNOT be made Efforproofed by process/product design
Reserved for Severity '9' Line Item Closure	0	The hazard has been mitigated	

Table 8. Detection index for FMEA

Recommended actions column is used to document additional plans intended to reduce the Severity, Occurrence & Detection. Reduction can be accomplished by changing the design or process, improving the prevention method or improving the detection method, etc. Prevention methods that have not yet been verified (unproven) should be entered in this column.

RPN is (Risk priority number) an index which is used as an indicator to criticality of the operation. If RPN of an operation is above a certain level defined by the company, that operation need to be examined carefully and improvements have to be made in order to prevent the potential issue. In some cases, even if the RPN is below the maximum value set for criticality, that operation is considered to be critical if severity number is 9. For each critical operation, the improvement task is assigned to a person to be responsible and track the improvement process. After definition of the recommended actions, RPN is recalculated according to to-be state of the system.

6.6. Design of Experiment

Continuous improvement is a never-ending story. The purpose is to improve the manufacturing efficiency and reduce costs by optimizing the processes. Pareto is a very useful tool which allows us to detect the most frequent inefficiencies in processes. It allows us to prioritize and focus on the main problems. After detecting the problems, it is necessary to develop insights

and correct the inefficiencies. But it is not an easy task. One problem may have several reasons and studying all possible independent variables which potentially affects the issue is very time consuming and costly. DOE is a very useful method which enables testing multiple potential causes at the same time. DOE can be used to identify the critical parameters, reduce the variation, determine sources of variation and consequently to design higher quality product and processes.

Designed experiment is defined as the manipulation of controllable factors at different levels with the aim of observing their effects on dependent variables [10]. Controllable factors are independent variables which are process parameters (Xp's) indicated on section 5. The main goal is to first identify and second is to optimize the process parameters. To do so, it is necessary to understand the relationship between dependent and independent variables by making observations. However, observations can't be done without forcing the required conditions to the process. To test the process, firstly process parameters which potentially causes the quality issues should be identified. As mentioned before multiple parameters can be selected for DOE and their contributions to the issue could be identified by prioritizing them numerically. DOE answers two simple questions:

- Which factors influence the performance of the product or process?
- How should these factors be adjusted the best?

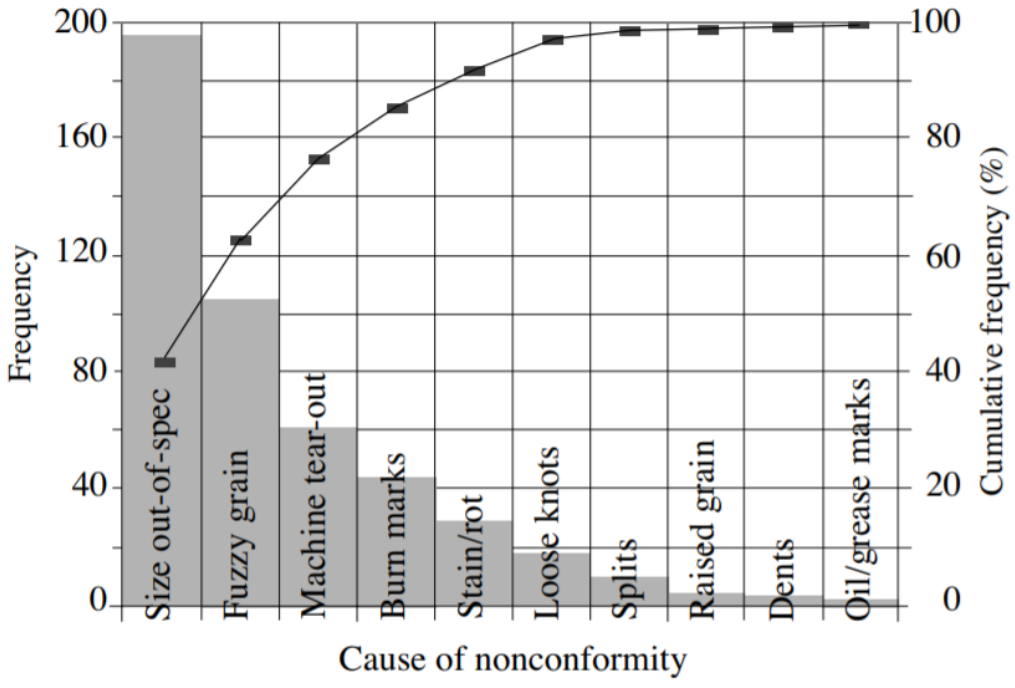


Figure 15. Pareto chart example [11]

First step is to recognize or foresee the problems by analyzing customer feedbacks, costs, EoL (End of Line) tests, in-line SPC data, scraps etc. Pareto charts is another useful tool to prioritize the occurrence of defects in sub-processes. In Whirlpool most of the workstations has up-to-date Pareto charts and they make the detection of problems easier. An example of Pareto has been shown in Figure 15.

Second step is to decide the experimentation strategy about how to run the experiment, how much data is needed, frequency and sequence of data collection etc. After the strategy, objectives of the activity must be defined. By asking right questions, the efficiency of learning will be increased significantly. This step includes a list of questions about the process in which we would like to learn by conducting the experiment. Last step before running the DOE is the definition of factors which has a potential effect on the process. Relevant factors could be listed by several methods such as experience, know-how, literature research, brainstorming sessions etc. [12].

6.7. Measurement System Evaluation

MSE is used to demonstrate if a measurement system is suitable for determining whether the measured characteristic is acceptable for the consumer or a downstream manufacturing process. Measurement systems are not always stable. Since it's not possible to expect a process to be stable and show no variation over time, the same situation is valid for measurement systems. Measurement is also a process and variations exist in these systems as well. As a consequence, they need to be tested and validated in a certain time frequency. In order to improve a measurement system, it must be understood what factors cause imperfections. The main characteristics of a measurement system are: discrimination, precision/repeatability, accuracy, reproducibility and stability. There are several factors which may drive the measurement system away from being perfect. Some of the factors are:

- Operator: for the same parts, different operators may get different measurement averages
- Reproducibility: capability of the operators may be different to get the same measurement averages for same parts
- Machine: different machines used for the measurement may give different averages for the same parts
- Others: day to day, shift to shift, supplier to supplier variations are possible.

A standard data collection for measurement system evaluation in Whirlpool has been done by following procedures and the procedure is illustrated in Figure 16.

- 5 parts are randomly selected from the line making subassemblies.
- 3 operators are selected to measure the parts. In this process, the operators are responsible for measuring samples of sub-assemblies.
- Each operator measures each part three times.
- The operators are instructed to use techniques and practices that they would normally use.

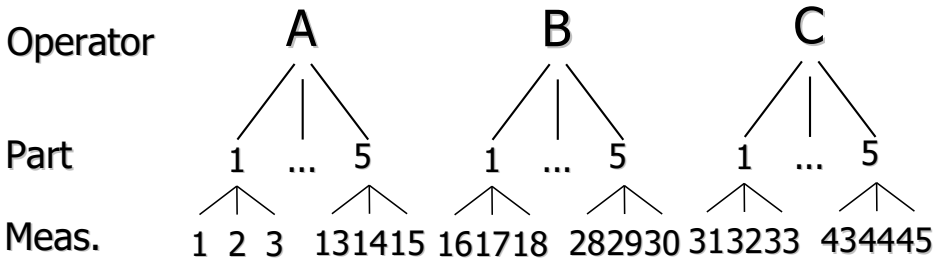


Figure 16. MSE data collection strategy

Collected data should then be analyzed by using Minitab to check if the characteristics of the measurement system are able to satisfy the minimum requirements. Minitab visualizes the data and gives outputs such as range charts, mean charts, box plots etc. Range chart shows if the measurement system stable in variation, consistent and predictable. Mean charts show if the measurement system is capable of distinguishing between parts. Box plots show if there's a distinct variation among operators.

7. Project i100

i100 is a new induction hob model developed by Whirlpool in which I took part and spent huge part of my internship period. It is a new induction hob model introduction project conducted through APQP by Whirlpool. Aim of this NPI is mainly cost reduction. The product consists of four main components; burner box, coil tray, electronic board and glass-bracket assembly. A representation of the main components of the product has been shown in Figure 17.

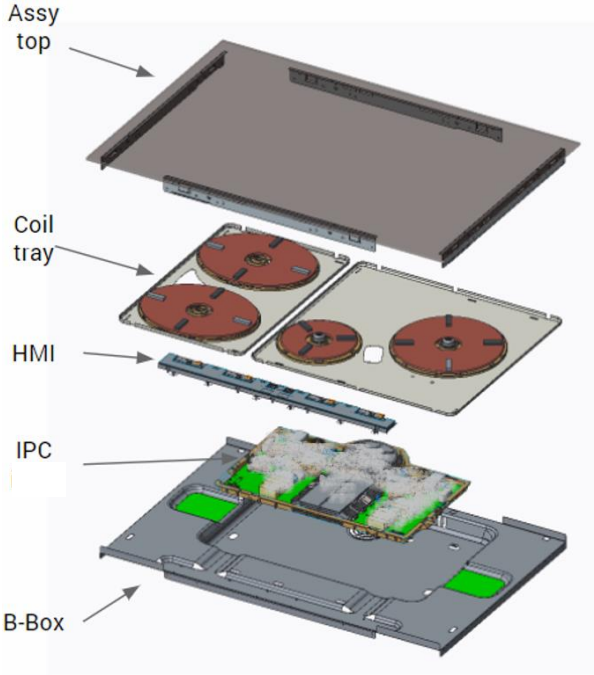


Figure 17. i100 main components

As in almost all APQP projects, there are external and internal suppliers involving into product development. In i100 case, coil tray, coils, IPC, burner box and glass of the top assembly are being produced by external suppliers.

Our main focus during my internship was to assign capability to coil-glass distance. It's a high impact characteristic defined by product design and the process was not able to meet the capability requirements. The aim was to improve the process and assign capability. In this section a comprehensive overview of the problem solving tools and techniques has been done.

7.1. APQP Activities and Structure

NPI requires coordination and management of many internal and external parties. APQP standardizes and assigns tasks for each group. The Operations Excellence team established for the product development consists 8 main teams which are:

- Whirlpool Production System
- Central Industrial Engineering
- Materials Engineering
- Energy, Environment, Health and Safety
- Quality
- Costing
- Plant Industrial Engineering

- Manufacturing Technical Leader

My focus during my internship period was the tasks related to Quality. The activities to be conducted by quality department within APQP scope has been listed in Table 11.

	PROJECT DELIVERABLES	OWNER
APQP PHASE 2 PRODUT DESIGN AND DEVELOPMENT	Special Characteristics (product)	Central Quality, APQP Lead
APQP PHASE 3 PROCESS DESIGN AND DEVELOPMENT	Process FMEA	Central Quality
	DFT [Design for Test / Test Coverage]	Central Quality
	Special Characteristics (process)	Central Quality
	Pre-launch Control Plan	Central Quality
	Process Instructions	Central Quality
	Preliminary Process Capability Study Plan	Central Quality
APQP PHASE 4 PRODUCT AND PROCESS VALIDATION	Measurement System Analysis / Gage R&R	Central Quality
	Preliminary Process Capability Study	Central Quality

Table 9. APQP Quality team deliverables

Comprehensive information of all these activities listed above are further explained in the following sections. Special characteristics studies are explained under CPM topic in section 5.

7.2. Critical Parameter Management

Critical Parameter Management is embedded within APQP phases. CPM activities are assigned to quality department as it can be seen in Table 11. Central quality supports product level characteristics and conducts process level characteristics studies.

CPM tracking of the products in Whirlpool is being done by using an Excel worksheet. As a first step it is necessary to understand customer requirements and categorize them by product attribute all. So the product attributes should be listed first. As an input for this activity, the data coming from master HoQ, FMEA's (safety, product) and field failure data has been used. The standard list in which Whirlpool uses for the definition of attributes contains 12 elements. While listing the attributes, a selection from those 12 elements should be done. Definition of each element is listed in Table 12.

Attribute	Definition
Aesthetics	Appearance of the product from the end customer point of view
Capacity	Usable space of the product on primary functional dimensions
Core Performance	Degree to which a product fullfills purchase drives for customer benefits; functions and related claims
Craftsmanship	Fit and feel of the product
Energy	Energy usage (efficiency. consumption. or comparison) and related claims
Installation & Logistics	Requirements from end of line. through distribution channels. and into customer homes
Noise & Vibration	Requirements related to product sound and vibration output (level and quality)
Reliability	Basic quality requirements of operating life (usually 1.4. and 10 years)
Service	Requirements regarding ease of service and diagnostics
Usability	Requirements related to operating product for intended function(s)
Safety & Codes	Compliance to agency. regulatory. and internal requirements
Stakeholder	Cost. target SIR/TCQ. architecture metrics. manufacturing. end of life requirements

Table 10. List of product attributes

Under each topic product level characteristics big Y's are branched in the next step. This step includes Translation of VOC into system requirements. Some examples of the Y's for the i100 product are; time to boil, browning distribution, pan detection, power deliver (to pot/pan), product installation etc. These are the voice of engineering that is translated from step one. Step 3 includes determination of intermediate y's for contributing subsystems/module sets. Subsystem level y's are identified for each Y at this step. For example, for a Y = "aesthetics of glass", a y is defined as "scratches in glass top" because scratches affect the aesthetics. As indicated in CPM section, step 4 is the determination of lower level characteristics and optimization of design and step 5 is the determination of the process characteristics and design optimization.

When I started taking a part of the project, the CPM process was already in step 3. Product level characteristics was already defined and one of the y's which is coil-to-glass gap, was not satisfying the process capability. As quality control team we mainly focused on one special characteristic subsystem level (little "y") which is coil-to-glass gap in the glass bracket assembly which is indicated as top assembly in Figure 17. That is a high impact characteristic and minimum expected Cpk is 1,67 as indicated in section 5.3. Under this y, there are many lower level process characteristics (X) which affects the product level characteristic. On the other hand, y affects 4 product level characteristics (Y's). Coil is the heating component of the product and the distance of the coil to the top glass is very important in case of heating performance. The Y's and y's identified at the time when I started the project has been shown in Table 13.

Product Level (Big "Y")	Subsystem Level (Little "y")
Time to Boil	Coil-To-Glass "gap" capability
Browning distribution	Coil-To-Glass "gap" capability
Pan Detection	Coil-To-Glass "gap" capability
Heat transfer (to pot/pan)	Coil-To-Glass "gap" capability

Table 11. Relationship of product level characteristics

As it can be seen from the relationship table, the coil to glass gap is very important for the customer satisfaction. The distance between coil and glass is determined by the value of z shown in Figure 18. The values are used to divide the assembly in pieces so that we can investigate them separately. Our main parameter is “z” which is hole to glass distance. The hole is the point where burner box with coil is screwed into assembly. z value is determined by y and x values. y is the glass-bracket gap and x is the hole distance.

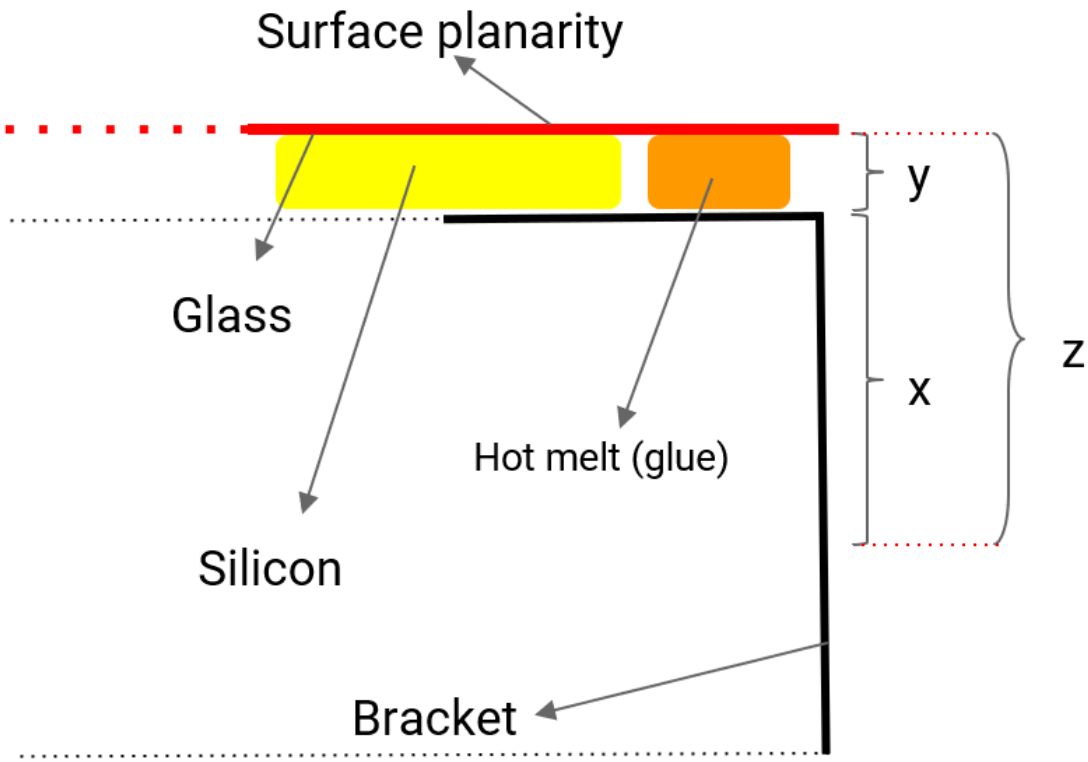


Figure 18. Glass-bracket assembly

Process capability studies has been done to see if the process can satisfy the requirements for x, y and z values. Capability studies are explained under section 7.3. It has been seen that the process is not sufficient for the project. After we discovered that the process is not capable, the

challenge is to identify the lower level process characteristics to satisfy the minimum capability for product level characteristics (y). Next step is to identify which process level characteristics (x's) are related to the coil-to-glass gap. To be able to solve this puzzle, first thing to do is to learn more about the process. Process characterization is used to better understand the process. In this context, process mapping, PFMEA, DOE, and MSE activities have been performed.

7.3. Process Capability

Coil to glass distance is determined mainly by glass-bracket assembly. The distance between glass and brackets on the assembly determines the heat transfer. The assembly contains four brackets and one glass. A representation of the glass-bracket assembly has been shown in Figure 19.

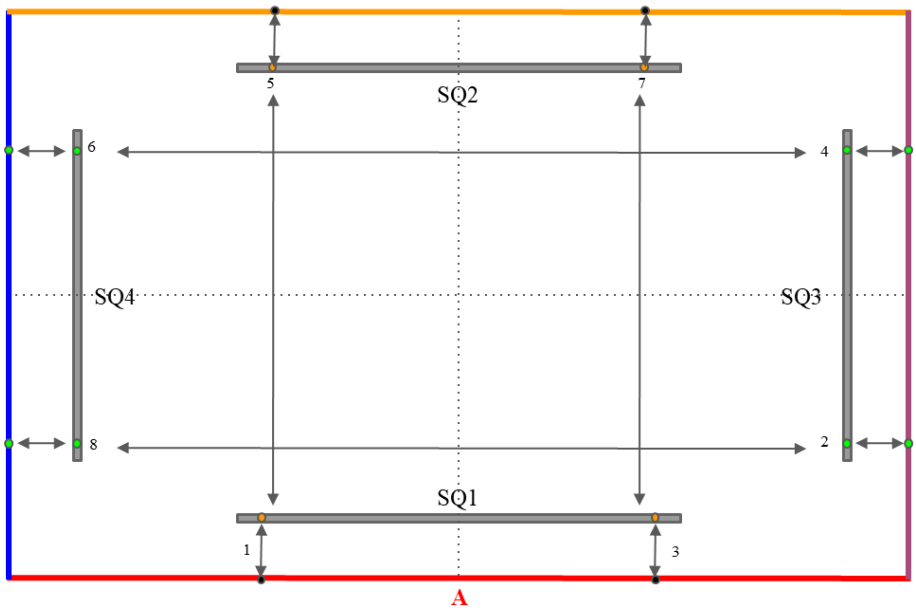


Figure 19. Glass bracket assembly scheme used for capability studies

The assembly consists of 2 components and they are being assembled by gluing process. Brackets are made by Whirlpool by stamping process and the glass comes from an external supplier.

For the first capability assessment of gluing process, 48 samples of assembly are collected in 2 different working days and morning and afternoon shifts. Process Design team defined the specification limits for the gap for a reliable heating as 0,8 - 1,1 mm. With the capability study we would be able to assess the processes. All samples are numbered according to production times. The strategy for the gap measurements is to assign numbers and measure for 8 points of 4 brackets. This allows us to analyze the inclination of each bracket as well. Process capability is measured for 8 points separately. The results are given in the Table 14.

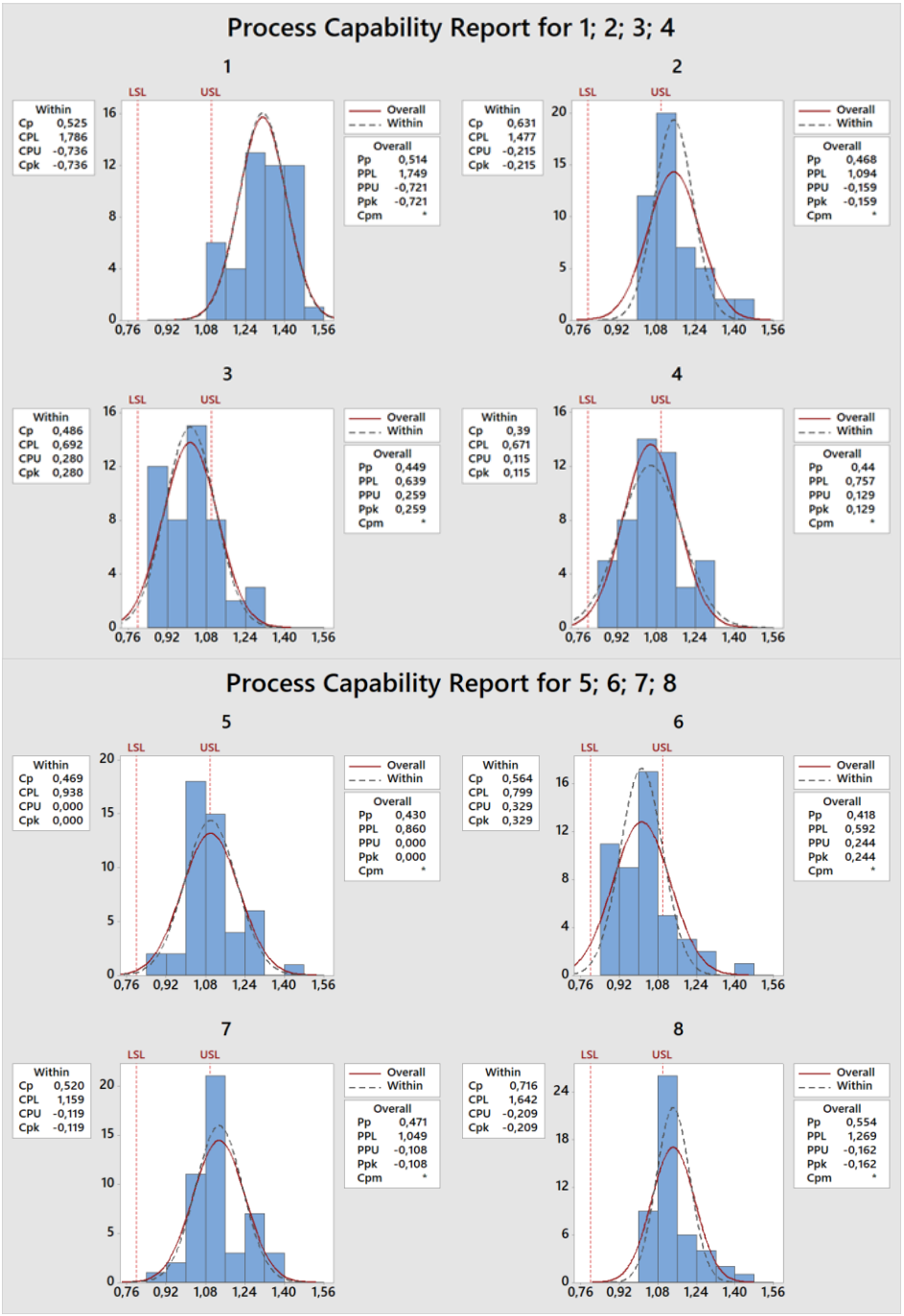


Table 12. Process capability analysis

As it can be seen from the table, Cp and Cpk values are far from the target value 1,67. The process is not able to satisfy the minimum requirements. This means x and xp's of the glass to bracket gap has to be found and optimized.

Capability study has also been performed to assess the capability of stamping process. Process map of the stamping process can be seen in section 7.4. As an input a stainless steel coil has been used. Stamping machine produces 2 brackets in one stamp. Those two brackets are named as "matrice 1" and "matrice 2". By doing this we will be able to observe the variations between

2 brackets. There are 3 key dimensions of brackets that has an influence on glass-bracket gap asindicated in Figure 20.

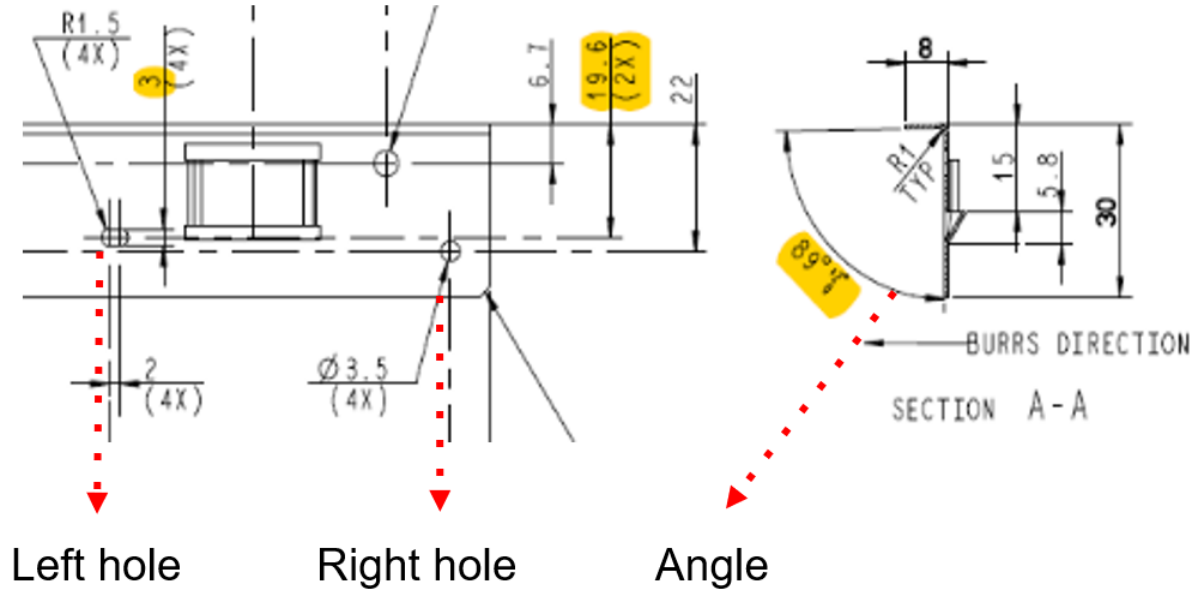


Figure 20. Key dimensions of the brackets

Sampling strategy for the capability study is as follows:

- 48 samples have been collected in total
- 24 samples of matrice 1 and 24 samples of matrice 2
- Samples have been collected from 3 times of the process. Process starts when it's loaded with a new coil. 16 from the beginning of a new production, 16 from the middle and 16 from the end. This helps us to analyze the contribution of the coil dimensions to the problem.

Tolerances for the hole positions are given as +/- 0,1mm and 90 +/-1mm for the angle. The results of the capability analysis for hole positions and angle are given in Figure 21.

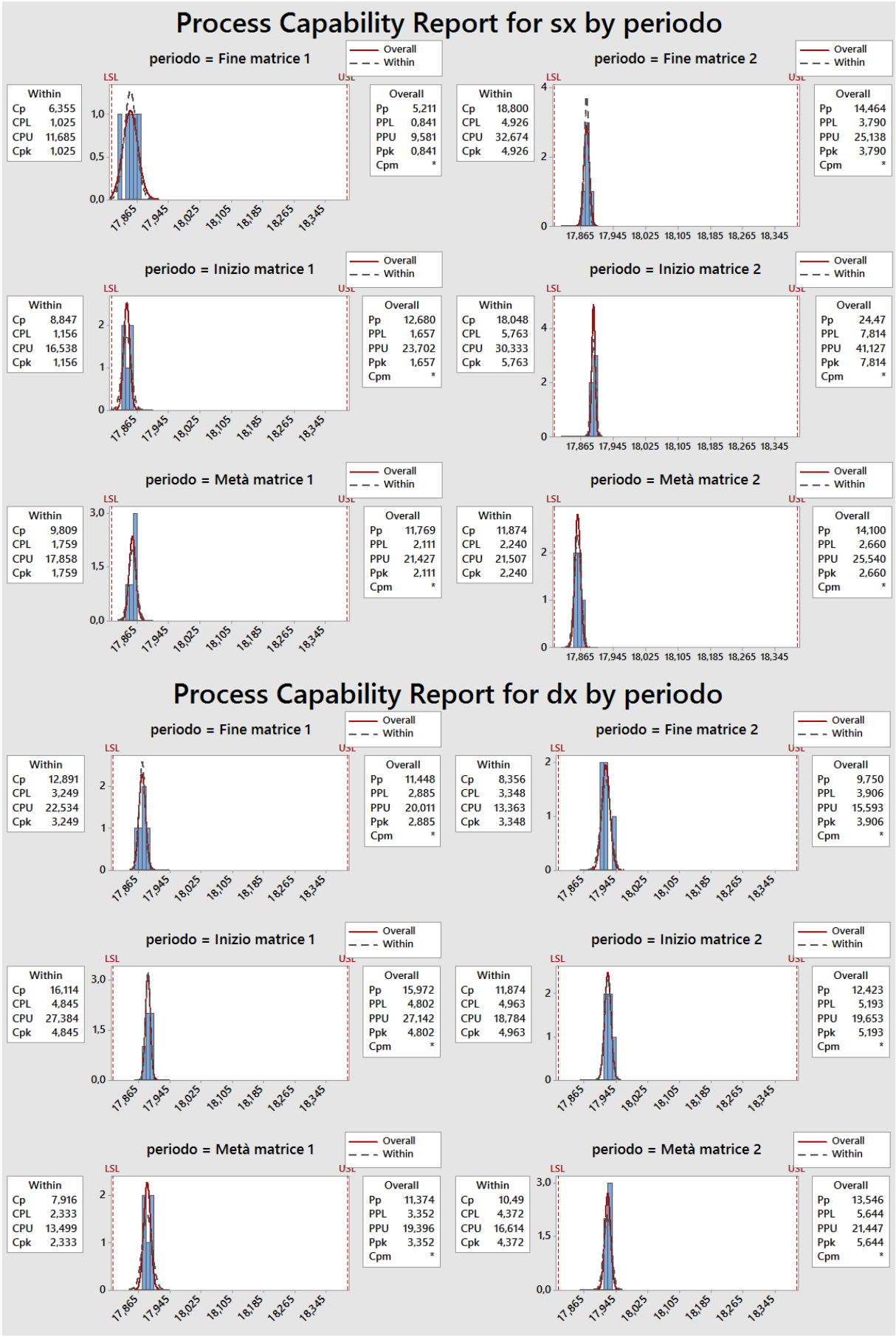


Figure 21. Process capability for hole distances of brackets

7.4. Process Mapping

In order to learn more about the process and to detect the potential failure modes, process mapping has been done first. Coil to glass distance is affected by glass-bracket assembly. Process capability of stamping and gluing processes are under desired limits. Stamping is the process which uses steel coil as an input and turns it into brackets. The process consists of 12 operations as shown in Figure 22.

Cpk of the stamping process is very low as indicated in section 7.3. Distortions in bracket angle and hole distance may result in failure on gluing process and as a consequence influences the glass-bracket gap.

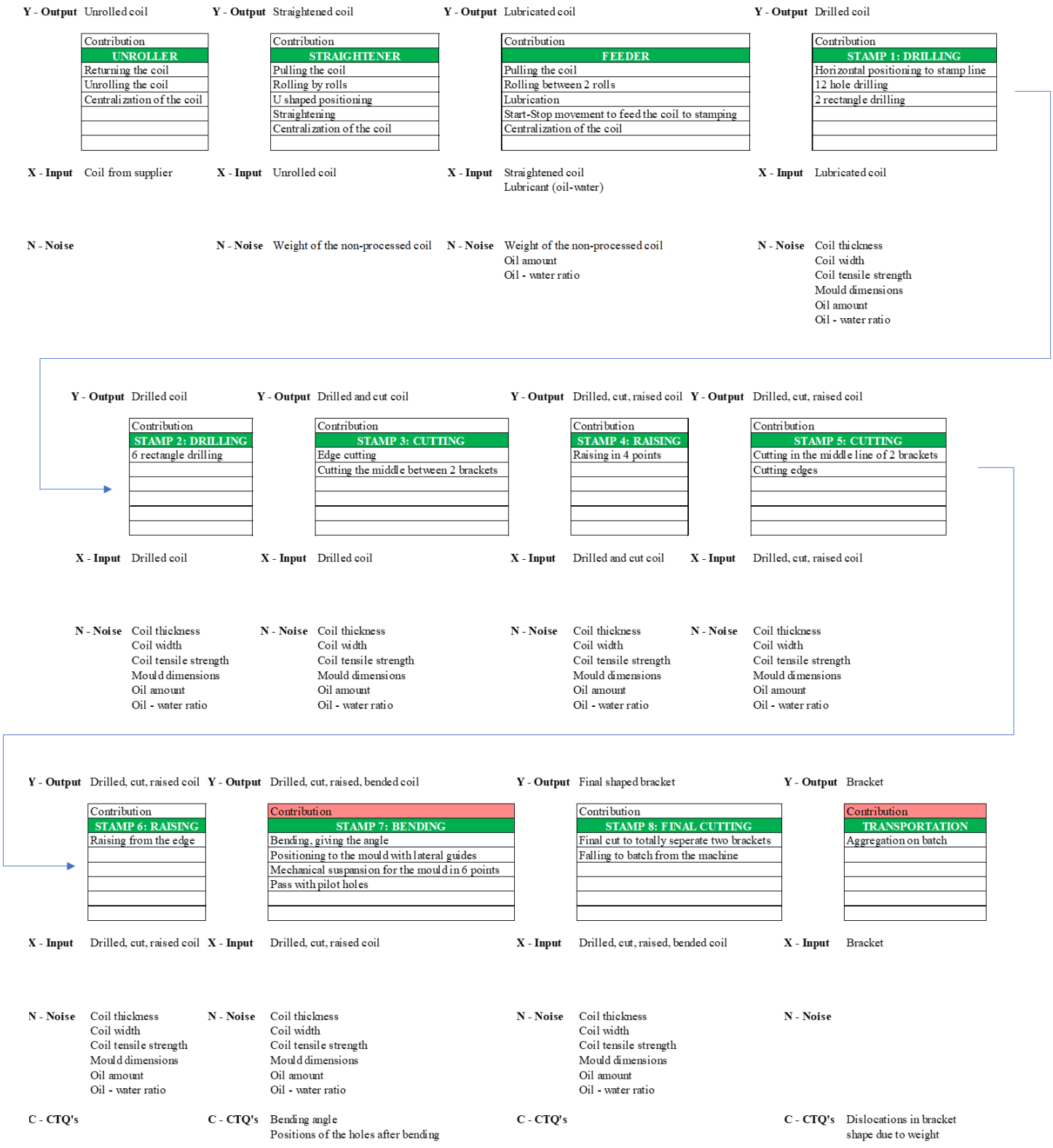


Figure 22. Stamping process map

7.5. Measurement System Evaluation

Measurements for the capability analysis has been performed by using a feeler gauge which has 0,5mm of tolerance. The use of the tool for gap measurement has been shown in Figure 23.

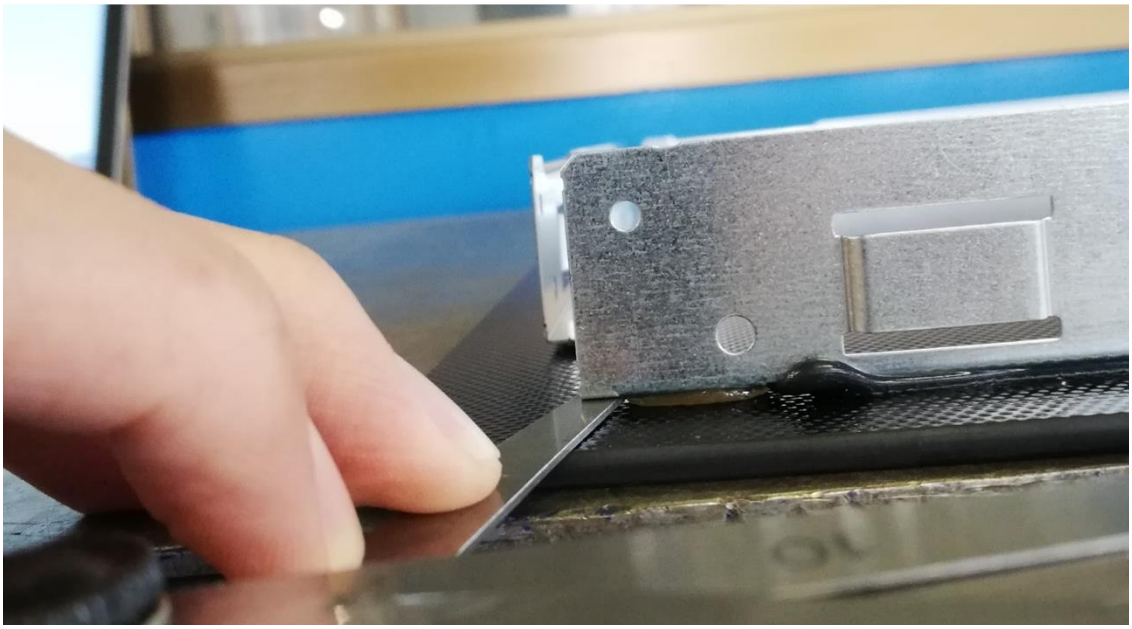


Figure 23. Gap measurement with feeler gauge

Evaluation of the measurement tool has been done by MSE. For this purpose, extra measurements have been performed by 2 operators Emre and Vamsi. 5 samples are randomly selected among 48 samples and measured 2 times by each operator. The data collected has been shown in Table 15.

Operator	Seq.	Glass	Glass - Bracket Gap				Glass - Bracket Gap			
		#	1	2	3	4	5	6	7	8
EMRE	1	1	1,2	1,05	1,05	1,15	1	0,85	1,1	1,15
		2	1,2	1,05	1,1	1	1,05	0,95	1,15	1,1
		3	1,45	1,1	1	1,05	1,15	1,05	1,2	1,15
		4	1,3	1,25	0,95	0,95	1,2	1,1	1,25	1,1
		5	1,25	1,15	0,95	1	1,1	0,95	1,05	1,15
EMRE	2	1	1,25	1	1,05	1,1	1,05	0,9	1,1	1,15
		2	1,25	1,05	1,15	0,95	1,15	1	1,15	1,1
		3	1,45	1,1	1	1,05	1,15	1,05	1,25	1,2
		4	1,4	1,25	1	1	1,25	1,1	1,25	1,2
		5	1,3	1,1	0,9	1	1,1	0,95	1,05	1,1
VAMSI	1	1	1,2	1,05	1	1,1	1	0,9	1,05	1,15
		2	1,2	1,05	1,15	1	1,1	0,95	1,15	1
		3	1,45	1,25	1	1,15	1,15	1,15	1,25	1,2
		4	1,35	1,25	1	1,05	1,2	1,15	1,2	1,15
		5	1,25	1,1	0,95	1	1	1	1	1,1
VAMSI	2	1	1,2	1,05	1,1	1,1	1	0,9	1,1	1,1
		2	1,2	1,1	1,2	1	1,05	1	1,15	1,05
		3	1,45	1,15	1	1,1	1,1	1,05	1,25	1,2
		4	1,4	1,3	1	1	1,2	1,1	1,25	1,15
		5	1,3	1,15	0,95	1	1,15	1	1,05	1,1

Table 13. MSE Data

Tolerance limits for the glass-bracket gap are defined as 0,8-1,1mm. The feeler gauge has sensitivity of 0,05mm. This tool was preferred since it was already available which does not imply any extra cost, and it was the least time consuming among all available measurement tools. The Minitab analysis results has been shown in Figure 24.

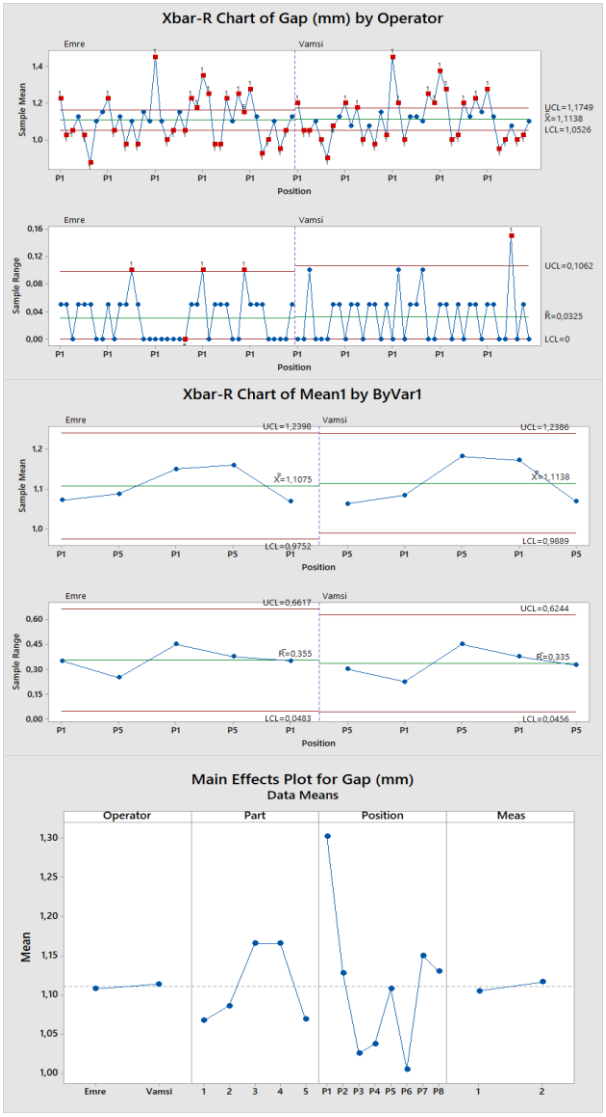


Figure 24. MSE analysis results

It has been seen from the analysis that the discrimination was not enough with the tool used and the precision was not enough for our SPC objectives. After assessment of the results, it has been decided to use an alternative measurement tool. Our next solution was using MetraScan 3D laser scanning measurement tool which is more time consuming and costly. The laser scanning tool has already been passed MSE and more precise than feeler gauge. It enables us to observe variables other than the gap as well; such as glass surface planarity, bracket-to-bracket distance etc. According to laser measurements, the capability did not show any severe difference and it was still not able to satisfy the minimum design requirements for the gap.

Figure 25. MetraScan 3D laser scanning tool [13]

7.6. Design of Experiment

DOE is a very useful tool to understand the relationship between variables of the process and product parameters. There are two product parameters in glass-bracket assembly which we encountered problems in quality and we have decided to use DOE to be able to understand the causes of the phenomena.

First critical parameter is glass-bracket gap. This gap is very important since it has a direct contribution on glass to coil distance and it affects the heating performance of the hob. For a reliable heating, the quality limits for the gap has been designed as 0,8 - 1,1mm by the design team. A representation of the gap has been shown in Figure 26.

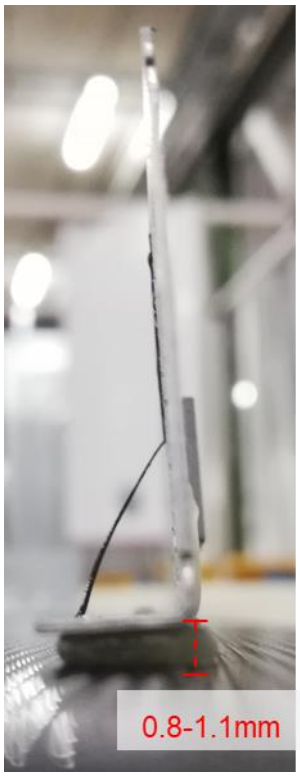


Figure 26. Glass-bracket gap

By using process FMEA and process maps, potential contributors to the issue has been listed as:

- Bracket temperature (Hot vs cold)
- Hot melt temperature (High vs low)
- Curing time of silicone (Longer vs shorter)
- Pallet shape (Good vs bad)
- Pallet setup (For glass size bigger vs smaller)
- Glue quantity (High vs low)
- Bracket parts (Distorted vs not)
- Glass parts (Planarity flat vs distorted)

16 samples of glass-bracket have been glued into each other in scope of DOE. An FRD for the DOE study has been prepared by Master Black Belt of our Quality Control team as shown in Figure 27.

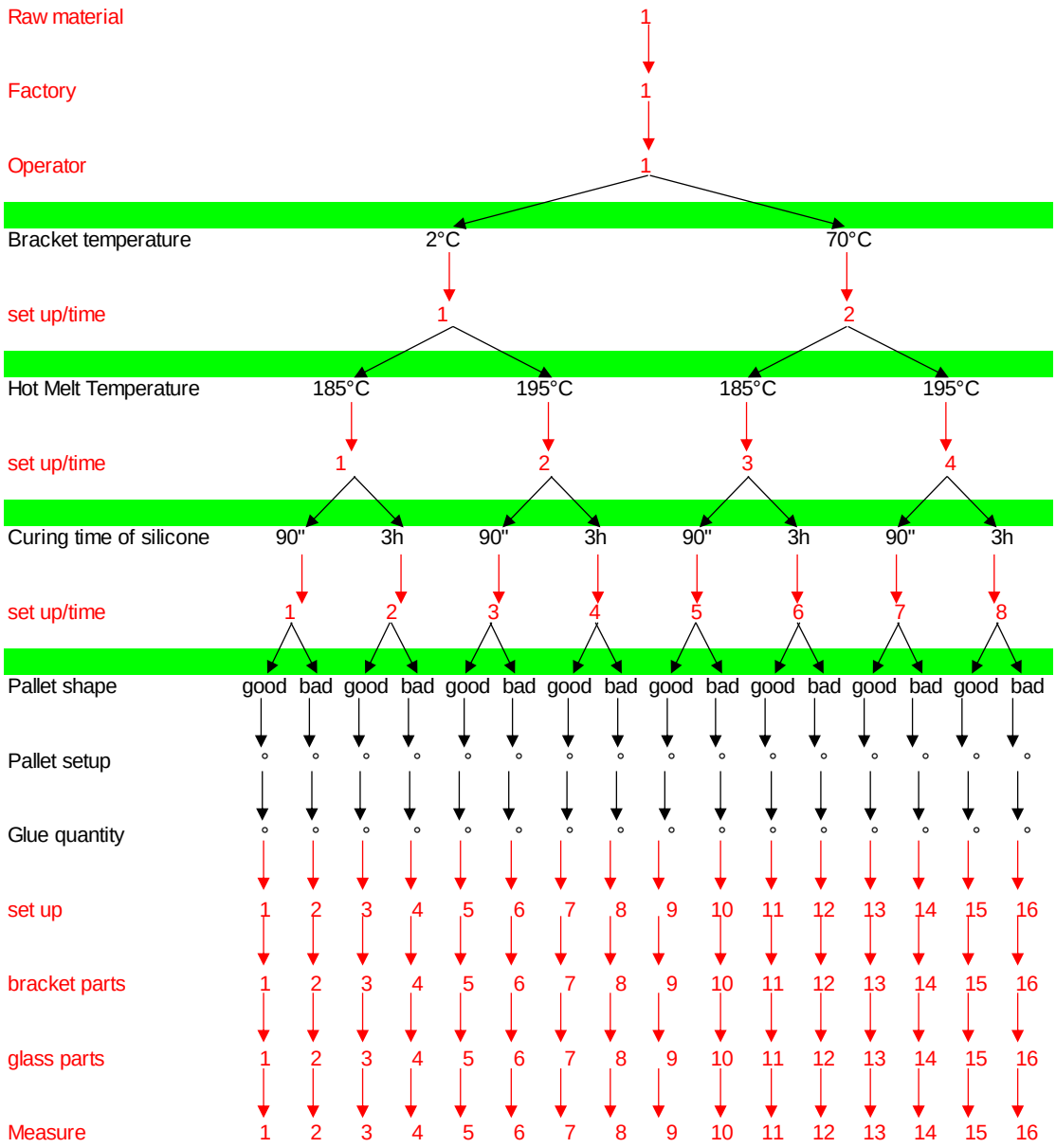


Figure 27. FRD of DOE for gluing process

Brackets which have been measured during capability studies has been used in DOE. All brackets are numbered and classified as good or bad according to their parameters (angle, distortion etc.) Half of the brackets are heated to 70°C and the other half are assembled in 2°C.

Hot melt (glue) temperature affects the quality of the assembly since it may result in rapid or slow cooling. When the glue cool down slowly, glass-bracket distance may get distorted. So it has been tested in 185 and 195 °C to understand the relationship.

Silicone cools down slower than the hot melt since it requires higher curing time. So we wanted to test it with curing time of 3 hours and 90 seconds to see if the distortions are caused by movements before the silicon gets cured. We have let half of the assemblies wait 3 hours before being transferred to containers.

i100 has two different dimensions of glass. We have tested half of the samples with smaller glass size and the other half with bigger size. Pallet setup changes for each size.

Glue quantity is adjustable. Since its' curing time is lower than silicone it may be the main determinant of the gap between glass and bracket. We have set the quantity for lower and higher quantities than standard.

Surface planarity of the glasses are measured by using a special measurement tool which touches 123 points. They are classified as distorted or good parts and used half by half in the DOE.

Pallet shape could be a potential contributor since it may distort parts of the assembly. All pallets are not exactly the same. Some has different holder heights and some are very dirty compared to others. To understand the variations, all pallets are characterized and they are classified as good and bad. A summary of all these parameters listed above has been shown in Figure 28.

Factors, Level s & Prediction Table

Easy to manipulate	Minitab code	Factor	(-1)	(+1)	Predicted Best level	Predicted Importance (H - M- L)	Theories
N	Bracket_T	**Bracket temperature**	2°C	70°C	70°C	M	Factory environment conditions, warmed up with machine, cooled down below normal. It is expected a better glueing conditions with warmed parts.
N	Hot_Melt_T	**Hot melt temperature**	185°C	195°C	195°C	H	It simulates the glue temperature when applied in the process. Expected better resulsy when at 195°C
Y	Glue_Qty	**Glue quantity**	min	max	min	H	Less gap is expected with minimum value of the glue.
N	Curing_t	**Curing time of silicone**	90 sec	10800" (3 h)	3h	HH	It simulates the storage time before usage. Expected better results with higher time.
Y	Pallet_sh	**Pallet shape**	good	bad	good	HH	It simulates a not maintained pallet. Good pallets are expected to have better results.
Y	Pallet_stp	**Pallet setup**	60 cm	70 cm	NA	NA	it simulates the 2 dimensions of the hobs. No specific prediction available but expected betetr situation with 60 cm set up

Figure 28. Parameters and values used in DOE

For all the samples of assembly, the details of glass, bracket used are noted down in an Excel sheet. The gap results are measured after the assembly as indicated in Figure 29.

Glass #	Hot_Melt_T	Curing_t	Pallet_sh	Pallet_stp	Glue_Qty	Glass - Hole Dist,(mm)				Glass - Bracket Gap				Glass Planarity				Pallet Bracket - Glass Dist,				Distorted? (angle)	Bracket Temp
						Left	Bott	Right	Top	Left	Bott	Right	Top	Left	Bott	Right	Top	Left	Bott	Right	Top	Visual chec	°C
1	185°C	>3h	good	70 cm	max	19,2	18,9	19,2	19,23	1,41	1,04	1,27	1,38	-0,23	-0,40	-0,12	-0,37	1,29	1,06	1,32	1,16	N	2
2	185°C	>3h	bad	70 cm	min	19,1	19,1	18,83	18,74	1,24	1,34	0,99	1,02	-0,16	-0,21	-0,14	-0,53	1	0,69	0,8	0,96	N	2
3	195°C	>3h	bad	70 cm	max	19,3	19,2	19,05	19,07	1,46	1,38	1,24	1,26	-0,20	-0,46	-0,20	-0,43	1	0,69	0,8	0,96	N	70
4	195°C	>3h	good	70 cm	min	19,2	19,1	18,95	19,15	1,47	1,18	1,23	1,29	-0,18	-0,38	-0,12	-0,37	1,29	1,06	1,32	1,16	N	70
5	185°C	>3h	good	60 cm	max	19,3	19	19,18	19,35	1,44	1,27	1,45	1,47	-0,17	-0,22	-0,02	-0,23	1,29	1,06	1,32	1,16	N	70
6	185°C	>3h	bad	60 cm	min	19,1	18,8	19,23	19,26	1,21	0,92	1,36	1,42	-0,16	-0,16	-0,17	-0,12	1	0,69	0,8	0,96	N	70
7	195°C	>3h	bad	60 cm	max	19,7	19,6	19,4	19,52	1,78	1,67	1,49	1,6	-0,28	-0,27	-0,27	-0,40	1	0,69	0,8	0,96	N	2
8	195°C	>3h	good	60 cm	min	18,9	18,4	18,6	19,25	1,06	0,54	0,76	1,51	-0,14	-0,11	-0,06	-0,15	1,29	1,06	1,32	1,16	Y	2
9	185°C	90 sec	good	70 cm	min	19,1	18,4	18,6	19,35	1,15	0,5	0,86	1,48	-0,08	-0,13	-0,04	0,02	1,29	1,06	1,32	1,16	Y	70
10	185°C	90 sec	bad	70 cm	max	19,5	19,1	19,1	19,5	1,65	1,25	1,25	1,64	-0,06	-0,09	-0,05	-0,11	1	0,69	0,8	0,96	N	70
11	195°C	90 sec	bad	70 cm	min	19,4	18,6	18,7	19,35	1,51	0,87	0,86	1,6	-0,08	0,12	-0,02	-0,2	1	0,69	0,8	0,96	Y	2
12	195°C	90 sec	good	70 cm	max	19,3	19,1	19,05	19,65	1,31	1,18	1,13	1,73	-0,06	-0,07	-0,03	-0,07	1,29	1,06	1,32	1,16	N	2
13	185°C	90 sec	good	60 cm	min	18,9	18,4	18,57	19,2	0,96	0,5	0,66	1,29	-0,13	-0,11	-0,06	-0,18	1,29	1,06	1,32	1,16	Y	2
14	185°C	90 sec	bad	60 cm	max	19,5	19,3	19,18	19,43	1,64	1,33	1,28	1,52	-0,09	-0,2	-0,15	-0,16	1	0,69	0,8	0,96	N	2
15	195°C	90 sec	bad	60 cm	min	19,3	19,1	19,1	18,96	1,45	1,24	1,27	1,13	-0,14	-0,11	-0,09	-0,14	1	0,69	0,8	0,96	N	70
16	195°C	90 sec	good	60 cm	max	19,4	19,1	19,04	19,31	1,56	1,26	1,22	1,5	-0,2	-0,17	-0,03	-0,2	1,29	1,06	1,32	1,16	N	70

Figure 29. DOE Results

To evaluate the data collected, it is necessary to analyze the data and prioritize the contributions of different variables to the issue. Which brings us into a very useful tool; the Pareto chart. Master black belt of our team has used the MiniTab program to analyze the data. Graphs and charts have been illustrated in Figure 30.

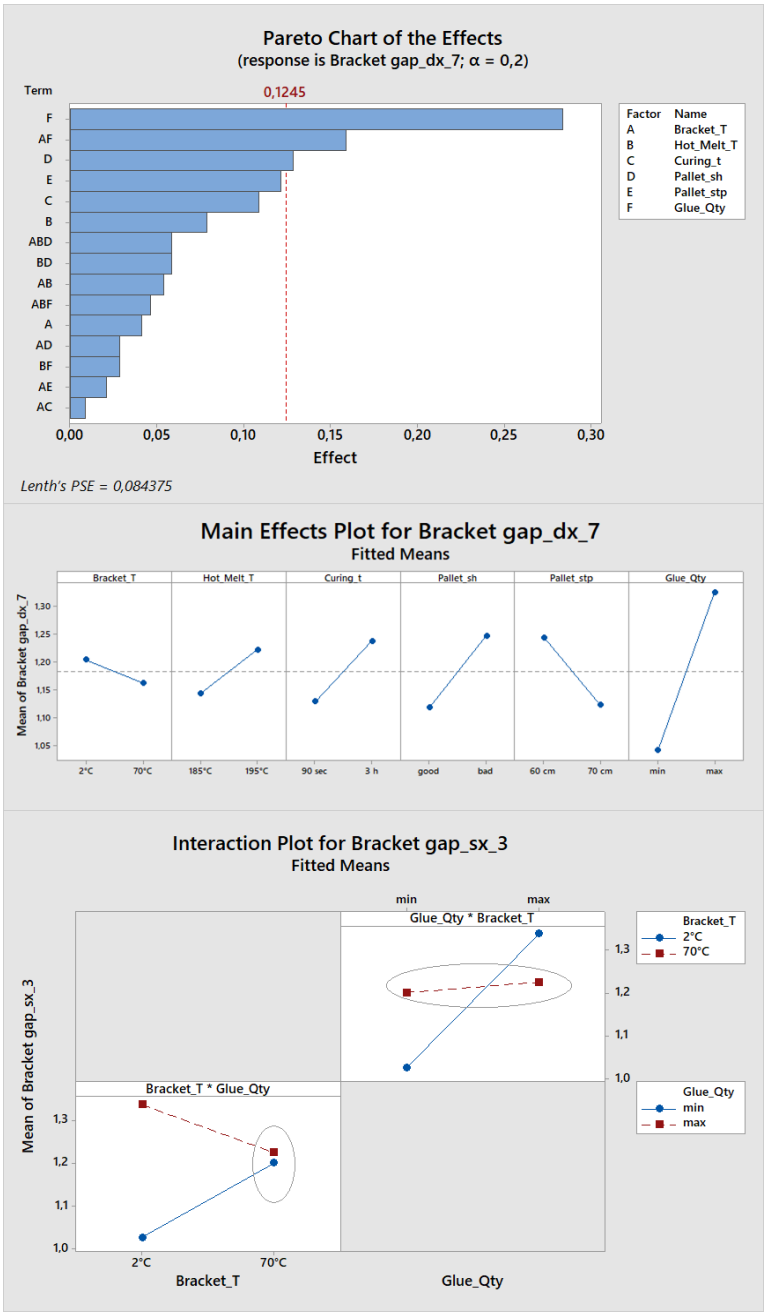


Figure 30. Pareto Chart, Main Effects, Interaction for glass-bracket gap (from top to down)

As it can be seen from the Pareto chart, glue quantity is the major contributor to the issue. The other two graphs prove that as the quantity gets higher, glass-bracket gap increases. So it can be concluded that optimizing the glue quantity could solve the problem.

Bracket temperature is the second main contributor according to the Pareto chart. By looking at the second and third graphs we understood that bracket temperature and glass-bracket gap are inversely proportional to each other. As temperature increases, gap decreases. So optimizing the bracket temperature would help solving the issue. A bracket heating phase should be added before adding the hot melt. The recommended action has been planned and delivered to plant quality team.

Third main contributor is pallet shape. Planarity and height of the holders, cleanliness of the pallet are important for a reliable assembly. The problem can be seen in Figure 31.

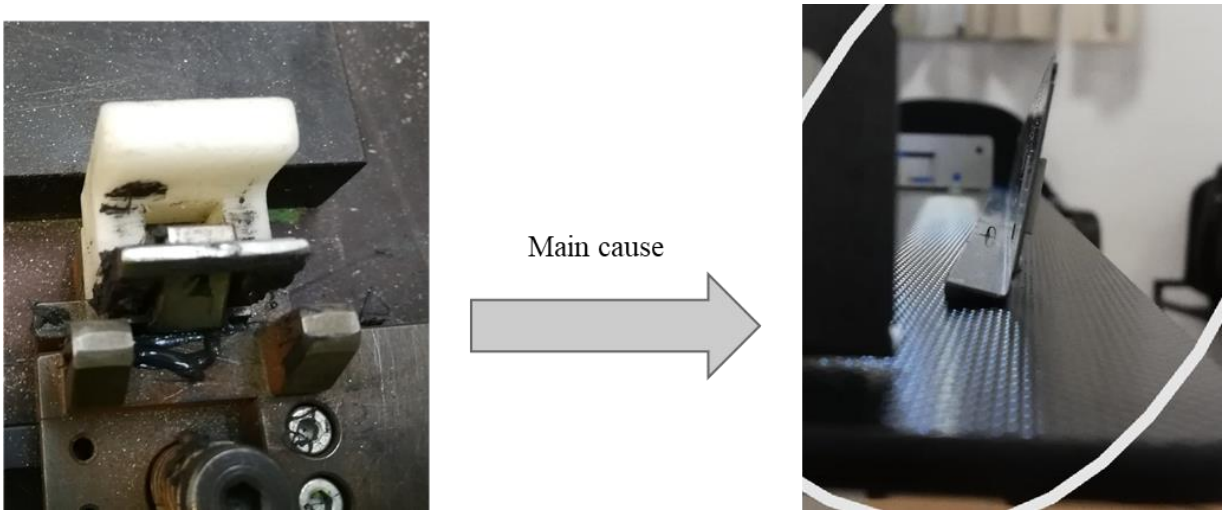


Figure 31. Silicon drops of pallet

Bad bracket positioning on pallet results in distorted bracket angle. It's caused by silicon drops on pallets during gluing process by creating dirt. Recommended action is scheduling a cleaning plan which needs to be performed every 1 hour.

8. Conclusion

The i100 project was a very big and promising project which is a perfect example of industry 4.0. The company sees the project as a future state of all other production lines of Whirlpool. As the quality control team, we worked in collaboration with many teams, external and internal suppliers. Thanks to the project I improved my skills in teamworking and project management while learning technical literature of quality control as well.

The use of APQP and CPM helped teams to be more structured and made it easy for them to keep in touch in every step without getting lost in such a complex project. Although APQP is being used mainly in the automotive industry, Whirlpool has perfectly implemented APQP into

their production system. I mainly took part in activities assigned to quality control by APQP and shared them step by step in my report.

The project has not yet finished while I completed my internship. Our activities comprise many pieces of research and problem definitions. We have also defined recommended actions to be completed by several parties taking part in the project. The main goal was the launch of new product implementation without any imperfections in the production system.

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