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Optimization of pneumatic actuators with the use of design for Six Sigma methodology

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ABSTRACT

Purpose: The first aim of this paper is to optimize pneumatic actuator behavior using a structured approach to define and control system factors in order to achieve targeted output values. The second aim is to present a structured optimization process supported by Measurement System Analysis (MSA) and Design of Experiment (DOE) tools in practical applications.
Design/methodology/approach: A complete approach for optimizing an unknown system with a structured approach known from DFSS methodology is used in the practical example of pneumatic actuators. DFSS methodology requires a detailed project definition, but ensures good quality of measurement data and a well-prepared optimization process supported by known DOE tools.
Findings: The structural approach for system optimization known from DFSS methodology provides a good fit for the optimization of a pneumatic actuator to achieve specified targets. Teams working on system optimization not only set the parameters but also gather a large amount of valuable information about how the mentioned system works, and what the main factors influencing the final results are. The gathered knowledge can be used to create a robust design with the lowest possible cost.
Research limitations/implications: The results obtained from Measurement System Analysis and Design of Experiment are valid only for chosen factors and, importantly, only in the range used in both statistical methods. Extrapolation outside the statistical model boundaries is forbidden. Therefore a critical aspect is to agree within the project team on the correct factors and their levels.
Practical implications: The optimization of pneumatic actuators can be achieved by a structured approach consisting mainly of project definition, measurement system analysis and final optimization through DOE tools to achieve given targets for displacement and time simultaneously.
Originality/value: First Time Through optimization of a pneumatic actuator system as an example of any system treated as a black box, meaning a system with an unknown relationship between input and output. Design for Six Sigma methodology presented in a practical approach.
Keywords: Design for Six Sigma; Optimization of system; MSA; DOE; First Time Through

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1. Introduction

There are different approaches used for system optimization, namely (i) trial-and-error, (ii) the analytical method, (iii) different models of Design of Experiment (DOE).

The weakest approach is the so-called 'trial-and-error' which basically has no structure. There are steps taken to adjust input factors in order to achieve output in the range of a given specification. There are numerous trials leading to failures, not improving understanding of system behaviour and only providing solutions by chance.

The analytical method, usually used by scientists, is based on analysis of a mathematical model representing the system under investigation. The disadvantage is that the approach requires full understanding of the physics and complexity of a given system and, additionally, complex mathematical analysis needs to be performed.

Another possibility is to control all the possible factors by changing one factor at a time (OFAT). This requires many tests, which can provide solutions towards specified targets, but does not detect factor interactions, therefore the optimum solution can be missed easily.

The proposed approach is taken from Six Sigma methodology. This method is a structured approach starting with the problem definition, followed by measuring of the baseline, then gap analysis linked with improvement actions and finalized by a control phase. The key tool used for the improvement phase is Design of Experiment (DOE), which allows the system to be optimized in line with target values [7,10,12,14].

2. Background

This paper presents the Six Sigma approach in system optimization. The selected system is a pneumatic actuator providing displacement for a certain distance in the required time. The paper describes an experimental study performed on a pneumatic actuator system in a laboratory environment, however, it can also be easily extended to an industrial environment. An example of such a system can be found on production lines in the automotive industry. Pneumatic actuators are used to deliver components or sub-assemblies during the assembly process on a production line. The key parameters of the described system are distance and response time. The problem lies not only in achieving the targeted displacement and response time, but low variation is also mandatory to maintain the stability of system functions. Any failure can cause an interruption to manufacturing process tack time or incorrect assembly operation. The pneumatic actuator system is presented on Fig. 1, this system is used to deliver components to the production line with the following requirements:

a. the distance of component delivery to production line in the range of 44 to 46 cm,
b. the time of component delivery must be in line with tact time, a range of 2.45 to 2.55 s,
c. the ability to transport components of different weight.

3. System optimization

In a classic approach, the engineer optimizing the described or similar system uses analytical methods which require precise models or costly trial-and-error experiments. Such an approach results in a long development lead time of the complete system. Additionally, such an approach is not optimized in terms of performance and total cost, as the factor interactions or correct preparation can be missed. Six Sigma offers both a process and tools helpful in numerous development or repair projects, one of which could be system optimization [1].

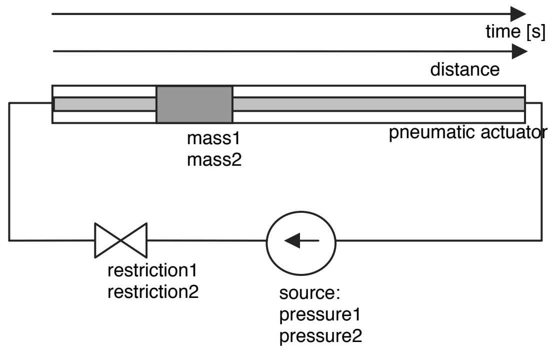

Fig. 1. Pneumatic actuator scheme

Six Sigma is a structured approach for repair projects or process/product development projects, known as Design for Six Sigma (DFSS). The first type of project is run through the well-known DMAIC process. The first letters of this acronym come from 5 phases called: Define, Measure, Analyse, Improve and Control. The development path is led by the DMADV process which stands for Define, Measure, Analyse, Design and Verify [2,3,4].

This article presents the idea of each step of the DMADV process used for process development. The DMADV process starts with Project Definition [5,6].

4. Define phase

The define phase is intended to start the project, including team and timing creation, definition of the project with a problem description and objective statement including metrics definitions. Metrics are used to track changes achieved during a Six Sigma project.

A sample of a problem description is attached below:

Problem description: There is a pneumatic actuator system designed to provide specified movement to the distance of n, but the time is also considered as a metric of secondary importance to be achieved in m seconds.

5. Measure phase

The measure phase is dedicated to analysis of the measurement system used to provide data for analysis in the next project steps. Two measurement systems have been identified which provide the following information: time and displacement. In non Six Sigma projects, the measurement system is not deeply analysed, potentially only calibration and bias is checked. Six Sigma provides roadmaps for measurement system analysis supported by a variety of statistical tools like: (i)Linearity and Bias, (ii) Stability (XR charts) , (iii) Gage Type I and (iv) Gage Type II. Not only measurement equipment is taken into analysis because the measurement system includes equipment, personnel, method and parts used in the measurement process. As previously described, time and distance are measurement systems used in our example project. The first and also key step in Measurement System Analysis (MSA) is planning. The process, method and equipment must be analysed, the range of interest must be specified and, finally, a measurement experiment must be designed. The standard approach for MSA is to use a tool called Gage R&R, set up as follows: at least 10 parts are measured by 2 operators with 2 trials. Such a set up is needed in order to understand repeatability (the difference between two measurements of the same operator) and reproducibility (the difference between the average measurement of operator 1 and 2) [8,9,15].

The statistical output of MSA for distance is presented on Fig. 2. The most important is to understand where the problem is located: repeatability and / or reproducibility. In the presented case, a greater problem has been found in reproducibility – which means the difference in measurement between operators 1 and 2. As an improvement action, standardization and training is needed. The key is to understand the 95% Confidence Interval for the measurement system, which is $\pm 2\sigma$ (Standard Deviation). For distance, the 95% CI is equal to ± 1.6 mm. The project team needs to find out if such precision of the measurement system is sufficient. In our case, we approved this measurement system even though improvements are possible. Visualization of Gage R&R is shown on Fig. 3. For example, the upper graph on the right-hand side presents all measurements for each component. In extreme cases, the range of measured values is up to 2 mm. The graphs below present our main problem, which is the difference between the first and second operators. The last graph on the right-hand side presents the average measurement per component for operators 1 and 2, which are shown in different colors. The graphs on the left-hand side represent details of statistics which are omitted in this article for a clear overview of the described project.

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.662500	97.11
Repeatability	0.487500	71.46
Reproducibility	0.175000	25.65
OP	0.175000	25.65
Part-To-Part	0.019697	2.89
Total Variation	0.682197	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.813941	4.88365	98.55
Repeatability	0.698212	4.18927	84.53
Reproducibility	0.418330	2.50998	50.65
OP	0.418330	2.50998	50.65
Part-To-Part	0.140346	0.84208	16.99
Total Variation	0.825952	4.95571	100.00

Fig. 2. Statistical output of Gage R&R for distance

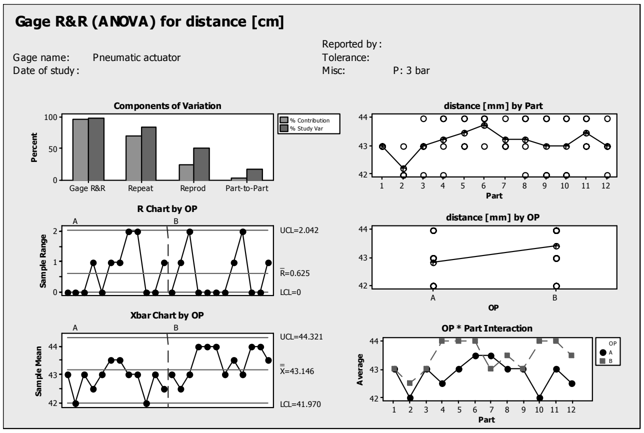

Fig. 3. Graphical output of Gage R&R for distance

The same set up of components was used to measure the time needed to achieve the desired distance. Figure 4 shows statistical output for Gage R&R analysis for a time where we can see that the main problem exists in repeatability. Repeatability is defined as the difference between measurements for the same operator per component.

Fig. 5. shows a graphical representation of statistical output for Gage R&R on time measurement. For instance, the middle graph on the right-hand side shows no difference between the measurements of operators 1 and 2.

Gage R&R

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0023907	92.95
Repeatability	0.0023907	92.95
Reproducibility	0.0000000	0.00
OP	0.0000000	0.00
Part-To-Part	0.0001813	7.05
Total Variation	0.0025719	100.00

Source	StdDev (SD)	Study Var (6 * SD)	%Study Var (%SV)
Total Gage R&R	0.0488943	0.293366	96.41
Repeatability	0.0488943	0.293366	96.41
Reproducibility	0.0000000	0.000000	0.00
OP	0.0000000	0.000000	0.00
Part-To-Part	0.0134635	0.080781	26.55
Total Variation	0.0507141	0.304285	100.00

Fig. 4. Statistical output of Gage R&R for time

The project team decided to approve the measurement system even though there are possibilities for further improvement. The decision is supported by analysis of the confidence interval for the measurement of time and displacement, which are practically acceptable for this project. Further analysis can be conducted with the use of data provided by the measurement systems. Besides approval of the data source, we also understand the variations caused by measurement system.

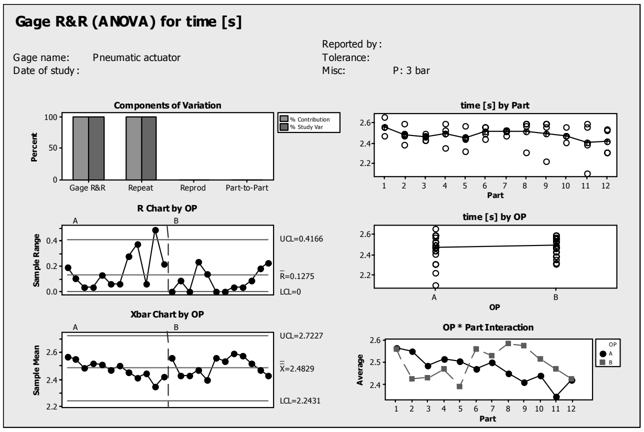

Fig. 5. Graphical output of Gage R&R for time

6. Analyse and design phases

After the measure phase, a Six Sigma project moves to the analyse phase. The analyse phase in the DMADV flow is meant to review the screened design concept in line with the requirements gathered in the define phase. The chosen design concept needs to be detailed in the design phase [5,15].

The most powerful tool for the design phase is Design of Experiment (DOE). This tool is used to optimize any system that can be controlled by more than 1 factor and has at least 1 response. The key item for success is correct planning for the experiment, which needs to include discussion on the factors enabling control of the certain system; noise factors and agreement how the experiment will be conducted. A DOE experiment is a structured plan of tests with multiple factor combinations and with measured responses for each combination. Statistics are used to calculate the main effect plot, interaction and provide an equation representing behaviour of our system. This equation is a key element for DOE, because we can calculate the optimum solution based on it [3,11,13].

The DOE plan is a matrix built as a combination of a factor's levels. A factor is a parameter that allows control of the system response, and factor level is the set up of a certain factor. One of the important rules for DOE is the independence of factors, which means that a change of 1 factor doesn't change the set up of other factors. In our experiment, there are 3 factors selected, each of which has two predefined levels, coded as -1 and +1. The graph presented on Figure 6 shows the so-called Main Effect Plot. The Y- axis is a response from our system for a different set up of control factors. Looking at the difference between the response for low (-1) and high (+1) settings for a specified factor, we can find the main effect factor for our experiment. In the presented case, the main effects can be found for the 'pressure' and 'restriction' factors. The 'mass' factor has a low effect on response, as the time and distance can be achieved for two different component types represented by two values of mass.

The main effect plots are interesting to review to understand the effect of factors on response. It is key to understand the calculation method for this plot. Each value for a taken factor level (e.g. pressure: -1) is calculated as an average of all responses where a certain factor has been set to a defined level. Because the average can lead to incorrect conclusions, it is good practice to look at a Multi-Vari chart. An example of such a graph is presented on Figure 7, where the response is shown as the time for different combination factor levels. The 'pressure' factor is represented by different symbols visible in the legend on the right-hand side. The 'mass' factor has been divided by means of panels, the left-hand side of the graph represents mass with a setting of -1, the right-hand side stands for the setting +1. The last factor, 'restriction', divides each panel to the left (-1) and right-hand (+1) sides. In the given example, it is visible on the Multi-Vari chart that mass has a low effect on response (no inclination of the green line) and strong effects on restriction and pressure.

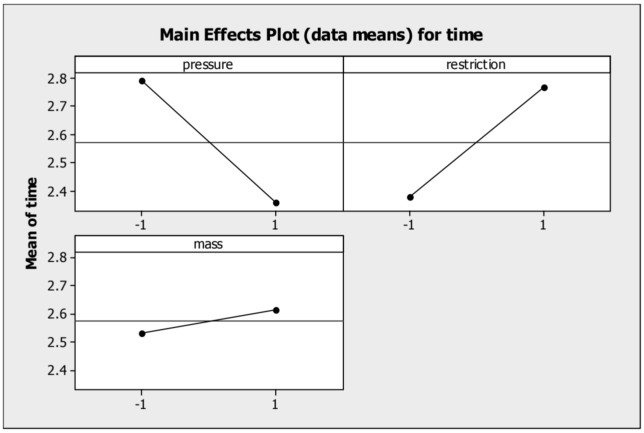

Fig. 6. Main Effect Plot for time

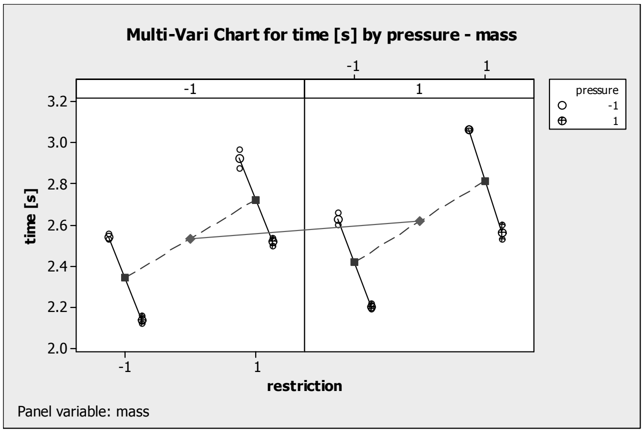

Fig. 7. Multi-Vari Chart for time.

The relationship between the 3 discussed factors and response distance is shown on Figure 8. The main effect on distance is caused by the 'restriction' factor.

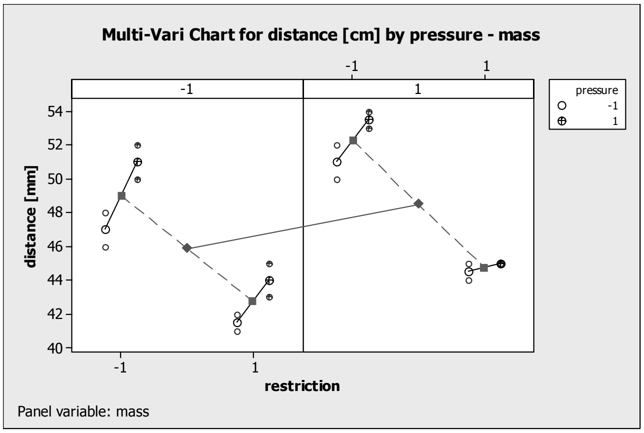

Fig. 8. Multi-Vary chart for distance.

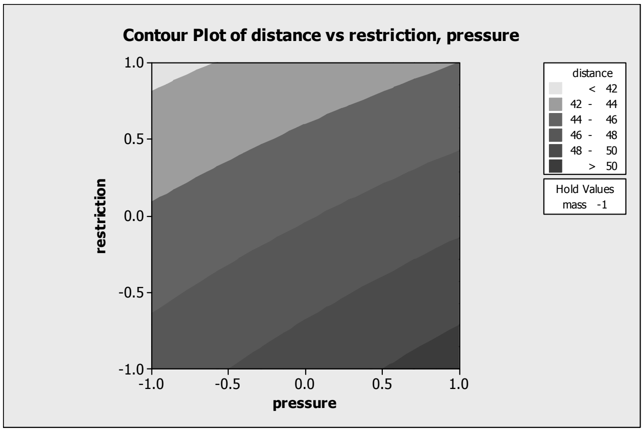

Fig. 9. Contour plot for distance

It should be noted that the main effects for both responses are driven by the restriction and pressure factors. The contour plot (Figures 9 and 10) represents response in a scale shown by different colour scaling versus 2 dimensions. On each contour plot, it is possible to find areas where the response meets the target. The earlier specified targets for our responses are the following:

- distance: 44 to 46;
- time: 2.45 to 2.55.

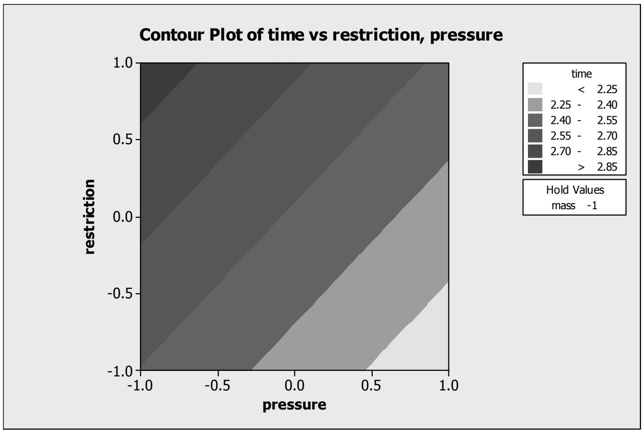

Fig. 10. Contour plot for time

7. Conclusions

The Six Sigma approach for system optimization was found to be very successful. The reason is First Time Right results guaranteed by correctly followed Six Sigma process and tools used to answer key questions to topics.

The first key question was project definition. It has been observed that a detailed project definition is often omitted in engineering projects. The correct project definition MUST understand customer requirements, and provide a clear project objective supported by target values for the main project deliverables.

The measure phase ensures correct quantification of the project problem or requirements and a sufficient quality of input data by Measurement System Analysis (MSA)

The analyse and improve phases are concentrated on the data driven approach to finding the root cause of problems or key solutions and implement in project boundaries.

The verify phase looks at performance to ensure that project requirements are fulfilled in the long-term period.

Such a combination of process and powerful tools will always win against a trial and error approach.

Contour plots are a graphical representation of the equation provided by DOE in a range of levels for selected factors. The project team needs to find an area which is in line with our target values and find a corresponding level of two factors. Taking as an example the contour plot for distance drawn versus restriction and pressure (Fig. 9), there is an area where the response is in line with the target range, being 44 to 46 cm. For this range, several combinations of factor pressure and restriction can be chosen.

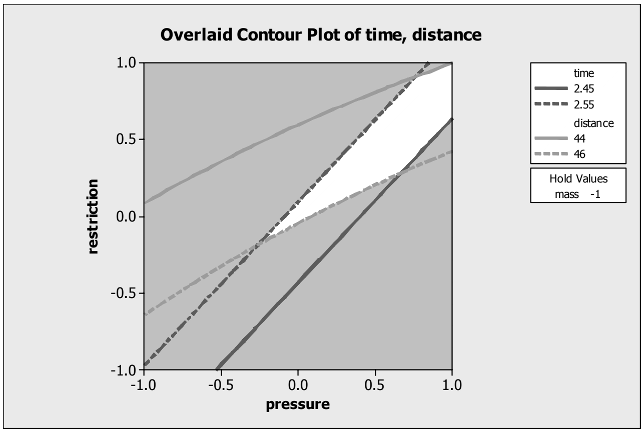

Fig. 11. Overlaid contour plot of time and distance

However, there is a second requirement for response time specified as a range of 2.45 to 2.55 s. The contour plot for time response is presented on Fig. 10 where, as on the previous contour plot, the range where the target is fulfilled can be easily found.

The key aspect is to achieve both targets at the same time and therefore the overload contour plot is shown on Fig. 11. Green lines represent the range where distance is in line with its target, red ones represent fulfilment of the target for time response. The white colour represents the area where both targets for their responses are met. This means that levels of both factors must be obtained within the white area, the best in the middle zone to minimize potential off target responses.

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