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Tools for Advanced Control Processes in Plastic Injection Moulding Technology

Eliška Cézová (0000-0002-1000-3411)
Department of Designing and Machine Components, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Prague 6, Czech Republic. E-mail: Eliska.Cezova@fs.cvut.cz

This article describes some of the tools used for quality control in injection moulding. The quality control tools are introduced and their use is demonstrated in the next section with a practical example. The selection of appropriate methods was based on proven quality control methods that were chosen to work in synergy with each other. The use of FMEA, Ishikawa diagram and Pareto diagram isdemonstrated by a practical example.

Keywords: Quality control, control processes, injection moulding, plastic technology, Ishikawa diagram, FMEA, Pareto Diagram

1 Tools for advanced control processes in plastic injection

All modern manufacturing plants must implement and adhere to strict quality control and management standards. Not only is the quality of the products verified and managed, but also the operating condition of the machines and any breakdowns are monitored, from which an appropriate and timely maintenance plan can be derived. To maintain and increase productivity levels, quality management must strive for continuous improvement in production, aiming at more efficient processes, reducing costs. If a company stops improving its processes, it will (sooner or later) be overtaken by competitors.

In the past decades, a number of basic quality management tools have been developed and implemented for effective quality management. In the following section, we will discuss some of these quality management tools, which include FMEA (Failure Mode Effects Analysis), Pareto diagram and Ishikawa diagram. With the help of these tools, the manufacturing process can be thoroughly documented, which gives the best chance for its control and optimization, see [1] and [2], [8], [9], [10].

In general, by adopting an appropriate product quality management system, better results, happier customers, and more efficient processes can be achieved, leading to reduced production costs and increased productivity. The proportion of well done work (i.e. defect-free products) increases and the number of rejects decreases. Most established companies have usually adopted an ISO 9001 quality management system or follow ISO 10004: 2010 - Quality management system - Customer satisfaction - Guide to monitoring and measurement. Nowadays, quality management is an integral part of the production process and its management. At each step of the production process, quality control of the product (or individual operations) is carried out by production operators or dedicated quality control personnel. It is a well-documented fact that modern production techniques, modern machinery and streamlining of the production workflow lead to stable and high quality final products. This can be further supported and improved by effective education and training of production, maintenance and inspection personnel, see [4] for more details.

This article focuses on the specific case of injection moulding production as an example for the application of advanced quality management. The plastic injection moulding technology is described in detail in [7], including the time involved in the process. This paper can be seen as an introduction to a more detailed description of advanced quality management and process control tools.

2 Defects in the plastic injection moulding process

The clogged inlet system can occur due to the wrong choice of material. The most appropriate material usually is a pure granulate (possibly mixed with a chosen colour dye), see Figure 1 (which does not block the inlet system). An example of inappropriate material can be, for example, poorly crushed plastic with dye (see Figure 2), which when used often blocks the inlet system. This leads to the machine failure that stops the entire production cycle, which results in downtime and consequent economical losses.

***Fig. 1** Pure granulate*

***Fig. 2** Crushed plastic dye*

Figures 3 to 7 show examples of defective mouldings.

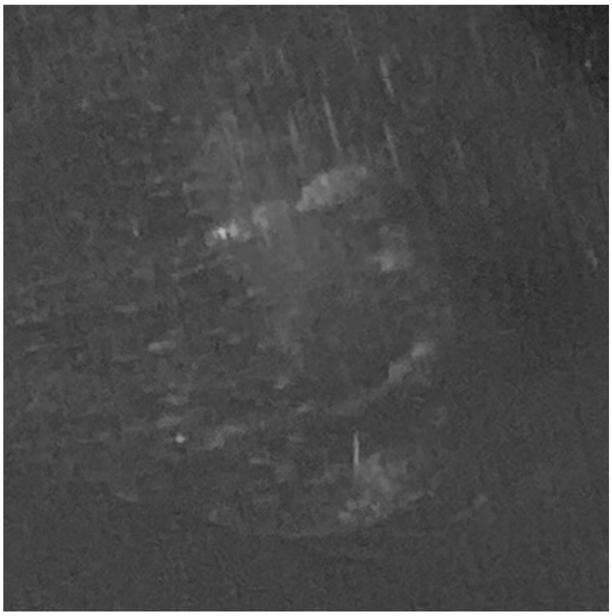

***Fig. 3** Faulty product with bubble and local change of surface colour*

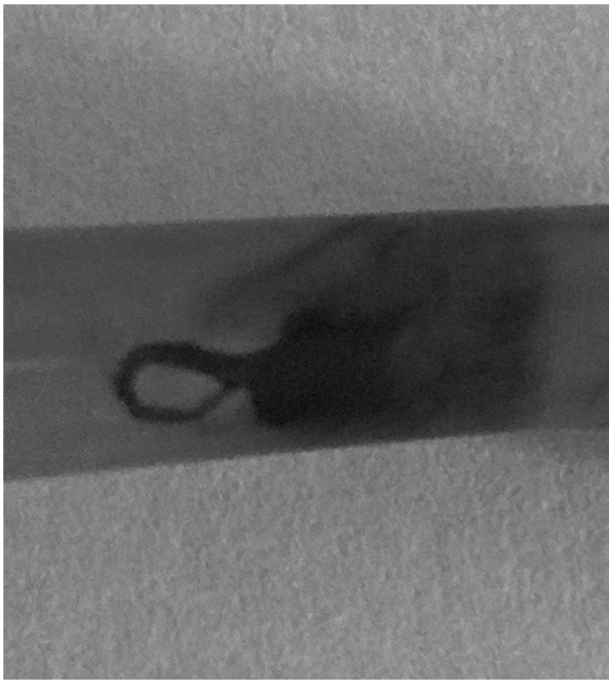

***Fig. 4** Faulty product*

***Fig. 5** Faulty product flash*

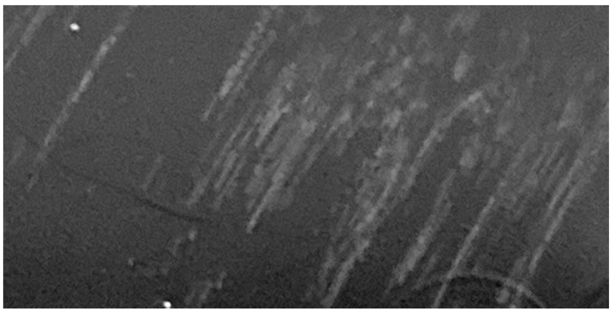

***Fig. 6** Faulty product with silvery stripes*

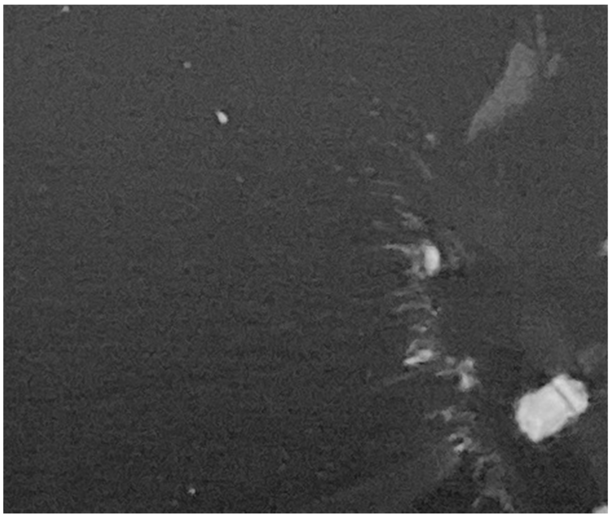

***Fig. 7** Faulty product uncoloured material*

3 Identification of causes of defects in plastic injection

The identification of causes for all defects is a crucial and inevitable step in the process management and optimization. The Ishikawa (or fish-bone) Cause-and-Effect diagram shown in Figure 8 is an example of a technique that may be used to simplify and formalize the identification of individual causes leading to defects and faulty products.

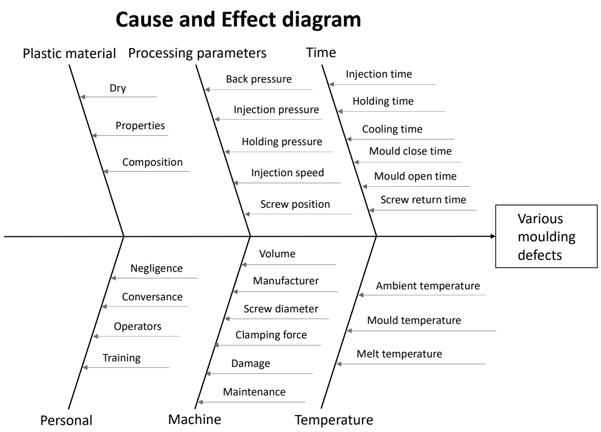

***Fig. 8** Ishikawa diagram for identification of cause-effect relations in plastic injection moulding*

The fishbone diagram is useful in industry, so we can analyse the problems in plastic injection moulding, make a comprehensive analysis.

It is necessary to analyse the plastic material, check its properties, the flow rate of the material (material that has high flow rate can be processed faster). If we use crushed plastic, we need to set the correct size of the crushed material. Quite often then the machine gets jammed because large pieces are not able to be melted properly by the machine. If we focus on the processing parameters, we can adjust them in this way, for example, reducing the injection speed, reducing the adhesion pressure, reducing the injection pressure, increasing the position change, reducing the cylinder temperature, reducing the mould temperature, slightly reducing the back pressure, reducing the initial screw position, etc.

There may also be improper mould filling (inadequate mould design), mould deflection, mould material, poor moulding workmanship. Uneven cooling would cause a difference in plastic flow, plastic on the hotter sides should flow faster.

Another cause could be a problem with the moulding machine, for example, that the clamping force has been incorrectly selected (clamping force is not sufficient, causes flashing of parts). It is also necessary to check if the plates of the moulding machine are worn or damaged. Another problem may be directly with the design of the part, as the wall thickness may be unevenly designed, etc.

More details on this topic can be found, e.g., in [5] and references therein, together with the description of some other useful techniques.

4 FMEA in plastic injection

FMEA (Failure Mode and Effects Analysis) is an analytical method used to ensure that potential problems are taken into account and addressed during product and process development. FMEA can be used in the design stage of a process as well as in the analysis of the existing production process.

The Failure Mode and Effect Analysis (FMEA) procedure is described in the CSN EN 60812 standard. The aim of this standard is to describe the FMEA and the Failure Mode and Criticality Analysis (FMECA).

The first step of the analysis is the identification of all possible types of moulding process failures. The FMEA works with the so-called Risk Priority Number (RPN) methodology, which indicates the degree of risk of a given problem regarding its significance (S), occurrence (O) and detectability (D). The evaluation is performed using a numerical scale in the range from 1 to 10. These three-point evaluations are multiplied together for each possible defect, which gives the so-called risk priority number RPN (RPN = S x O x D). In general, the groups of faults with a higher RPN number are considered much more important and therefore corrective measures should be proposed for them as a matter of priority.

For example, the following potential risks may occur in a given plastic injection moulding process:

- Failure to deliver the granulate by the production date.
- Non-delivery of packaging material according to the order.
- Undetected defect of granulate.

- Granulate interchange.
- Release of production with several attempts.
- Mixing of starting pieces for production.
- The dimensions of the product do not correspond to the production documentation.
- Non-measurement of dimensions.
- Visual defects (overflow, stain, dot, smudges, scratches).
- Cold joints on the product.
- Mixing inlets between the finished products in the package.
- Wrong number of pieces in the package.
- Marking the package with the wrong label.
- Exchange of right and left pieces.
- Non-conforming part of the package.
- Poorly packaged parts.
- Impurities in the packaging and on the parts.
- Do not use a barcode reader.

To evaluate the performance of a production process, the producer has to set some indicators of employee productivity, scrap production, and time utilization of machines. Employee productivity is determined as the ratio of sales revenue to the number of employees. Scrap numbers are an indicator of an inefficiency of production processes. Scrap data are often presented in the form of Pareto diagram analysis, which is described below.

Some of the defects that occur when injecting plastics are due to poor choice of material. An example is shown in Figure 3, where it can be seen that the crushed plastic granulate has an irregular size, which leads to frequent failures of the machine and producing defective products. Some of these common defects are recorded in the above FMEA table. Further examples of defects in mouldings are shown in Figures 4 and 8.

A small percentage of machine error also occurs when pure granulate is used. The granulate must have the correct moisture. If this is not the case, faulty mouldings will be produced. Other possible defects are described in [7].

Tab. 1 *Example FMEA*

Requirements	Potential failure mode	Potential causes of failure	Potential effects of failure	S	O	D	RPN
Screw speed control of injection press	Bubbles	Screw speed setting too high	Part weaken in strength and need to be scrap	5	5	2	50
Screw speed control of injection press	Material non homogenity	Screw speed setting too low	Impact subsequent process and result in scraps of molded component as cosmetics appearance is affected & cause drooling	5	2	4	40
Packing material to make a complete fill	Flashes	Packing setting too high	Impact subsequent process and result in scraps of moulded component as cosmetics appearance is affected & cause dimensions out of specs	5	5	3	75
Decompression control of injection press	Silver streak	Decompression too long	Impact subsequent process and result in scraps of moulded component as cosmetics appearance is affected	4	5	3	60

5 Pareto diagram for plastic injection

In the 19th century, the Pareto chart was invented by Vilfredo Pareto. It is a type of chart that is a combination of a bar and line chart, where the columns showing the frequency for each category are ordered by size (highest column on the left, lowest on the right) and the line represents the cumulative frequency in percentage. A Pareto diagram is used to show the importance of each category. The Pareto diagram is appropriate to use when analysing the frequency of incidents of a given process that may have multiple causes and the most significant causes need to be identified. When constructing a Pareto chart, it is necessary to determine the categories that will be displayed, what variables will be measured, and what time period the measurement will cover. For example, using a Pareto chart, it can be determined that only a certain group of products from the entire production program, only some of the nonconformities from all the nonconformities, only some of the causes from all the identified causes, are decisively involved in the emerging problems.

The input data for the construction of a Pareto diagram are usually information on the occurrence of defects, their causes over a certain period of time, which must be suitably stratified by product type, defect type, cause type, etc. The basic assessment is therefore the frequency of occurrence.

Individual steps of the analysis of non-conformities mouldings:

1. Compiling tables with individual non-conformities in a given period and quantifying their incidence.

2. Ranking non-conformities in descending order of frequency and expressing their frequency as a percentage.

3. Calculating the cumulative number of non-conformities and the cumulative percentage of non-conformities.

4. Constructing a Pareto diagram from the counted values (number of non-conformities and cumulative number of non-conformities in percentage).

5. Determine the vital minority based on the four procedures:

I. Procedure - consists of finding the breakpoint on the Lorenz curve (the red curve in the Pareto diagram) that separates vital minority of non-conformities from the less important majority of non-conformities. Non-conformities located to the left of the breakpoint represent the vital minority non-conformities and non-conformities to the left of the tipping point constitute the minority of non-conformities.

II. The procedure is based on calculating the average number of occurrences of a single non-conformities according to formula:

$$\frac{Sum\ of\ the\ incidence\ of\ all\ non-conformities\ for\ the\ period}{Number\ of\ non-conformities} \tag{1}$$

After which the number of non-conformities whose occurrence exceeds the calculated the average value are designated as the vital minority and the others non-conformities as less important majority.

III. Procedure - consists in finding a disagreement in the Pareto diagram in which the cumulative number of non-conformities in percentage terms reaches a value greater than 50%.

The disagreements to the left of this non-conformities, inclusive, constitute the vital minority and the others a minority.

IV. Progression - consists of finding a disagreement in the Pareto diagram in which the cumulative number of non-conformities in percentage terms reaches a value greater than 80%. The disagreements to the left up to and including this non-conformities form a vital minority and the others a minority.

Considering a 5-day interval of non-conformities for one machine that had only one-shift operation. The following data were obtained and are adapted and summarised in Table 2.

Tab. 2 *Type of non-conformities for a single shift operation (5 days interval)*

Type of non-conformities	Number of non-conformities	Cumulative number of non-conformities	Number of non-conformities in %	Cumulative number of non-conformities in %
Silvery stripes	84	84	34.15	34.15
Flash	45	129	18.29	52.44
Overflows	42	171	17.07	69.51
Stopping the machine	30	201	12.19	81.7
Bubbles	15	216	6.09	87.79
Burn marks	13	229	5.29	93.08
Cycle time exceeded	10	239	4.07	97.15
Other	7	246	2.85	100
Total	246	x	100	x

Table 2 summarises the non-conformities that occurred during the 5 days of single-shift operation in plastic injection moulding. The first column shows the types of non-conformities that occurred during production. The second column shows the number of non-conformities. The third column is the cumulative total of the number of non-conformities. In the fourth column the number of failures expressed as a percentage and in the last column the cumulative number of failures expressed as a percentage. From Table 2, the non-conformities are expressed in a Pareto diagram see Figure 9.

After constructing the Pareto diagram, a vital minority of non-conformities were determined to based on four procedures:

- 1. Breakpoint: 4 non-conformities
- 2. Average occurrence per non-conformities $= \frac{246}{8} = 30{,}75$
- 3. 50% criterion: 2 non-conformities
- 4. 80 % criterion: 4 non-conformities

Considering a 5-day interval of non-conformities for one machine that had only 3-shift operation. The following data were obtained and are adapted and summarised in Table 3.

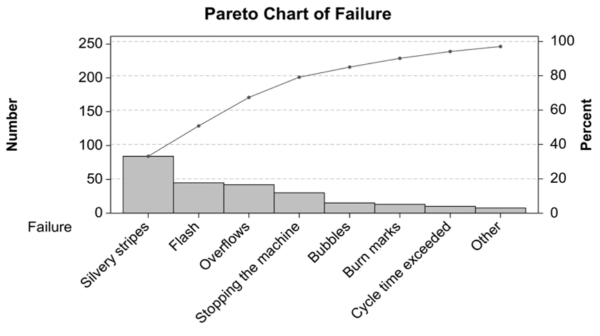

Fig. 9 *Pareto diagram for a single shift operation (5 days interval)*

Tab. 3 *Type of non-conformities for a 3-shift operation (5 days interval)*

Type of non-conformities	Number of non-conformities	Cumulative number of non-conformities	Number of non-conformities in %	Cumulative number of non-conformities in %
Stopping the machine	65	65	25.69	25.69
Overflows	59	124	23.32	49.01
Bubbles	32	156	12.65	61.66
Cycle time exceeded	24	180	9.49	71.15
Flash	23	203	9.09	80.24
Burn marks	20	223	7.9	88.14
Silvery stripes	18	241	7.12	95.26
Other	12	253	4.74	100
Total	253	x	100	x

After constructing the Pareto diagram, a vital minority of non-conformities were determined to based on four procedures:

- 1. Breakpoint: 2 non-conformities
- 2. Average occurrence per non-conformities $= \frac{253}{8} = 31{,}625$
- 3. 50% criterion: 3 non-conformities
- 4. 80 % criterion: 5 non-conformities

Figure 10 shows these non-conformities in a Pareto diagram based on Table 3.

If we consider the annual interval of non-conformities for one machine that had only one-shift operation. The following data were obtained and are adapted and summarised in Table 4.

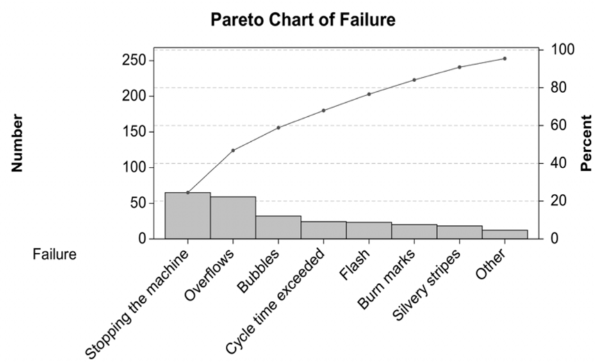

Fig. 10 *Pareto diagram for a 3-shift operation (5 days interval)*

Tab. 4 *Type of non-conformities for a single shift operation (1year interval)*

Type of non-conformities	Number of non-conformities	Cumulative number of non-conformities	Number of non-conformities in %	Cumulative number of non-conformities in %
Silvery stripes	4364	4364	30	30
Flash	3450	7814	23.72	53.72
Overflows	2347	10161	16.14	69.86
Stopping the machine	1678	11839	11.54	81.4
Bubbles	879	12718	6.04	87.44
Cycle time exceeded	643	13361	4.42	91.86
Burn marks	546	13907	3.75	95.61
Other	639	14546	4.39	100
Total	14546	x	100	x

After constructing the Pareto diagram, a vital minority of non-conformities were determined to based on four procedures:

- 1. Breakpoint: 4 non-conformities
- 2. Average number of occurrences per non-conformities: ... non-conformities. Average occurrence per non-conformities $= \frac{14546}{8} = 1818{,}25$
- 3. 50% criterion: 2 non-conformities
- 4. 80 % criterion: 4 non-conformities

Figure 11 shows these non-conformities in a Pareto diagram based on Table 4.

If we consider the annual interval of non-conformities for one machine that had only 3-shift operation. The following data were obtained and are adapted and summarised in Table 5.

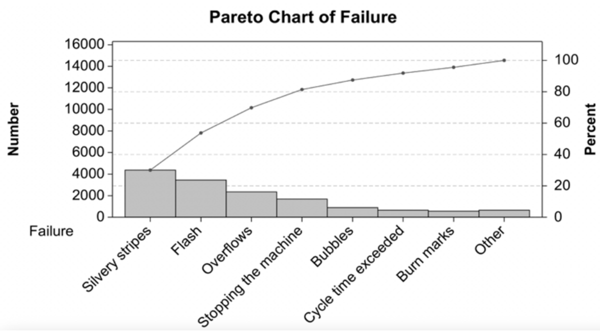

Fig. 11 *Pareto diagram for a single shift operation (1year interval)*

Tab. 5 *Type of non-conformities for a 3-shift operation (1year interval)*

Type of non-conformities	Number of non-conformities	Cumulative number of non-conformities	Number of non-conformities in %	Cumulative number of non-conformities in %
Stopping the machine	3457	3457	25.1	25.1
Overflows	3179	6636	23.09	48.19
Bubbles	1728	8364	12.55	60.74
Cycle time exceeded	1329	9693	9.65	70.39
Flash	1256	10949	9.12	79.51
Burn marks	1087	12036	7.89	87.4
Silvery stripes	989	13025	7.18	94.58
Other	746	13771	5.42	100
Total	13771	x	100	x

After constructing the Pareto diagram, a vital minority of non-conformities were determined to based on four procedures:

- 1. Breakpoint: 2 non-conformities
- 2. Average occurrence per non-conformities $= \frac{13771}{8} = 1721{,}375$
- 3. 50% criterion: 3 non-conformities
- 4. 80 % criterion: 6 non-conformities

Figure 12 shows these non-conformities in a Pareto diagram based on Table 5.

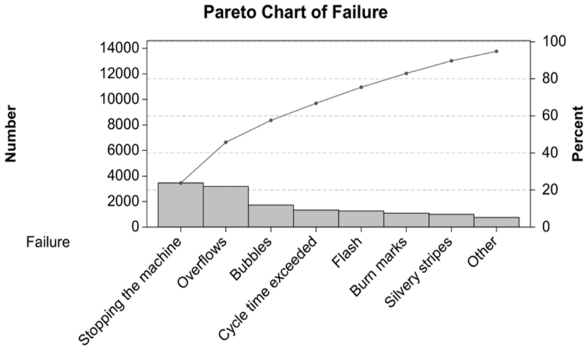

Fig. 12 *Pareto diagram for a 3-shift operation (1 year interval)*

Figures 9 and 10 show some individual cases of the Pareto diagram in practice. The first diagram shows a single-shift machine operation cycle, where the machine is stopped after eight hours. The second Pareto diagram shows three shifts, where the machine runs in continuous operation until routine maintenance or repair of the machine is needed. In both cases the five days interval was observed. Longer observations during one year led to Pareto diagrams in Figures 11 and 12, where again the defects in single shift and three-shift operation regimes are compared. For details see [3] and [7].

As can be seen from the Pareto diagrams, each operation mode is specific, leading to different defect counts. With one shift operation per year, the most common are silvery stripe type of defects. During three-shift operation regimes per year, the machine is most often stopped (for malfunction or maintenance).

6 Conclusions and remarks

Mathematical and statistical methods can be used in the design and routine operation of the injection moulding process. Their use leads to the prevention of non-conforming (defective) products or the prevention of defective/faulty production equipment and thus to a higher overall efficiency of the entire production process. The advantage of using these methods is that they can effectively identify areas that should be focused on when managing and improving the quality level of the production process.

In the case of using FMEA in process design, the experience of a known 'model process' that has already been analysed can be used in the design of a similar process. In this way, identical mistakes can be avoided already at the process design stage.

The individual quality management tools can be used separately, but their appropriate combination designed for use in this particular process brings a synergistic effect.

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