VŠB – TECHNICAL UNIVERSITY OF OSTRAVA

FACULTY OF METALLURGY AND MATERIALS ENGINEERING

METHODS OF QUALITY PLANNING AND IMPROVEMENT

Study support

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STUDY INSTRUCTIONS

You have received the study materials for the combined study of the course of ***Methods of Quality Planning and Improvement*** *of the follow-up master's fields of study of Economics and Management in Industry, Modern Metallurgical Technologies and Thermal Engineering and Ceramic Materials.*

PREREQUISITES

There are no prerequisites required for this course.

COURSE OBJECTIVE AND LEARNING OUTCOMES

The objective of this course is to master the selected procedures and methods of quality planning and improvement. In the field of quality planning, the attention is paid to the methodological approaches to product quality planning and to selected methods of quality planning, such as the QFD, FMEA methods, process capability analysis and the group of seven new quality management tools. In the area of quality improvement, the attention is paid to the improvement methodology and the seven basic tools of quality management.

AFTER STUDYING THE COURSE THE STUDENTS OBTAIN:

Knowledge outputs:

- *students will be able to characterize and classify the methods of quality planning and improvement*
- *students will be able to identify the appropriate methods for various situations.*

Skill outputs:

- *students will be able to apply selected methods of quality planning and improvement*
- *students will be able to interpret the results of the application of the methods and to propose appropriate measures.*

THE FOLLOWING PROCEDURE IS RECOMMENDED TO STUDY EACH CHAPTER:

When working with the study supports, the recommended way is to proceed in a logical sequence and to practice the topics at the same time.

METHODS OF COMMUNICATION WITH THE TEACHERS:

The teacher will introduce the course content and specify the requirements for the credit and exam to students at the beginning of the semester. The communication with the teacher takes place during lectures and tutorials or via e-mail.

CONSULTATIONS WITH THE COURSE GUARANTOR OR THE LECTURER WILL TAKE PLACE:

- *during consultation hours,*
- *following an appointment made by e-mail or phone.*

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INTRODUCTION

The recent market development has been associated with constantly increasing requirements for the quality of products and services. To meet these requirements, manufacturers and service providers have to pay more attention to quality management processes. The key components of quality management include quality planning and quality improvement.

Quality planning is a wide range of activities deciding about the final quality of products or services that are executes mainly during the designing and development stages. At present, it is a widely acknowledged fact that the stages prior to the production or provision of a service contribute up to eighty percent to the final quality. Focusing on quality planning has a significant economic impact, because the elimination of non-conformities before the actual execution requires only a fraction of the cost that would have to be incurred on their identification during the execution stage, or at the customer's place.

The planned product quality and the methods ensuring it, however, cannot remain unchanged, because the customer requirements are changing and the continuous development of science and technology brings a whole range of new opportunities for improvement. It is therefore necessary to strive for continuous quality improvement, which is currently a key attribute for maintaining the competitiveness of companies.

Effective quality planning and continuous quality improvement cannot be achieved without the use of appropriate procedures and the application of suitable methods. The methods of quality planning include, for example, QFD [1,2,3], design review [1], FMEA [1,2,3,4], proces and machine capability analysis [1,2,3,4], measurement system analysis [2] and the group of seven new quality management tools [1,5,6], while the quality improvement methods include, for example, a group of the seven basic quality management tools [1,4,7]. The presented study support is more closely dealing with the groups of seven new and seven basic quality management tools.

1 SEVEN NEW QUALITY MANAGEMENT TOOLS

Study time

8 hours

Objective

After studying this chapter:

- you will be able to explain the principles of the seven new quality management tools and the purpose of their use
- you will learn the application procedure of the seven new quality management tools.

Explication

Quality planning is defined as part of quality management focused on setting the quality objectives and specifying the processes, as well as the resources necessary to meet these objectives. An effective quality planning process can be ensured by using appropriate methods. For example, the QFD is an appropriate tool to transform the customer requirements into the quality characteristics of the designed product. The design review is a suitable method for a complex assessment of the design ability to meet the quality requirements. The FMEA will minimize the risks of possible failures of the product during its production and use. The process capability analysis evaluates the long term capability of the processes to produce products of the desired quality.

The activities focused on quality planning also include a significant application of the tools belonging to the seven "new" quality management tools. The name of the seven "new" tools is used in order to distinguish this group of tools from the seven basic tools of quality management.

While the seven basic tools are used primarily to deal with the issues of quality control, the seven "new" tools find their application especially in quality planning, within which it is necessary to process a variety of information, to define the quality objectives and to propose the appropriate procedures and methods to achieve them.

The seven "new" quality management tools include [1,5,6]:

1) Affinity diagram
2) Interrelationship diagram
3) Systematic (tree) diagram
4) Matrix diagram
5) Matrix data analysis
6) PDPC diagram
7) Network diagram.

These tools have some common features: they use teamwork, their result is an illustrative graphic output, and some of them are quite simple. A maximum effect in the application of these tools can be achieved if they are not used in isolation but as an organically integrated set of methods.

1.1 AFFINITY DIAGRAM

An affinity diagram is an appropriate tool for creating and organizing various items relating to a specific problem. When using an affinity diagram, these items are divided into natural groups, which explain the structure of the problems you are dealing with. The processing of an affinity diagram allows you to obtain and organize a lot of valuable items in a relatively very short time.

The creation of an affinity diagram takes place in a team and intuitive thinking in particular is used during its processing. The team composition should approximately correspond to the problem you are dealing with; however, it is advisable to add some "non-experts" into the team as well.

The processing of an affinity diagram should be performed in the following steps:

1) ***Definition of the problem***

The first step of the team should be to clarify and clearly define the problem. To keep the attention of the team, it is recommended to write the problem you are trying to solve on a visible place.

2) ***Creation of ideas and their recording***

The task of the team is to use brainstorming to gather as many ideas that could help you to solve the problem as you can. The effort is to obtain as many ideas as possible, because it is assumed that the more ideas you have, the more likely it is that there will be such ones that could significantly contribute to the solution of the problem. All the gathered ideas are continuously recorded on cards.

3) *Arrangement of the ideas into natural groups*

After the end of the discussion, the cards with the gathered ideas are placed on a large enough area, and they are subsequently put together into natural groups according to their relations.

4) *Naming the groups of ideas*

An important step after the formation of the groups of related ideas is their naming, which should accurately characterize the different groups.

5) *Displaying affinity diagram*

Affinity diagrams are designed on the basis of the achieved results, and they illustratively show all the ideas arranged in groups (see Figure 1.1).

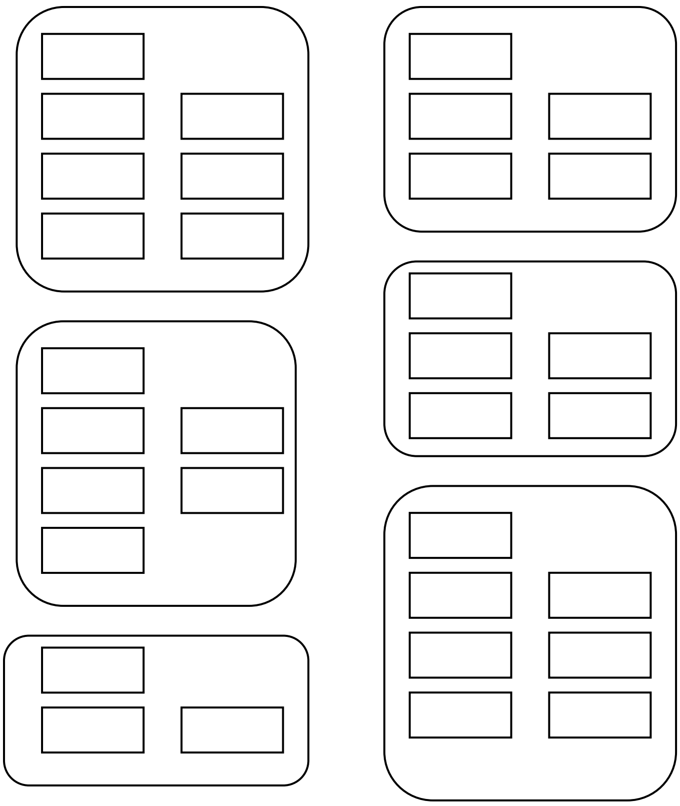


Fig. 1.1 Affinity diagram structure.

The affinity diagram method is, with regards to the amount of processed ideas, highly effective. Unlike various discussions on normal meetings, where many ideas remain unspoken and many expressed ones are never considered, the processing of an affinity diagram makes use of all the ideas. The processing of an affinity diagram leads to a deeper understanding of the problem and is a very good starting point for its solution.

The application of an affinity diagram is particularly suitable in cases where you are dealing with a problem that is complicated and difficult to process, and it requires the involvement of a group of resolvers, and it is necessary to find a solution that is not in line with the traditional approach. An affinity diagram can be recommended in a number of situations when revealing the essence of the problems or finding ways how to solve them. It can be very well used to search for answers to questions such as: "What can be done to increase customer satisfaction?", "How to improve the quality of the products?", "What properties should our new product have?", etc.

1.2 INTERRELATIONSHIP DIAGRAM

An interrelationship diagram enables you to use the analysis of logical or causal relations between the individual ideas to determine the time priorities for the execution of the individual activities or to determine the root causes of a problem.

The input data needed to create an interrelationship diagram can include the ideas generated during the affinity diagram processing. Usually, however, you do not work with all the ideas, because the interrelationship display could be quite confusing, but only with the individual groups of ideas or ideas in one selected group.

The processing of an interrelationship diagram takes place in a team again and should be performed in the following steps:

1) ***Display of the problem and ideas***

The problem you are trying to solve is recorded in the middle of a suitable work area and the ideas related to the problem are placed around it.

2) ***Identification and mapping of the relationships among the ideas***

The task of the team is to analyze the logical or causal relations between the individual ideas. The identified relationships are shown by arrows which, in the case of logical relationships, go from the starting point to the effect and in the case of causal relationships from the cause to the effect. The arrows are also used to show the relationship to the solved problem.

3) ***Assessment of the relationships***

The identification and mapping of the relationships is followed by an assessment of the number of incoming and outgoing arrows for each idea, and the values are recorded in a diagram (see Fig. 1.2). This is basically an evaluation saying how many times the idea under consideration was in relation to others as a starting point (or a cause), and how many times as an effect.

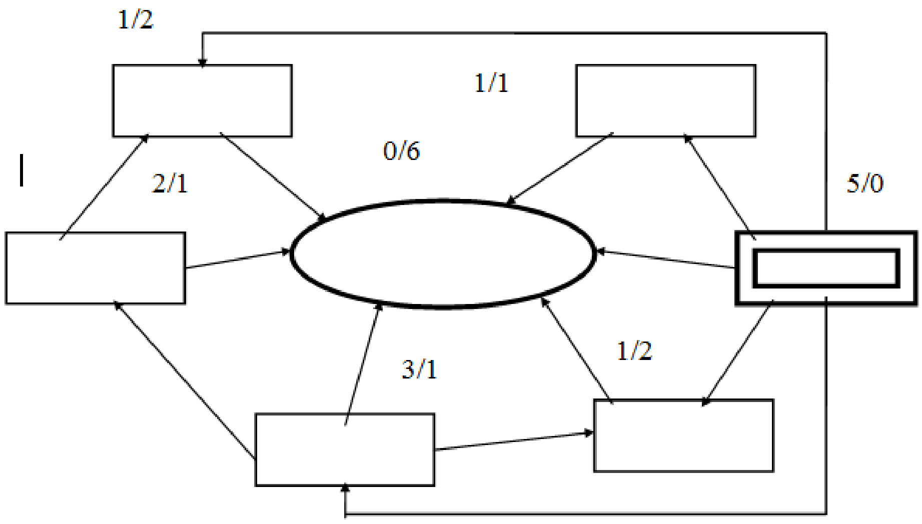


Fig. 1.2: Interrelationship diagram structure.

4) ***Determination of the key starting point or cause***

The idea with the highest number of outgoing arrows represents the key starting point or the root cause of the problem depending on whether it is a logical or causal relationship. Similarly, the idea with the highest number of incoming arrows represents the key effect. At the same time, we determine the order of the other ideas from the key starting point or cause to the key effect.

An interrelationship diagram is a suitable method used to look for answers to questions such as: "Where to start and how to proceed with the activities designed to increase customer satisfaction?", "How are the causes of low quality of our products related with each other and which cause is the key one?" etc.

1.3 SYSTEMATIC (TREE) DIAGRAM

A systematic diagram is a clear illustration of the systematic decomposition of a unit into the individual parts. It is a suitable tool, for example, for breaking a problem into sub-problems, for displaying the structure of the problem causes, for creating a plan to solve a problem or to decompose the main customer requirements into more specific ones. For example, a systematic diagram can be used during the preparation of a plan to solve a problem, where the individual processes are logically decomposed into sub-processes, which are subsequently broken down into the individual activities.

A systematic diagram should be created in a team again, and its preparation in the event of processing a problem solution plan should take place in the following steps:

1) ***Defining the objective***

The first step of the team work is to define the objective to be achieved, and to write it down on the left edge of the workspace.

2) ***Gathering ideas (activities) to solve the problem***

In cases where the processing of a systematic diagram follows the formation of an affinity diagram, it can be based on the previously created ideas. If a systematic diagram is processed directly, the ideas related to the problem in question must be created by means of brainstorming. The individual ideas should be recorded on cards.

3) ***Gradual decomposition of ideas into more specific activities and addition of logical gaps***

A systematic diagram is processed by a sequential assignment of cards with ideas, which always develop the previous level until the sufficient level of detail (see Fig. 1.3) is achieved. This gradual decomposition can be made easier by means of suitably selected questions. In case of a detection of logical gaps, the team operatively adds other evolving ideas by means of brainstorming.

4) ***Construction of a systematic diagram***

A systematic diagram should be redrawn into a clear graphical form, once sufficient level of detail has been achieved and eventual logical gaps have been added. A compiled systematic diagram represents an illustrative logical arrangement of all sub-steps, whose execution should ensure the achievement of the planned objective. The gradual decomposition of more complex activities should be carried out to such an extent to obtain specific sub-tasks that can be assigned the responsibilities of the individual workers.

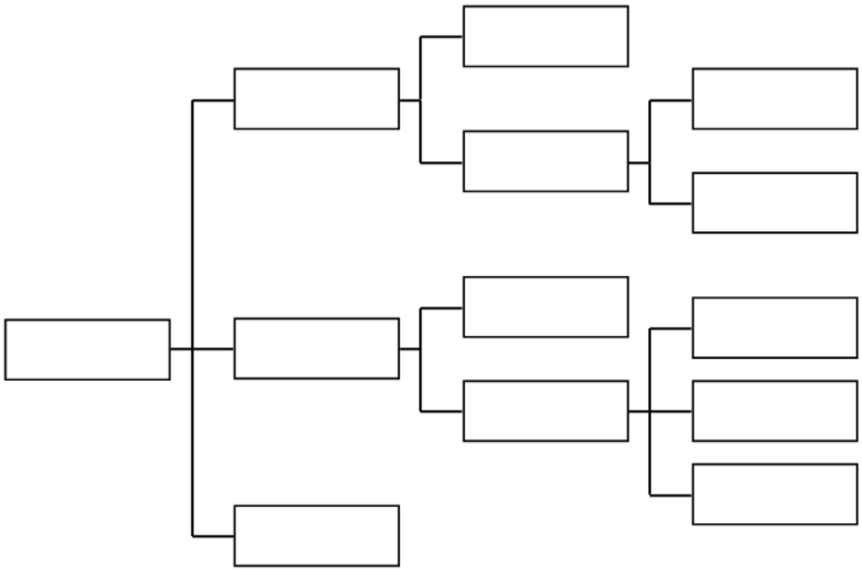


Fig. 1.3 Systematic diagram structure.

1.4 MATRIX DIAGRAM

A matrix diagram is used to assess the interrelationships between the elements of two or more areas of the problem. Its use helps to add the missing elements of the analyzed areas, to identify and eliminate the "white spots" in the information base related to the problem, to define the most important elements of the individual areas, and to optimize their value.

The most commonly used matrix diagrams are of "L" shape, and they analyze the relations between the elements of two areas. The individual areas (multidimensional variables) in a matrix diagram may take different forms, such as requirements, activities, product properties, process parameters etc. The diagrams used in the QFD method [1, 2, 3] represent the examples of matrix diagrams of "L" shape, e.g. a matrix diagram analyzing the interrelationships between the customer requirements and the product quality characteristics, which is the base of the "house of quality" (see Fig. 1.4).

The work of the team processing a matrix diagram should take place in the following steps:

1) *Determining the individual problem areas*

The basic application usually involves two selected areas whose elements are subjected to a relationship analysis.

2) *Determining the elements of the individual problem areas*

It is advisable to use an affinity diagram and a systematic diagram to determine the sufficiently specific elements of the individual areas.

3) Analysis of the interrelationships among the elements of the areas

A matrix diagram is created on the workspace and the specified elements are recorded in the headings of the individual columns and rows. After that, the team analyses and qualitatively evaluates the strengths of the relationships between the elements of the individual areas. We usually distinguish four levels of relationships: strong dependence, average dependence, weak dependence and independence. The degree of dependence among the individual elements in the matrix diagram cells is expressed by suitably selected graphic symbols.

		QUALITY CHARACTERISTICS						
		Characteristic 1	Characteristic 2	Characteristic 3	Characteristic 4	Characteristic 5	Characteristic 6	Characteristic 7
PRODUCT REQUIREMENTS	Requirement A	◎	△			△		
	Requirement B		◎				○	
	Requirement C		○		◎			◎
	Requirement D		◎					○
	Requirement E	△		○	△		◎	
	Requirement F		◎			○		

◎	strong correlation
○	average correlation
△	weak correlation

Fig. 1.4 An example of an „L“ shaped matrix diagram analysing the relationships between the customer requirements and the product quality characteristics.

4) ***Matrix diagram analysis***

A processed matrix diagram provides a variety of valuable information. It is a suitable base for the team used to assess the completeness of the analyzed elements, to make a complex analysis of the relationships among the elements of both areas, and to assess the importance of the individual elements. The analysis can be performed on the basis of a visual assessment of the layout of the individual symbols and the rates of their occurrence in the individual rows and columns. For example, Fig. 1.4 clearly shows that the given product quality planning will require significant attention to quality characteristic 2, since its value affects the fulfilment of most of the product requirements.

1.5 MATRIX DATA ANALYSIS

A matrix data analysis is focused especially on comparing various options (variables) characterized by a variety of criteria (elements) and the selection of the best option. The options may be represented by the individual products, individual designs, individual suppliers, etc. Using graphical or numerical methods of matrix data analysis can help us, for example, to evaluate the most appropriate concept of the designed product or to make a selection of the most suitable supplier.

The general procedure of matrix data analysis should be done in the following steps:

1) ***Defining the objective of analysis***

2) ***Selection of the criteria for options evaluation***

The selected criteria shall correspond to the objective of the task, be measurable or at least evaluable, characterize the critical properties of the options and be independent.

3) ***Definition of the options assessed***

The probability that the selected option is closest to the optimum can be significantly increased by using a sufficient number of assessed options. The inclusion of the individual options into the group of the assessed options may be tied to the fulfilment of certain defined conditions.

4) ***Gathering data on the specific criteria of the individual options***

This step should lead to the collection of data on all the selected criteria of the assessed options. Comparable procedures should be used to obtain the data.

5) ***Defining the optimal option***

The definition of an optimal option based on the definition of the optimal values of the assessed criteria is an important step of the matrix data analysis.

6) ***Selection of a suitable method of matrix data analysis***

As already mentioned before, the matrix data analysis can take advantage of both numerical and graphical methods. It is advisable to always use one of the graphical methods.

7) ***Evaluation of the most suitable option***

The most suitable option is the one whose values of the criteria are the closest to the optimal option.

The initial data for the matrix data analysis will generally take the form shown in Table 1.1.

Tab. 1.1 Table of data used for matrix data analysis.

OPTION (VARIABLE) (i)	CRITERION (ELEMENT) (j)					
	1	2	3	4	…	n
1	x_{11}	x_{12}	x_{13}	x_{14}		x_{1n}
2	x_{21}	x_{22}	x_{23}	x_{24}		x_{2n}
3	x_{31}	x_{32}	x_{33}	x_{34}		x_{3n}
…						
m	x_{m1}	x_{m2}	x_{m3}	x_{m4}		x_{mn}

The matrix data analysis takes advantage, for example, of the following methods:

a) Principal Component Analysis

b) Determination of the "distance" among the multidimensional variables

c) Map

d) Glyph.

1.5.1 Principal Component Analysis

The Principal Component Analysis belongs to the multidimensional statistical methods used for reducing the number of elements of multidimensional variables. Its application is based on an analysis of mutual correlations, where new "artificial" elements are created among the original ones, and the elements that affect a substantial part of the total variation of the original elements (the so-called principal components) are selected from the new elements. If you manage to explain the substantial part of the total variation of the original variables by means of several principal components, the selection of the most suitable option is much easier.

1.5.2 Determination of the distance between the multidimensional variables

When this method of matrix data analysis is used, the distances between the individual options (multidimensional variables) and the optimal one are evaluated by means of a suitably chosen metric.

A very important step in the determination of the distances is to ensure the numerical commensurability of the values of the individual criteria. This can be achieved, for example, through their conversion into a point scale or by introducing standardized variables.

A conversion of numerically incommensurable criteria into point evaluation can be done, for example, using the formula:

$$x_{ij,score} = \frac{x_{ij} - \min\limits_{i} x_{ij}}{\max\limits_{i} x_{ij} - \min\limits_{i} x_{ij}} \cdot 10 \tag{1.1}$$

where:

$\min\limits_{i} \, x_{ij}$ - minimum value of the j-th element of all variables

$\max_i x_{ij}$ - maximum value of the j-th element of all variables.

The standardization of numerically incommensurable criteria into standardized variables is done using the formula:

$$u_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j} \quad (1.2)$$

where:

u_{ij} - standardized value of the *j-th* element of *i-th* variable

$\bar{x}_j$ - average of the *j-th* element of all variables

s_j - sample standard deviation of the *j-th* element of all variables.

To express the distances among the individual variables, you can use, for example, the Minkowski metric working with the sum of the absolute values of the differences between the values of the individual elements (criteria) of the evaluated variables (options):

$$D_{ik} = \sum_{j=1}^{n} \left| x_{ij} - x_{kj} \right| \quad (1.3)$$

where:

D_{ik} - distance between variables *i* and *k,* expressed by means of Minkowski metric

x_{ij} - value of the *j-th* element of *i-th* variable

x_{kj} - value of the *j-th* element of *k-th* variable

n - number of monitored elements

An analysis of the calculated distances is focused primarily on comparing the distances of the individual variables from the optimal one. The variables with shorter distance from the optimal one can be considered more suitable than the variables whose distance is longer.

1.5.3 Map

A map is a clear graphic display of the position of the assessed options on a plane based on the values of two criteria. Displaying the items in the map allows their categorization in terms of the two assessed elements and an assessment of their proximity to the optimum. This simple graphical method is widely useable for the comparison of products, raw materials, production lines, suppliers, workers etc.

Figure 1.5 shows an example of a map comparing the individual suppliers with respect to the values of criteria A and C. The position of the suppliers with respect to the optimum indicates that from the point of view of the two criteria, Supplier DOD 1 is the closest to the optimum.

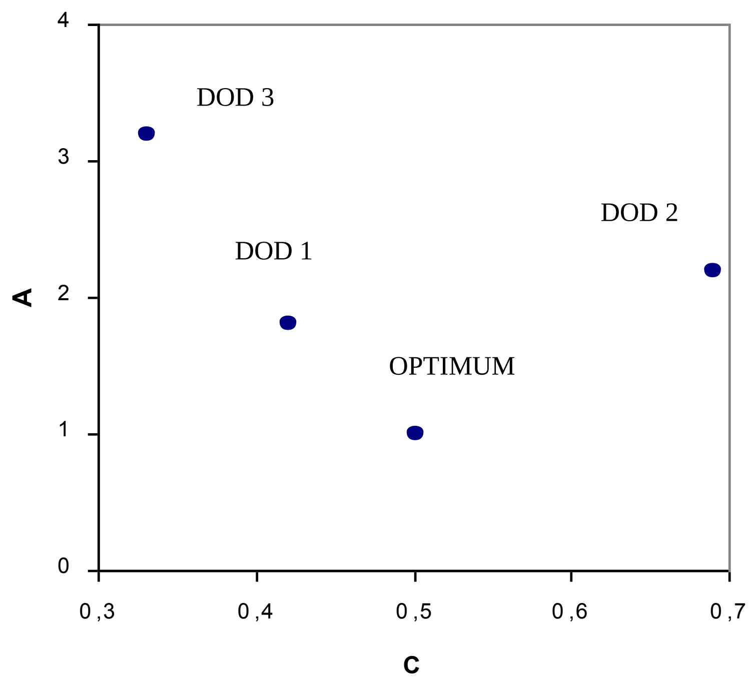


Fig. 1.5 Map comparing the individual suppliers from the point of view of criteria A and C.

1.5.4 Glyphs

Glyphs allow a graphical comparison of multidimensional variables containing three or more elements. The values of the elements (criteria) are placed on radially positioned axes (in the angle of 360/n) and their connection produces a bounded area that characterizes the properties of the variable in terms of all the monitored elements.

If the glyphs are required to have the necessary information capability, you must follow the general guidelines for their processing. In particular, all the axes should be arranged in the same direction to the better values of the elements (towards the centre or from the centre of the axes), in other words, the optimal option should be characterized either by the smallest or by the largest area.

One very important aspect of the processing of area diagrams is the selection of the scales on the individual axes which, in case of various criteria, would ensure their comparable impact on the size and shape of the displayed area. A Sun Ray Plot or a Star Symbol Plot can be presented as the examples.

a) Sun Ray Plot

In case of a Sun Ray Plot, the scales on the individual axes are made in such a way that the average value of the element (criteria) is situated in their half and the beginning and the end of the scale correspond to the selected minimum integral multiple of the standard deviation from this average value. The multiple is selected at the beginning of the construction to suit the display of all the values. The creation of the scale on the individual axes in case of three axes is shown in Tab. 1.2.

Tab. 1.2 The selection of scales on the axes of sun ray plots for the example using three elements (c - selected multiple of the number of standard deviations; m - number of displayed options; s_i – selection standard deviation of the element).

Axis	Beginning of axis	Middle of axis	End of axis
x_1	$x_{1,beg} = \bar{x}_1 - c \cdot s_1$	$\bar{x}_1 = \frac{\sum_{i=1}^{m} x_{i,1}}{m}$	$x_{1,end} = \bar{x}_1 + c \cdot s_1$
x_2	$x_{2,beg} = \bar{x}_2 - c \cdot s_2$	$\bar{x}_2 = \frac{\sum_{i=1}^{m} x_{i,2}}{m}$	$x_{2,end} = \bar{x}_2 + c \cdot s_2$
x_3	$x_{3,beg} = \bar{x}_3 - c \cdot s_3$	$\bar{x}_3 = \frac{\sum_{i=1}^{m} x_{i,3}}{m}$	$x_{3,end} = \bar{x}_3 + c \cdot s_3$

An example of Sun Ray Plots comparing three different suppliers based on five selected criteria is presented in Fig. 1.6. The displayed size of the areas shows that supplier “Dodavatel 1” is the closest to the optimum.

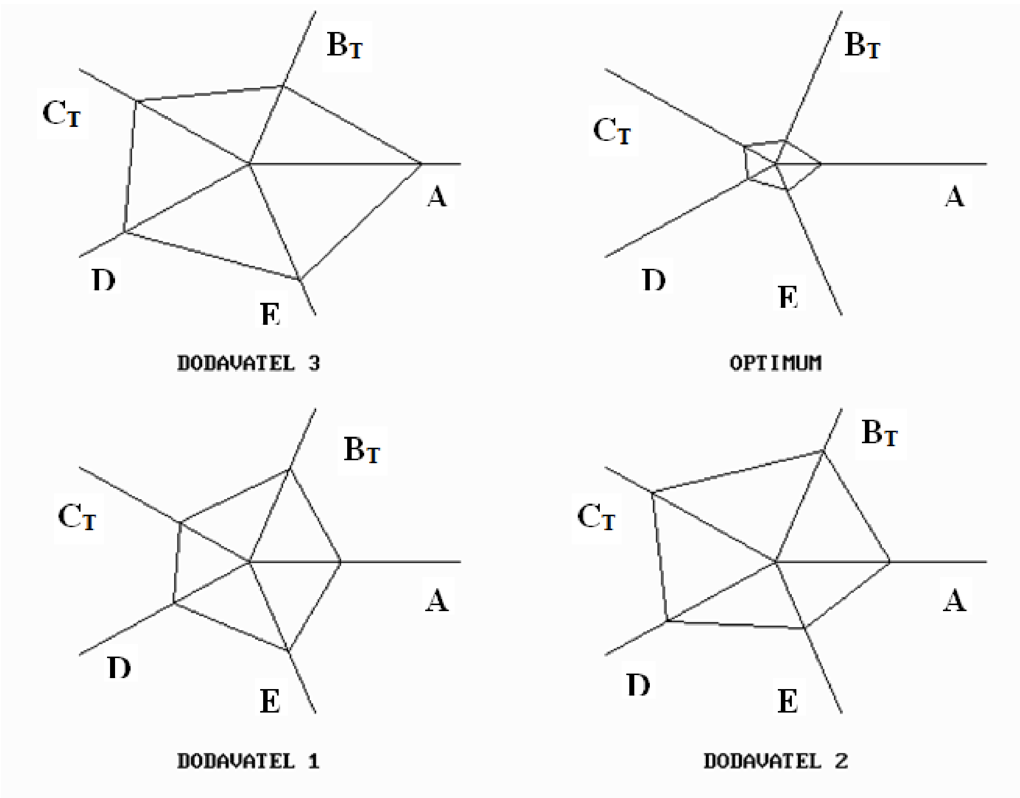


Fig. 1.6: Comparison of suppliers by means of a Sun Ray Plot.

b) Star Symbol Plot

In case of a Star Symbol Plot, the axes of the diagram (rays) do not exceed the area of the given polygon. The rays corresponding to the maximum value of the element having a selected unit length, and the rays corresponding to the minimum value represent the selected part of this unit length (a). In case of variables, whose values of the given element are located within the area between the minimum and maximum value, the lengths of the rays correspond to the relative values of the elements, which are calculated according to the formula:

$$x_{ij}^{*} = \frac{(1-a)\cdot\left(x_{ij} - \min_{i} x_{ij}\right)}{\max_{i} x_{ij} - \min_{i} x_{ij}} + a \qquad (1.4)$$

where:

x_{ij}^{*} - transformed value of the *j-th* element of the *i-th* variable

x_{ij} - original value of the *j-th* element of the *i-th* variable

$\min_i x_{ij}$ - minimum value of the *j-th* element of all variables

$\max_i x_{ij}$ - maximum value of the *j-th* element of all variables

a - parameter representing a quotient of the axis length corresponding to the minimum value of the element from the axis length corresponding to the maximum value of the element (usually a = 0.1).

An example of a Star Symbol Plot processed on the basis of the same data as the Sun Ray Plot in Fig. 1.6 is shown in Fig. 1.7. It is also evident that, from the point of view of the assessed criteria, supplier "Dodavatel 1" is the most suitable.

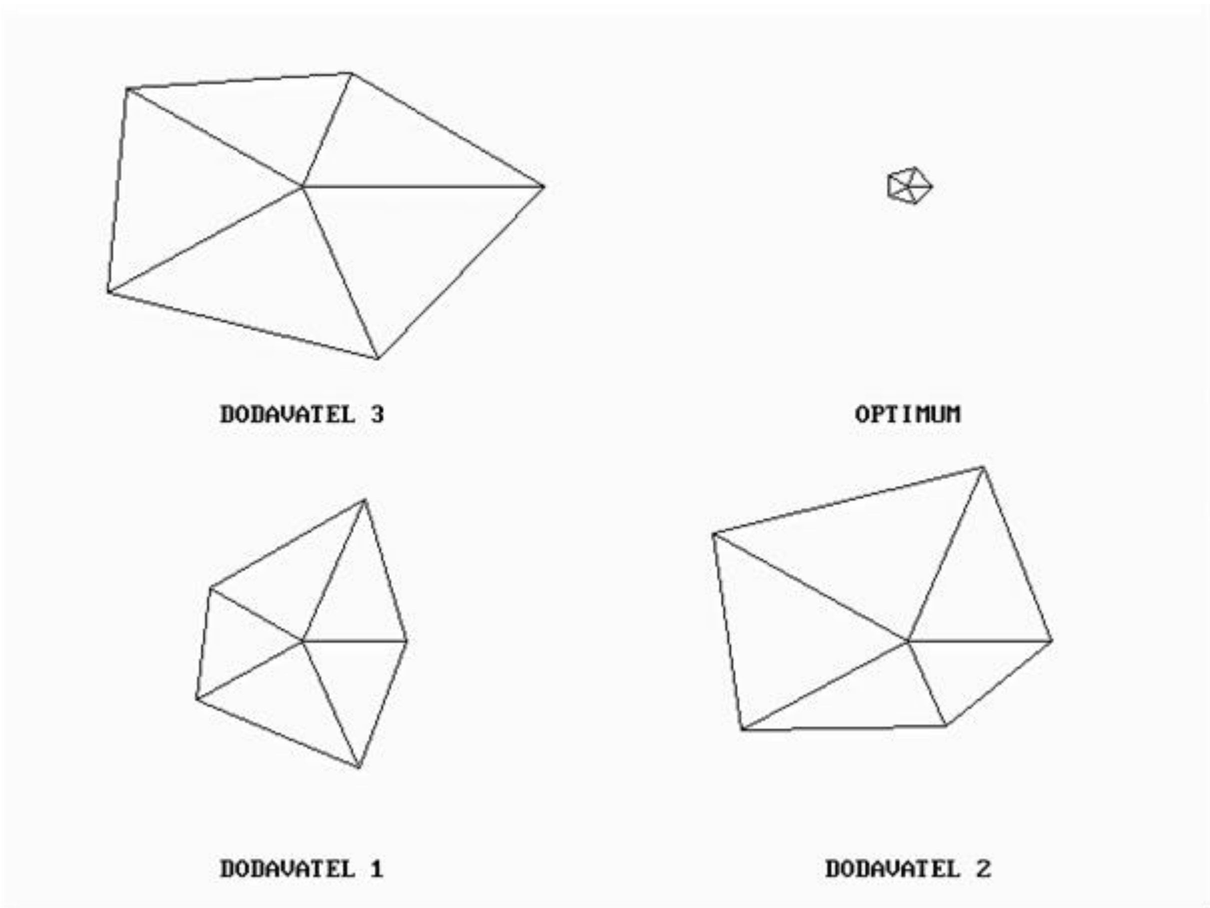


Fig. 1.7 Comparison of suppliers by means of polygons.

1.6 PDPC DIAGRAM

A PDPC diagram (Process Decision Program Chart) is a tool which is used for identifying the possible problems that may arise during the execution of the planned activities and for proposals of appropriate countermeasures.

A PDPC diagram is essentially an extension of the systematic diagram, which provides a systematic decomposition of the planned activity into specific sub-activities.

These activities are dealt with in a team by means of brainstorming in order to look for answers to questions:

- Can there be any problems while ensuring this activity?
- What measures should be planned in order to avoid these potential problems?

The answers to the second question (planned measures) are entered on the right side of the individual activities and are framed into "clouds" (see Fig. 1.8).

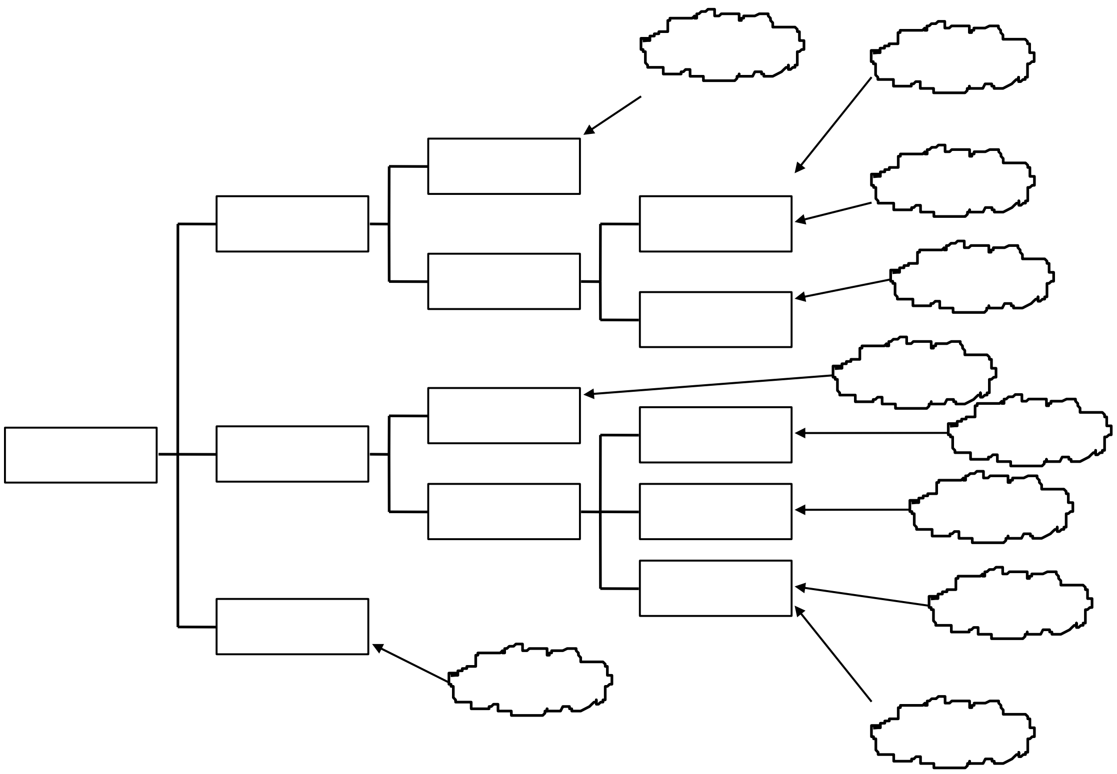


Fig. 1.8 PDPC diagram structure.

When searching for appropriate measures, you can use these options:

- Avoiding the problem (execution of the activities using another way).
- Reducing the probability of problem occurrence (changes of activities or addition of activities that reduce the probability of the problem occurrence).
- Preparedness for the possible occurrence of the problem (planning activities to cope with the problem, if it occurs).

A PDPC diagram is mainly used in cases when we deal with new challenges or new conditions of their solutions, or when achieving the goals is strictly time-limited.

1.7 NETWORK DIAGRAM

A network diagram is a useful tool for determining an optimal schedule of the course of a project consisting of a series of activities and their subsequent monitoring. The processing of a network diagram provides important data necessary to determine appropriate measures to reduce the overall duration of the project, to quickly assess the impact of the delay of the individual activities on the timetable, to make operational adjustments of the schedule in case of any changes of the duration of the activities, etc. Its contribution is the higher the more partial activities need to be executed to achieve the ultimate goal.

The most widely used method using a network diagram is the Critical Path Method (CPM).

The network diagram is a very valuable tool for projects of products quality planning, projects of quality improvement, projects of of management systems implementation, etc.

The processing of a network diagram should be performed in the following steps:

1) ***Identification of the activities necessary to achieve the objectives of the project***

The identification of the individual project activities should take place in a team. With regard to further processing procedure, it is beneficial to record these activities on cards.

2) ***Creation of a flowchart***

A sequential arrangement of the activities recorded on the individual cards in a team can optimize the sequence of the individual project activities and identify those activities that can take place simultaneously. An example of a flowchart is shown in Fig. 1.9.

3) ***Transformation of the flowchart into a network diagram***

A flowchart, which represents a chart defined by nodes, is not usually used for the evaluation of deadlines. A network diagram provides a more suitable arrangement. A network diagram is an edge-defined diagram consisting of nodes and links, respectively edges. The nodes represent the start and the end of the individual activities and they are indicated by circles, and the oriented links between these nodes represent the individual activities.

During the transformation of a flowchart into a network diagram, you have to make sure that each activity is clearly identified by the number of the node which it is going from and the node into which it is entering. The compliance with this condition sometimes requires the introduction of the so-called fictive activities, which are drawn by a dashed line in the network diagram. An example of the transformation of a flowchart into a network diagram is shown in Figure 1.9.

4) ***Estimation of the duration of the individual activities***

A qualified estimate of the duration of the individual activities is an important input for the processing of the execution schedule of the individual activities. The estimated durations should be based on a consensus of the team.

5) ***Network diagram evaluation***

The evaluation of a network diagram is performed in relative time. The calculations for each activity allow you to determine:

- The earliest start time - ES_{ij}, i.e. the earliest time when the (i,j) activity can start.
- The latest start time - LS_{ij}, the latest time when the activity (i,j) must start if the project is to be completed according to the plan.
- The earliest finish time - EF_{ij}, i.e. the earliest time when the activity (i, j) can be finished.
- The latest finish time - LF_{ij}, the latest time when the activity (i, j) must be finished if the project is to be completed according to the plan.

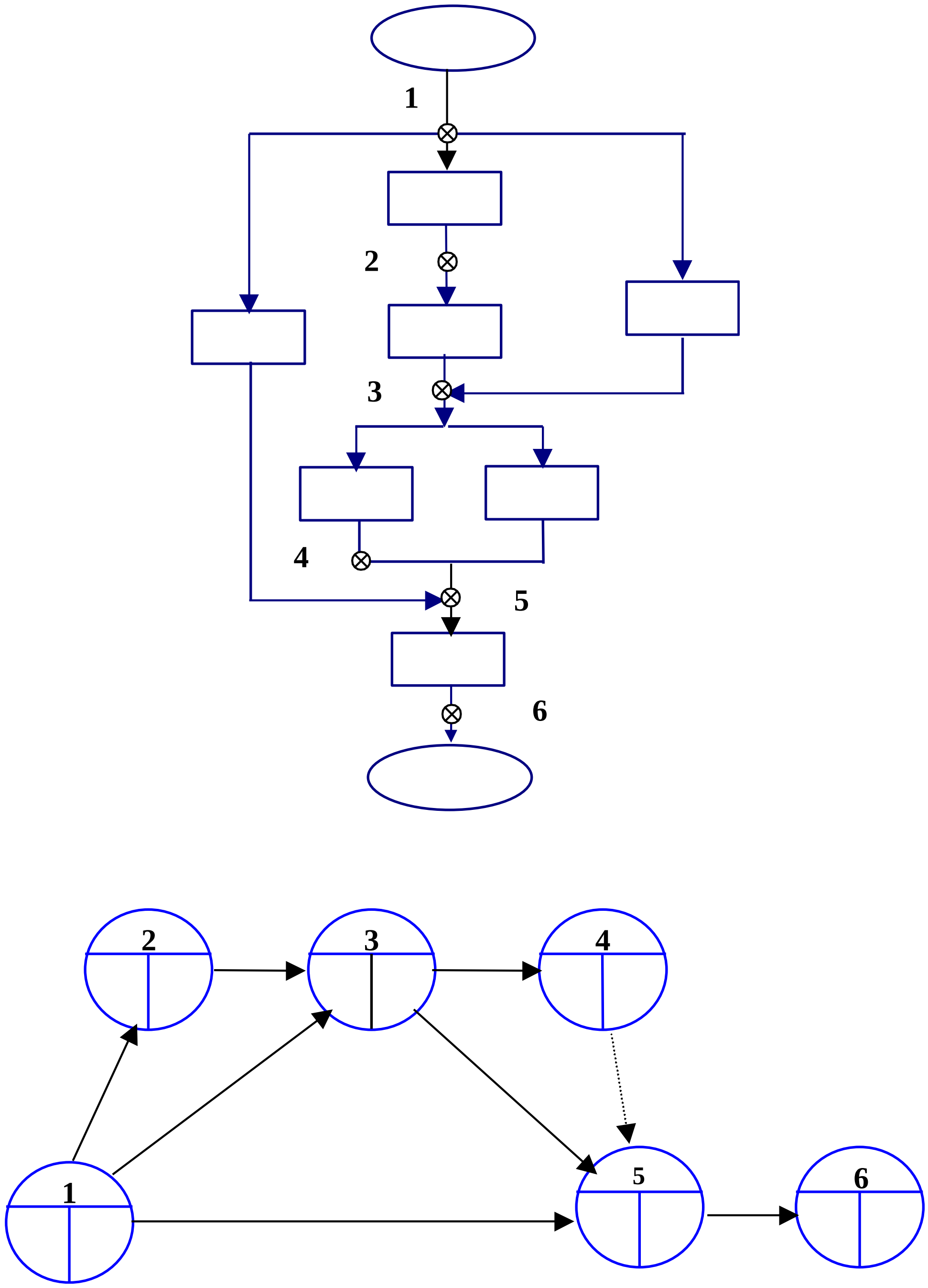


Fig. 1.9 Example of flowchart and the corresponding network diagram.

The nodes in the network diagram are divided into three parts so as to make it possible to record the number of the node (i), the earliest node time (EN_i) and the latest node time (LN_i). The earliest node time corresponds to the earliest start times of all activities coming from the node, while the latest node time corresponds to the latest finish times of all activities ending in that node. The method of recording of the data is shown in Figure 1.10.

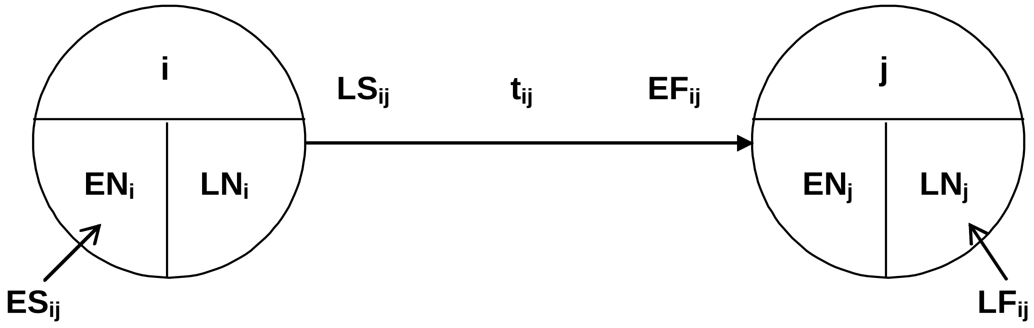


Fig. 1.10: Records of data in network diagram.

The actual calculations are based on the initial network node, whose relative expression of time is:

$$EN_1 = ES_{1j} = 0 \tag{1.5}$$

The individual activities lead us to the following nodes, while the earliest finish of each activity is always calculated as:

$$EF_{ij} = EN_i + t_{ij} \tag{1.6}$$

where: t_{ij} – activity duration (i,j)

Based on the values of the earliest finishes of the activities entering a specific node, you can determine the earliest node time, i.e. the earliest time when the activities coming from this node can be started. This time is determined as the maximum value of the earliest finishes of all activities ending in the node according to the relation:

$$EN_j = \max_i EF_{ij} \tag{1.7}$$

If only one activity is heading for the node, then the earliest finish of the activity is also the earliest node time.

The value of the earliest node time is used for further calculations, because it represents the earliest start time of all activities that come from the node:

$$ES_{jk} = EN_j \tag{1.8}$$

The presented calculations take place successively in all other nodes until the final network node is reached.

The latest finish times and the latest start times of the activities are counted in the opposite direction. It starts from the final node and the latest start times of the activities in the direction towards the initial node are calculated as:

$$LS_{ij} = LN_j - t_{ij} \quad (1.9)$$

The latest node times are calculated step by step as the minimum value of the latest starts of all activities coming from the given node (node i):

$$LN_i = \min_j LS_{ij} \quad (1.10)$$

At the same time the values of the latest node times correspond to the values of the latest finish times of all activities entering the given node:

$$LF_{ij} = LN_j \quad (1.11)$$

6) ***Determining the critical path***

The critical path in a network diagram is determined on the basis of the established time data. The critical path is the path from the initial to the final network node that takes the longest time. It is therefore a sequence of activities that have no time slack. The activities along the critical path (critical activities) therefore meet the condition that their earliest start time is simultaneously the latest start time, and the earliest finish time is simultaneously the latest finish time, i.e.:

$$ES_{ij} = LS_{ij} \quad (1.12)$$

$$EF_{ij} = LF_{ij} \quad (1.13)$$

A delay of any activity situated on the critical path will delay the whole project.

7) ***Calculation of time slacks of activities***

The next phase of the evaluation of a network diagram is dealing with the determination of the time slacks of activities that do not lie on the critical path. We usually distinguish among the total, free, and independent time slack.

When calculating the total time slack (TS_{ij}), it is assumed that all previous activities have ended at the earliest possible times, and all subsequent activities begin at the latest permissible times. This slack is calculated as:

$$TS_{ij} = (LN_j - EN_i) - t_{ij} \quad (1.14)$$

When calculating the free time slack (FS_{ij}), it is assumed that all previous activities have ended at the earliest possible times, and all subsequent activities also begin at the earliest possible times. Its value is calculated as:

$$FS_{ij} = (EN_j - EN_i) - t_{ij} \quad (1.15)$$

When calculating the independent time slack (IS_{ij}), it is assumed that all previous activities have ended at the latest permissible times, and all subsequent activities begin at the earliest possible times. Its value is calculated as:

$$IS_{ij} = \max(EN_j - LN_i - t_{ij};0) \quad (1.16)$$

The individual time slacks of activities follow the relation:

$$TS_{ij} \geq FS_{ij} \geq IS_{ij} \quad (1.17)$$

8) ***Recording the evaluated data in a synoptic table***

The evaluated earliest and latest times of activities and their time slacks should be recorded in a synoptic table for further analysis:

Activity	**Dura-tion**	**ES_{ij}**	**EF_{ij}**	**LS_{ij}**	**LF_{ij}**	**TS_{ij}**	**FS_{ij}**	**IS_{ij}**
(1,2)	t_{12}	ES_{12}	EF_{12}	LS_{12}	LF_{12}	TS_{12}	FS_{12}	IS_{12}
(1,3)	t_{13}	ES_{13}	EF_{13}	LS_{13}	LF_{13}	TS_{13}	FS_{13}	IS_{13}
(2,3)	t_{23}	ES_{23}	EF_{23}	LS_{23}	LF_{23}	TS_{23}	FS_{23}	IS_{23}

9) *Gantt chart preparation*

For practical use, it is necessary to convert the time data set determined in a relative time to concrete calendar terms. A calendar schedule of the individual activities is mostly processed graphically using a Gantt chart. It is an arranged horizontal bar column chart written down into a calendar network. The earliest start times of the individual activities correspond to the beginnings of the columns, and the earliest finish times of these activities correspond to the ends of the columns, and the total time slack magnitude is expressed by a straight line linked to the earliest finish time of the activities (see Fig. 1.11).

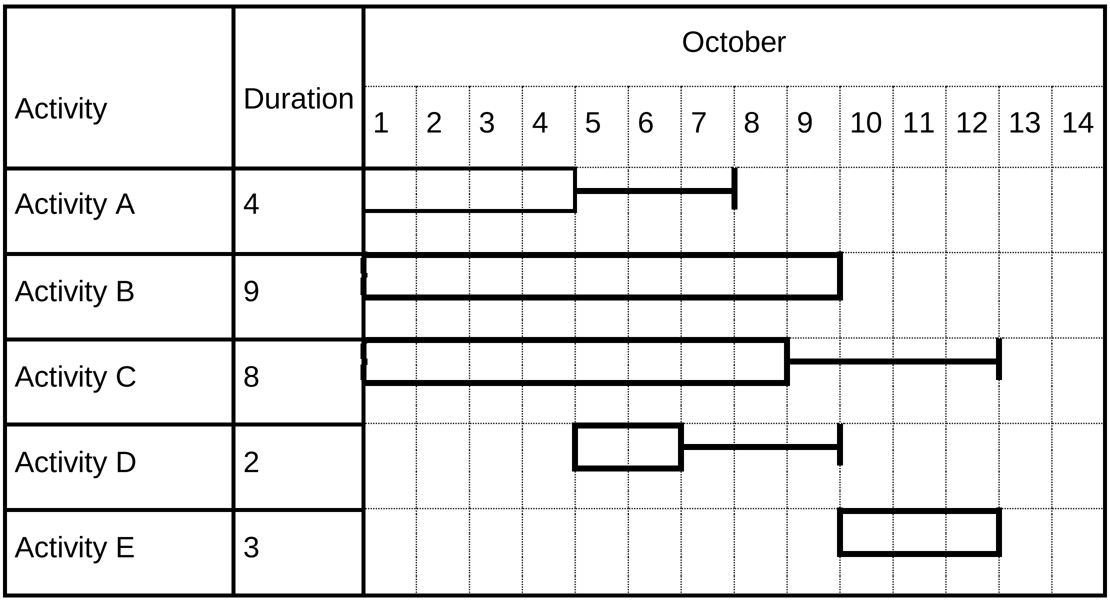
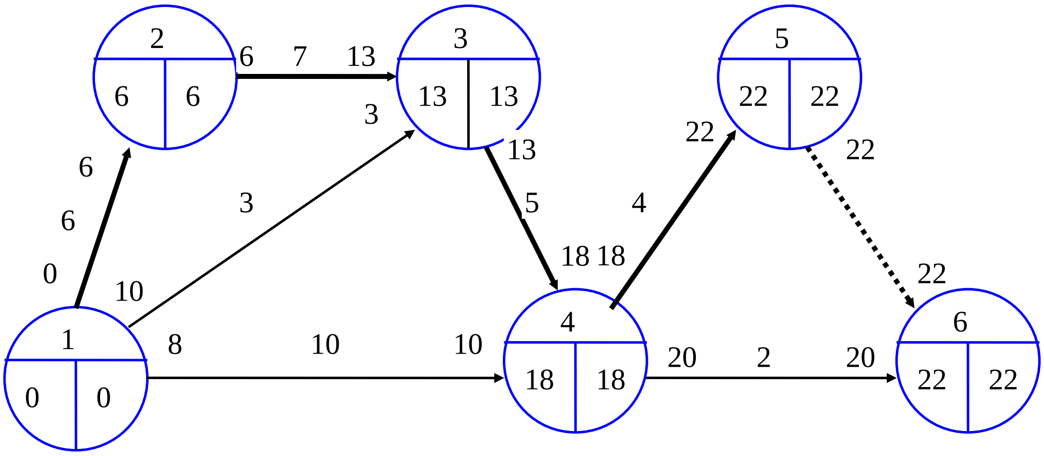


Fig. 1.11 An example of Gantt chart.

To illustrate the method of network diagram evaluation, we are presenting an example including table of the specified terms of the individual activities and the time slacks (see Fig. 1.12). The critical path in the network diagram is indicated by bold line. The critical activities, i. e. the activities that have no time slack, and the delay of which would delay the completion date of the project, are activities (1,2), (2,3), (3,4) and (4,5).



Activity	Duration	ES_{ij}	EF_{ij}	LS_{ij}	LF_{ij}	TS_{ij}	FS_{ij}	IS_{ij}
(1,2)	6	0	6	0	6	0	0	0
(1,3)	3	0	3	10	13	10	10	10
(1,4)	10	0	10	8	18	8	8	8
(2,3)	7	6	13	6	13	0	0	0
(3,4)	5	13	18	13	18	0	0	0
(4,5)	4	18	22	18	22	0	0	0
(4,6)	2	18	20	20	22	2	2	2

Fig. 1.12 Example of network diagram evaluation.

Summary of terms

Affinity diagram - a tool used to create and arrange various ideas related to a problem into natural groups.

Interrelationship diagram – a tool enabling you to use an analysis of logical or causal relations among the individual ideas to determine the time priorities of the execution of the individual activities or to determine the key causes of the problem.

Systematic diagram – a tool showing the systematic decomposition of a unit into individual parts.

Matrix diagram – a tool used to analyze the interrelationships between the elements of two or more areas of the problem.

Matrix data analysis - a tool used to compare different options characterized by a series of criteria and the selection of the best option, which takes advantage of both numerical and graphical methods.

PDPC diagram - a tool for the identification of potential problems that may arise during the execution of the planned activities and a plan of suitable countermeasures.

Network diagram - a tool used to determine an optimal schedule of a project course consisting of a series of activities, enabling you to identify the critical activities and to set the time slacks of the activities.

Gantt chart – an arranged horizontal column chart written down into calendar network presenting the time flow of the individual project activities.

Questions

1. Characterize an affinity diagram and its benefits.
2. Explain the evaluation method of an interrelationship diagram, and how you can use the results.
3. Explain what information may be obtained by matrix diagram processing.
4. Explain the general procedure of matrix data analysis.
5. How do you calculate the Minkowski metric and what conditions must be met for its use?
6. Explain the procedure used for processing and evaluation of glyphs.
7. What principle is used to create the axis scales in case of a Sun Ray Plot?
8. What types of measures can be used in a PDPC diagram?
9. Explain the evaluation method of a network diagram.
10. What is the critical path and how it is determined?

11. Name the types of evaluated time slacks of activities and the methods of their determination.
12. Explain the data recorded on a Gantt chart.

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2 SEVEN BASIC QUALITY MANAGEMENT TOOLS

Study time

8 hours

Objective

After studying this chapter:

- you will be able to explain the principles of the seven basic quality management tools and the purpose of their use
- you will learn the application procedure of the seven basic quality management tools

Explication

One of the basic principles of quality management is continuous improvement. Continuous improvement is an important part of achieving and maintaining competitiveness and it should become a permanent goal of every organization. Quality improvement is defined in the standards as "part of quality management focused on increasing the ability to meet the quality requirements".

The improvement activities have much in common with the general solution of problems. The main difference is that the improvement activities are planned and usually organized as parts of a wider program, while the activities solving problems are usually immediate and unplanned. Despite these differences, the similarity of the objective means that a similar approach in both cases can be used.

An effective prevention of nonconformities and continuous quality improvement today can no longer be achieved without the use of appropriate procedures and the application of appropriate methods and tools. The suitable basic tools are included in the group of the seven basic quality management tools.

2.1 METHODOLOGY OF QUALITY IMPROVEMENT

The basic model of quality improvement is represented by the Deming Cycle PDCA (Plan-Do-Check-Act). This cycle consists of four phases, which should allow quality improvement or changes. This cycle, which has no end, should be permanently repeated to ensure continuous improvement.

Plan	elaboration of a plan of improvement activities
Do	execution of the planned activities (usually in a smaller scale)
Check	monitoring and analysis of the achieved results (their comparison with the anticipated results)
Act	response to the achieved results and the implementation of a suitable process changes.

All the used methodologies of quality improvement or problem solution are more elaborated versions of the four basic steps of the PDCA cycle. One of the best known methodologies is the Quality Journal methodology.

2.1.1 Quality Journal methodology

The Quality Journal methodology is one of the systematic approaches to quality improvement [1, 2]. This methodology was taken from a Japanese approach to problem solving. It is a systematic procedure of process improvement that takes place in seven steps:

1) Identification of the problem
2) Monitoring of the problem
3) Analysis of the causes of the problem
4) Designing and executing the measures to eliminate the causes
5) Checking the effectiveness of the measure
6) Permanent elimination of the causes
7) Progress report on the problem solving and a plan of future activities.

1) ***Identification of the problem***

In this step, it is necessary to obtain and process maximum amount of information about the existing problems (opportunities for improvement), which will make it possible to set the priorities and to identify the most important problem. The target state to be achieved after the improvement and the expected benefits should be specified on the basis of description of the current state. It is also important to determine when the target state is to be achieved.

2) *Monitoring of the problem*

The actual monitoring of the problem involves investigating its characteristics from every possible angle and determining the conditions of its origin. It is also important to investigate the time and place of the occurrence of the problem and the type of its symptoms. Monitoring of the problem should take place directly on the workplace where the problem occurs.

3) *Analysis of the causes of the problem*

An analysis of the causes of the problem usually takes place in two phases: determining the hypotheses and verifying the hypotheses. The best procedure used to determine the hypotheses is team processing of cause-effect diagram, where the team identifies all the possible causes of the problem to be solved. The verification of the actual effect of the determined possible causes is based on data analysis. The analysis very often takes advantage of statistical methods, such as exploratory data analysis, regression and correlation analysis, analysis of variance, etc.

4) *Designing and executing the measures to eliminate the causes*

Once the main causes of the problem have been identified, the team should suggest measures to eliminate the causes. The individual suggested measures shall go through a detailed analysis and their advantages and disadvantages should be evaluated. It is particularly important to examine whether the implementation of the proposed measures will not be accompanied by undesirable effects, which could cause a new problem. The team should reach a consensus based on the analysis, select the optimal option and this option should be implemented (first usually in pilot version).

5) *Checking the efficiency of the measures*

The efficiency of the measure must be evaluated after its execution. The evaluation of the efficiency of the measure is based on a comparison of the results achieved before the execution of the measure and after its execution using suitable statistical methods. The relevant data should also include a complex assessment of all other changes, including the financial evaluation. If the executed measure turns out to be less efficient than expected, it is necessary to look for another, more efficient measure, or to go back to problem monitoring.

6) ***Permanent elimination of the causes***

In the event that the execution of the measure has led to the expected improvement, it is necessary to ensure the changes are permanently embedded. The standardization of the changes should be ensured by changing the documentation, by education and training of staff, and by checking the adherence to the changes.

7) ***Report about the problem solving procedure and future activities planning***

This final stage deals with the preparation of a report on the course of the problem solving, documented by concrete data and analyses. This report evaluates the achieved results and summarizes the problems that have not been completely resolved yet. The report should include proposals of actions needed to achieve the final solution of these problems. The final evaluation should also include an assessment of the solution process so that the good experience could be used in the following improvement activities.

The success and efficiency of the improvement activities are significantly higher as a result of the use of appropriate tools and methods in the individual solution steps.

The seven basic tools of quality management, which have been developed in Japan especially by K. Ishikawa and W. E. Deming, represent an important group of methods and tools of quality management which are used in the individual stages of continuous improvement.

The seven basic tools of quality management include [1, 2, 3]:

1) Flow chart
2) Cause-effect diagram
3) Data form
4) Pareto chart
5) Histogram
6) Scatter diagram
7) Control chart.

2.2 FLOW CHART

A flow chart is a graphical illustration of the sequence and the mutual relationship of all steps of a particular process. It can be either an already existing or a newly designed process.

A flow chart is a suitable tool especially for process analysis, analysis of its individual steps and branches, for the identification of the areas where problems may arise, for the analysis of the process in terms of the best position of check points, and for the identification of redundant activities. It represents a synoptic display of the process, which contributes to its better understanding, and it defines customers to the workers involved in the process.

It is beneficial to use team work for the processing of a process flow chart and it especially requires the participation of those who use or will use the described process. The processing of a flow chart should take place in the following steps:

1) ***Defining the beginning and the end of the described process***

In the event that the described process is too large, it is suitable to divide it into sub-processes to make sure the created flow charts are clear enough.

2) ***Identification of the individual process activities and their recording***

It is beneficial to record the individual activities on cards, and you can shuffle them or update them to gradually create the right sequence of the individual activities.

3) ***Preparation of a flow chart draft***

The preparation of flow charts takes advantage of established graphic symbols. The selected basic symbols are shown in Fig. 2.1.

4) ***Flow chart review***

A review of a prepared flow chart should take place with the participation of the workers who are or will be responsible for the execution of the individual activities.

5) ***Verification of the flow chart according to the actually ongoing process***

In the case of describing existing process, the correctness of the flow chart can be verified by means of a confrontation of this process with the actual course of the process.

A flow chart is, thanks to its graphic character, often used in quality management system documentation. In these cases, it tends to be accompanied by a responsibility matrix, which clearly identifies the relationships of the individual workers and the individual activities. The description of the level of involvement of the individual workers in the execution of the individual activities through the responsibility matrix is clear and, to some extent, it also enables you to analyze and optimize the degree of involvement of the individual workers.

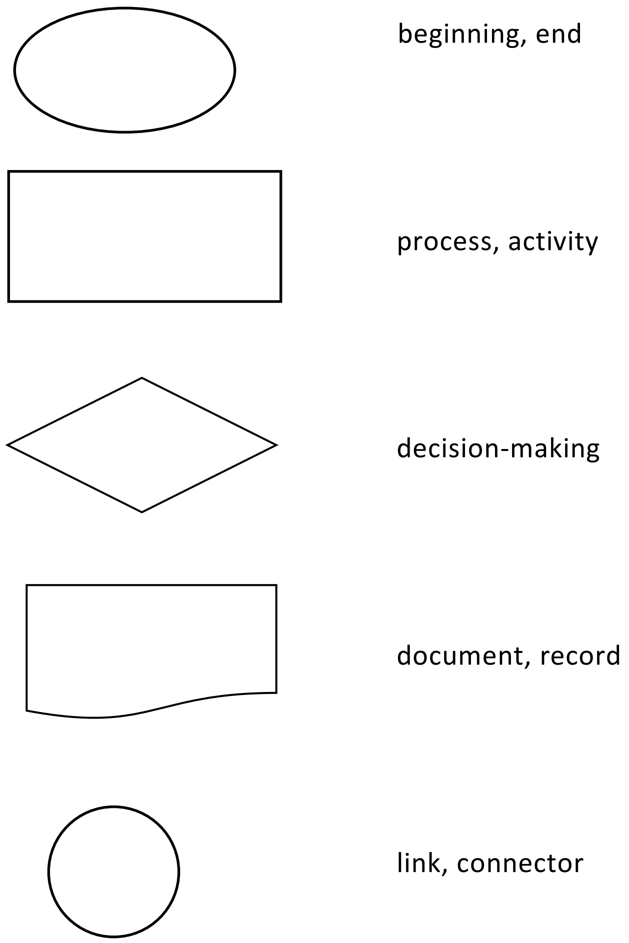

Fig. 2.1: Basic graphic symbols of flow chart.

2.3 CAUSE- EFFECT DIAGRAM (ISHIKAWA DIAGRAM, FISHBONE DIAGRAM)

A cause-effect diagram is an important graphic tool for the analysis of all possible causes of a particular effect (problem with quality). Its use represents a systematic approach to problem solving that helps to document all the ideas and suggestions. The processing of a cause-effect diagram should take place in a team using brainstorming.

Brainstorming

Brainstorming is a method of team work increasing the efficiency of creative thinking. It belongs to the methods with delayed evaluation. Its goal is to get as many ideas as possible related to the solved problem, which will only be analyzed and evaluated later. The more ideas you get thanks to brainstorming, the higher the probability that there will be ideas leading to the solution of the problem among them.

The following principles should be used during brainstorming:

- the discussion is managed only by the facilitator;
- no more than one person can speak at a time;
- everybody must express only the opinions related to the solved problem;
- there is absolute freedom of ideas;
- no ideas can be criticized or otherwise evaluated during this phase;
- all ideas must be recorded.

The procedure of the creation of a cause-effect diagram

The first step in the processing of a cause-effect diagram should be to establish the team. It should include experts from various fields related to the problem, but it is also suitable to have non-experts, who are not affected by the "operational blindness". The actual processing of a cause-effect diagram should be done in the following steps:

1) ***A clear definition of the problem***

Before starting their work, the team should clarify and clearly formulate the problem (effect) whose possible causes are being analyzed. The defined problem is entered in the box on the right side of the workspace, and there is a horizontal line heading towards it (see Fig. 2.2).

2) *Brainstorming - identifying the main categories of the possible causes*

In this step, it is necessary to identify the key areas in which the causes function and which may contribute to the formation of the analyzed problem. In case of a problem with product quality, the following main categories of causes are often used: material, equipment, methods, people and the environment. The main categories of causes are shown as the main branches in the diagram (see Fig. 2.2).

3) *Brainstorming - analysis of the possible causes of the problem*

The individual potential causes are gradually identified in the individual categories. All the causes that are not specific enough should include an analysis of the causes of these causes. The decomposition of the causes into sub-causes (causes of the causes) should continue until the root causes of the analysed problem are revealed.

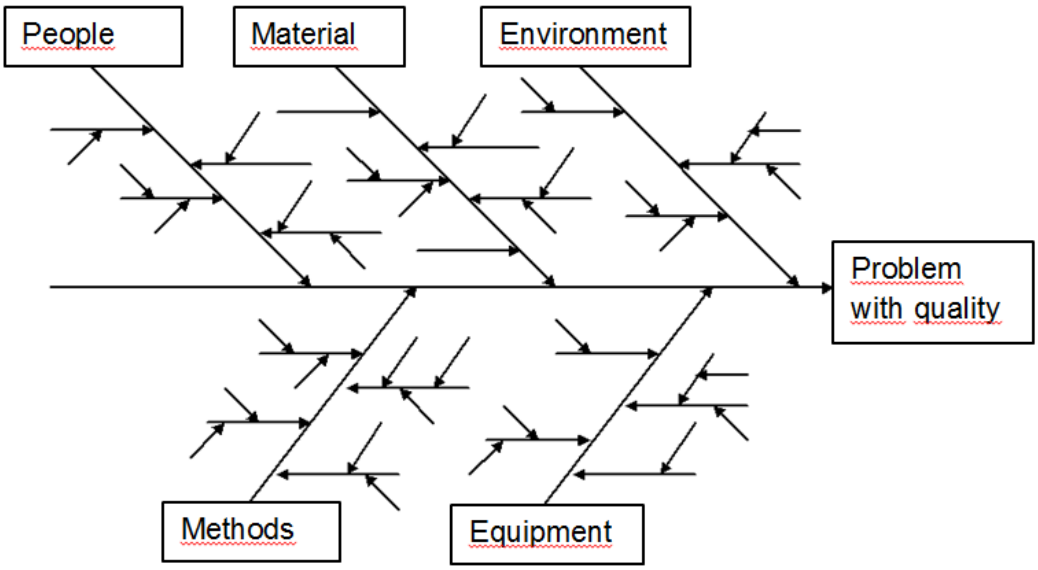

Fig. 2.2: Structure of the cause-effect diagram.

4) *Selection of the most important root causes*

The processing of a cause- effect diagram usually leads to the conclusion that there are many possible causes involved in its formation. Not all the causes, however, have the same impact on the formation of the problem, and we usually do not have sufficient resources to be able to address all the possible causes. That is why it is necessary to identify the most important causes. This provides a wide space for the application of statistical analysis of the existing or new collected data.

The first stage should, however, evaluate the most important causes based on the opinion of the team. The initial data can be obtained by voting of the team members where, for example, each member will choose the three most important causes of the problem according to his/her opinion and use the agreed point score system. The total score of the individual causes then represents the initial data for the evaluation of the most important ones. The preferable method of the identification of the group of the most important causes is Pareto analysis.

The processed cause-effect diagram should be a live recording that is constantly in use during the solution of the problem and that takes in the newly acquired information.

2.4 DATA FORM

Data forms are designed for systematic collection of data relevant for the management and improvement of quality. The collected data represent an essential starting point for the evaluation of the current state of the process, for the direction of continuous improvement, for the assessment of the effectiveness of the implemented measures, etc. The preparation of a data form, which can have both paper and electronic form, should ensure the collection of such data that provide the necessary information.

The preparation of a data form can be divided into several steps:

1) ***Definition of the purpose of data collection***

The first step in the preparation of a data form should be the clarification of the questions the collected data should answer.

2) ***Determination of the necessary data to achieve the purpose***

It is important to realize that the informative value of the collected data does not depend on their number only, but especially on a good choice of the monitored parameters. This selection should be based on the data processed in the cause-effect diagram, which have identified all the factors that can contribute to the solved problem.

3) ***Determination of the method of collected data analysis***

Before the actual preparation of a suitable data form, it is desirable to clarify how the collected data will be processed in the next step (the method of statistical evaluation, graphical outputs, etc.). The form design should be optimized according to the selected processing method.

4) ***The design of the data form***

Data forms should be easy to understand and sufficiently clear and must include all the important information about the conditions under which the collected data were acquired. This information should include the date, time, location, equipment, name of the worker who collected and recorded the data, the used measurement method and the type of measuring equipment, the identification of the monitored production batch, the production parameters, and other important data.

The knowledge of all these identification data is of great importance for data stratification. Data stratification is the sorting of data according to selected criteria, and it is very important for further evaluation of the collected data. The suitable aspects of data stratification can include, for example, the kind of detected non-conformity, the place of its occurrence, the production line, the production time section, the process control and other parameters of the process, as well as the type of material used, etc.

5) ***Verification of data form suitability***

The designed data form should be tested in real-world recording of the required data prior to its first practical application. Attention should be paid especially to its clarity, suitability of arrangement, lucidity, and whether it has sufficient space to record the individual data.

2.5 PARETO CHART

A Pareto chart is an important tool of managerial decision-making, since it allows setting the priorities in addressing quality issues in order to achieve the maximum effect through a purposeful use of the resources. It is also very suitable for an illustrative presentation of the main causes of the problem.

Pareto chart was named after V. Pareto, an Italian economist of the 19th century, who described the irregular distribution of wealth among the population; i. e. that a high share of the total wealth is owned by only a small percentage of the population. This phenomenon was transformed by an American expert J. M. Juran into quality management in this form: Most quality problems (80-95%) are caused only by a small share (5-20%) of causes contributing to them. This principle was named the Pareto principle, also it is called as 80/20 rule.

The individual causes must be understood in a broader sense. They represent the partial "bearers of deficiencies", such as the individual causes of non-conformities, but also the individual non-conformities, the individual products, the individual machines, the individual employees, etc. By applying the Pareto principle, you can, for example, determine that the problems are mostly caused only by a certain group of products from the entire production program, only by some non-conformities from all the occurring non-conformities, only by some of all the active causes, only by some machines of all the used ones, only by some of all the workers who influence the product quality, etc. This definition is very important in order to set the priorities during the solution of the problem.

This small group of causes is referred to as the "vital few" and the remaining part gradually became known as the "useful many". Using a Pareto chart, you can identify this "vital few", which allows you to focus the resources on the elimination of the causes that contribute most to the analyzed problem.

The processing of a Pareto chart should take place in the following steps:

1) ***Identification of the problem***

2) ***Determination of the causes contributing to the problem***

The input data for the processing of a Pareto chart mostly include the information about the causes that contribute to the occurrence of the analyzed problem. Depending on the type of problem, these can be the individual kinds of non-conformities, the individual products, the individual production facilities, the identified causes of the problem occurrence etc.

3) ***Selection of the method assessing the contribution of the individual causes***

The occurrence frequency during the monitored period is usually the basic aspect used in the evaluation of the contribution of the individual causes. The occurrence frequency, however, does not take into account the varying severity of the individual causes. The severity can be taken into account by introducing an appropriate severity coefficient, and the contribution of the individual causes can be assessed as the product of the frequency and of this severity coefficient. From a practical point of view, the contribution of the individual factors is best expressed in expenditure items.

4) ***Selection of the period during which the data are to be gathered and processed***

5) ***Sorting the individual causes according to their contribution to the problem***

The first step in the processing of the collected data is to sort the causes contributing to the problem according to the magnitude of their contribution (from the most to the least contributing).

6) ***Calculation of the cumulative sums of the contributions***

The cumulative sums of the contributions are determined by a successive summation of the contributions of the individual causes arranged by magnitude (see the previous step). At the same time, you should set the values of the relative cumulative sums as a percentage value.

7) ***Construction of a column chart***

A Pareto chart is a combination of a column chart and a scatter plot. The column chart compares the contributions of the individual causes to the analyzed problem in descending order. Y axis scale is chosen in such a way to also include the value of the total sum of all contributions.

8) ***Construction of the Lorenz curve***

The column chart is supplemented by the so-called Lorenz curve, which shows the values of the relative cumulative sums of the contributions as a percentage value (see Fig. 2.3). The relative cumulative sums expressed as a percentage are added to the right axis of the diagram before this broken curve is drawn. The scale on this axis should correspond to the scale on the left axis y. The individual points on the Lorenz curve are drawn at the level of the right edge of the individual columns.

9) ***Identification of the "vital few"***

Two kinds of criteria, which are constructed on a different basis, are usually used to determine the vital fews:

- certain selected value of the relative cumulative sum as a percentage value
- average value of contribution per cause (for example, the average expenditures on one type of non-conformity).

In the first case, and in compliance with the Juran formulation of the Pareto principle, the vital few should include the causes which correspond to app. 80% of the cumulative sum of the contributions, but sometimes is used smaller percentage (not below 50%) of the cumulative sum, which corresponds to shorter selection of the causes.

The identification of the vital few can make use of graphical evaluation. A parallel with the x axis is drawn at the level of the selected relative cumulative sum expressed as a percentage value, and a perpendicular to the x axis is drawn once the Lorenz curve has been reached. All the causes, whose columns are located to the left of the perpendicular, including the affected ones, belong to the vital few (see Fig. 2.3).

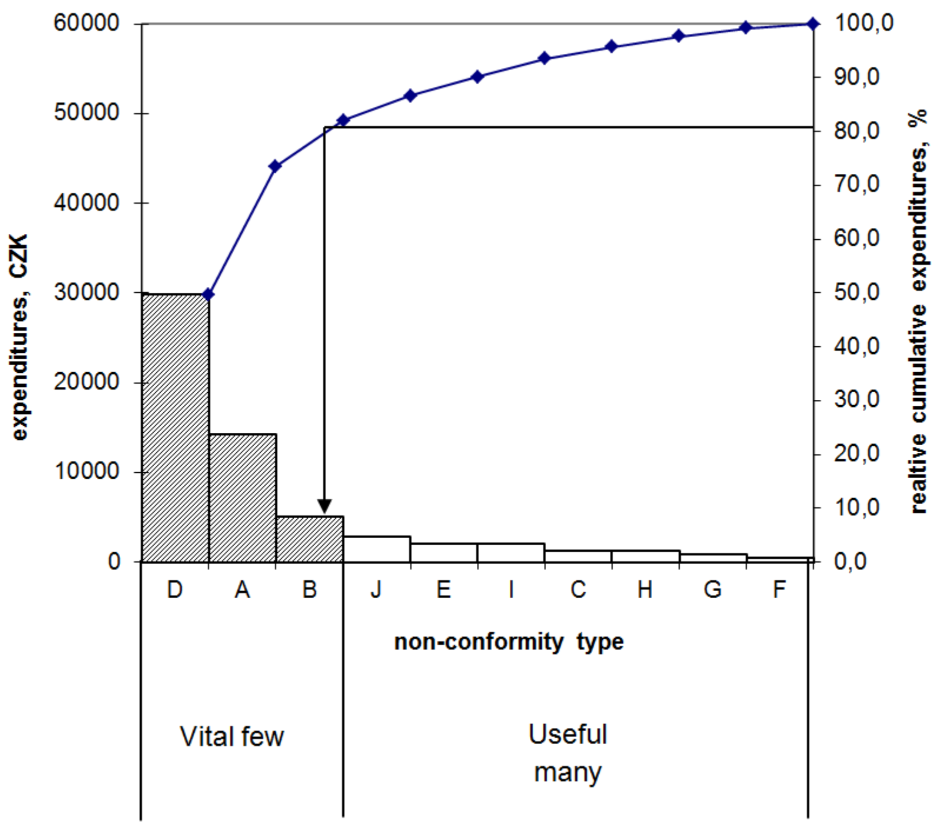

Fig. 2.3: Example of Pareto chart.

Corrective actions should primarily focus on the minimization of the causes belonging to the vital few. In case the expenses associated with these causes are reduce to zero, it will bring the most significant decrease of overall expenditures. New data should be collected after the implementation of the corrective actions under comparable conditions, followed by the processing of a new Pareto chart, and the relevant changes should be compared.

The elaboration of a Pareto chart does not always have to be based on the data from the already ongoing process. A Pareto chart can also be used, for example, to evaluate the "vital few" of the causes having effect on the occurrence of a problem on the basis of a team point evaluation of the causes analyzed during the processing of a cause- effect diagram.

2.6 HISTOGRAM

A histogram is a column chart expressing the distribution of the frequency of values in suitably selected intervals. A histogram provides important information about distribution of monitored variable and it is considered to be the basic graphical tool for the evaluation of the collected data. The possible utilizations of histograms are very broad; from input quality analysis, through process capability analysis, to the evaluation of the success of improvement activities, etc.

There should be a sufficient amount of data (at least 30 values) if you want to construct a histogram. The processing of a histogram should take place in the following steps:

1) *Definition of the minimum and maximum value*

2) *Calculation of the range*

$$R = x_{\max} - x_{\min} \tag{2.1}$$

where:
R – range
x_{max} – maximum value
x_{min} – minimum value

3) *Determining number of intervals*

To estimate the number of intervals, you can use some of the empirical relationships, which can be found in various textbooks dealing with statistics. These empirical relationships, which determine the suitable number of intervals as a function of the number of data in the set, however, often lead to different results. These are the reasons why it is often recommended to use only the framework range of intervals, usually from 5 to 20 intervals (a higher number for larger files).

4) *Determining interval width*

We normally use histograms with the same interval width, which is beneficial in terms of further analysis. The estimate of the interval width is carried out using the ratio of the range and the proposed number of intervals:

$$h \approx \frac{R}{k} \tag{2.2}$$

where:

h – interval width

R –range of data

k – number of intervals.

5) *Determining the lower limit of the first interval and the limits of other intervals*

The lower limit of the first interval should be selected in such a way to make sure the first interval contains the minimum value and to ensure a unequivocal assignment of the values to all the intervals. To meet the second requirement, it is beneficial to set the interval limits more accurately by one decimal place than the processed data, in order to avoid a situation where some of the values are equal to the interval limit. The upper limit of the first interval, which is also the lower limit of the second interval, and the limits of other intervals are determined by gradually adding the determined interval width.

6) *Processing interval frequency distribution table*

Interval frequency distribution table is the foundation for the preparation of a histogram. This phase may be quite long if you use "manual" processing of larger sets. It is better to use suitable software.

7) *Construction of the histogram*

As already mentioned before, histogram is a column chart. The y axis is used for the frequency of data in the individual intervals, which corresponds to the height of the columns. The scale on the x axis corresponds to the monitored characteristic. This scale allows a definition of the individual intervals - from the lower limit to the upper one. The widths of the individual intervals correspond to the widths of the columns. Given that the individual intervals follow each other, the columns of the histogram should follow each other as well.

In the event that there are tolerance limits prescribed for the monitored quality characteristic, they should be added to the histogram in order to make it possible to graphically assess the degree of compliance with them. An example of a histogram with tolerance limits is shown in Fig. 2.4.

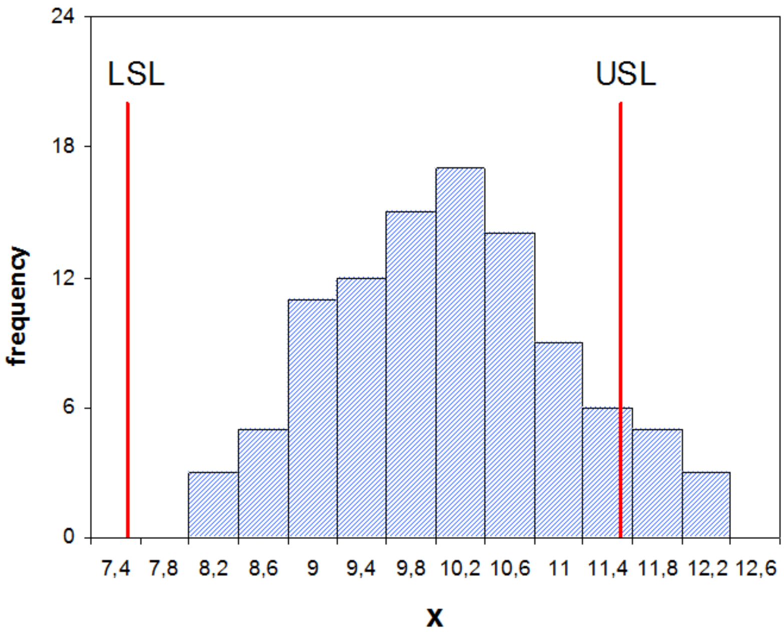

Fig. 2.4: Example of histogram with tolerance limits.

8) *Histogram analysis*

The analysis of a constructed histogram is focused mainly on its location, which characterizes the mean value of the monitored characteristic, on its width, which reflects the variability of the data, and on its shape, which allows you to detect some special causes of variability. Some of the basic shapes of histograms are shown in Fig. 2.5.

The most typical type of histogram we can encounter is a bell-shaped histogram, which illustrates the probability density of normal distribution (Gaussian curve). This distribution of the monitored characteristic can be found especially in cases where the variability of data is caused only by random causes.

A double-peaked (bimodal) histogram indicates that the analyzed set of data was created by combining two sets acquired under different conditions (different raw materials, different technologies, different shifts etc.). In case of this type of histogram, it is necessary to identify the special cause of it and to perform data stratification. The original set should be split into two sub-sets, which are then processed separately.

A plateau histogram generally arises in cases where the data were collected under varying conditions, i. e. as if several sub-sets, whose histograms overlap, were linked together. A histogram of this type is typically created when the monitored quality characteristic changes with time. It is usually caused by the effect of a known assignable cause resulting from the nature of the process (e. g. tool wearing, mold wearing etc.).

A comb-shaped histogram is characterized by a regular alternation of higher and lower frequency values in the individual intervals. This may be due to an inappropriate choice of interval limits with regards to the accuracy of the collected data.

An asymmetrical (skewed) shape of the histogram usually indicates a case where the values of the monitored characteristic lie close to the limit of definition area. A zero value represents an example of such a limit in case of physical variables that can only have positive values (e.g. dimension, concentration, weight, volume, etc.). In cases where the asymmetrical shape of the histogram is not caused by the proximity of data to the limit value, it can be a signal of the effect of assignable causes of variability. For some variables, however, the asymmetric distribution of the monitored characteristic may express its natural behaviour.

The so-called truncated histogram is characterized by one-sided or double-sided abrupt ending. It usually indicates that the manufactured products have gone through a sorting inspection, during which the products whose monitored quality characteristic had exceeded the tolerance limits were excluded from the original set.

A histogram with isolated values usually indicates the presence of outliers. With these values, the first thing to do is to determine the conditions under which they were established, and to assess whether they really belong to the set or whether they are, e.g., a result of incorrect measurements.

A histogram with a higher frequency in the edge interval (edge peak histogram) indicates a deliberate misrepresentation of the measured data in order not to exceed the specified tolerance limits. Fig. 2.5 shows an example of such a histogram, where the frequency of the values in the last interval has been significantly increased. In the event the upper tolerance limit of the monitored characteristic is situated near the upper limit of this interval, this raises a suspicion whether the measured values, which exceed this upper tolerance limit, have not been adjusted to a value lower than the tolerance limit.

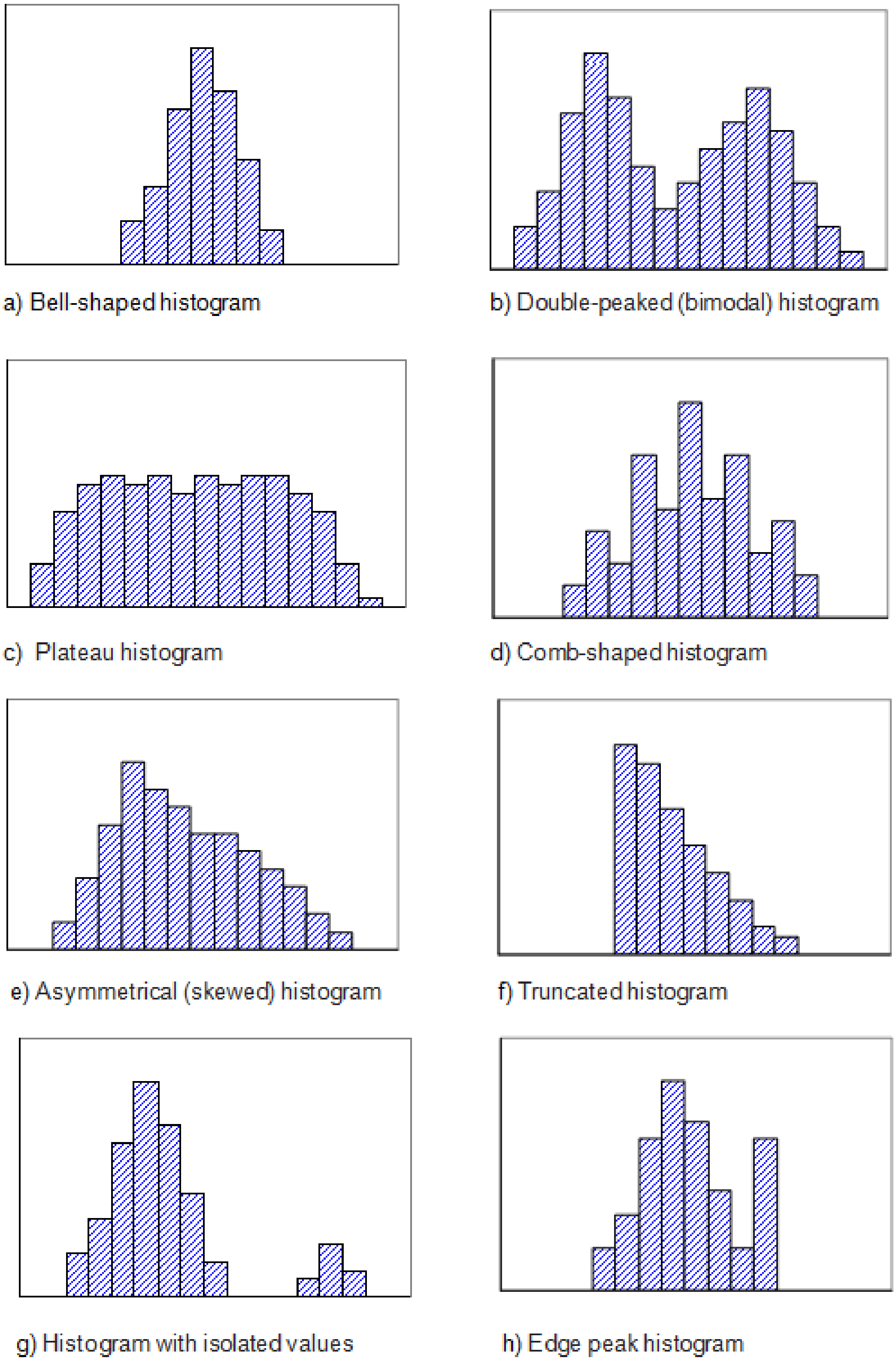

Fig. 2.5: Typical types of histograms.

2.7 SCATTER DIAGRAM

A scatter diagram is a graphical method used to study the relationships between two variables. You can use the scatter diagram to assess, for example, the mutual relationship between two product quality characteristics, the relations between a specific product quality characteristic and a selected process parameter, or to assess to what extent the measured data correspond to the correct values, etc.

The processing of a scatter diagram should be carried out in the following steps:

1) *Data gathering*

The construction of a scatter diagram requires a pairs of corresponding values of both variables. Generally, the more data are available, the more credible information about the dependence between the monitored variables can be provided by the scatter diagram. It is also necessary to remember that it is a set of data obtained under comparable conditions. If this is not so, it is necessary to stratify the data set in a suitable way and to process the sub-sets separately.

2) *Drawing the scatterplot axes, their designation and the selection of scales*

The explanatory power of a scatter diagram may be significantly influenced by the choice of scales on the axes. According to recommendations, the scales on the individual axes should approximately match the range of the values of the monitored characteristic, which allows you to fully utilize the entire area defined by the coordinate system. The choice of suitable scales requires a particular attention, because in many cases the scales on the axes are deliberately adjusted in order to provide misleading information.

3) *Drawing the points corresponding to the individual pairs of data*

The points are drawn in the scatter diagram using different graphic symbols. The most unambiguous way is to express the position using a cross or a star, where the intersection precisely defines the given position.

4) *Scatter diagram analysis*

The distribution of the points in a scatter diagram, which correspond to the individual pairs of values of the variables, characterizes the direction, shape and degree of closeness of the dependence among the monitored variables. In most practical cases, we come across the so-called stochastic dependencies that are characterized by certain scattering of the points. The reason of this scattering is usually the effect of other factors, such as the process parameter variability, the variability of the ambient conditions, the properties of the used materials etc. The scattering of the points is, of course, also influenced by inaccurately determined values of the analyzed variables, which is affected by a number of parameters, such as the inaccurate method of determination, inaccuracy of the measuring instrument, inaccuracy caused by the operators, etc.

The constructed scatter diagram provides the basic graphic information on the mutual relationship of the two monitored variables. To assess whether the dependence can be described using a suitable mathematical form, and whether this relationship is statistically significant, you have to conduct further evaluations. This can be done by means of a regression and correlation analysis.

An example of a scatter diagram with an appropriate regression function and the value of the coefficient of determination is shown in Fig. 2.6.

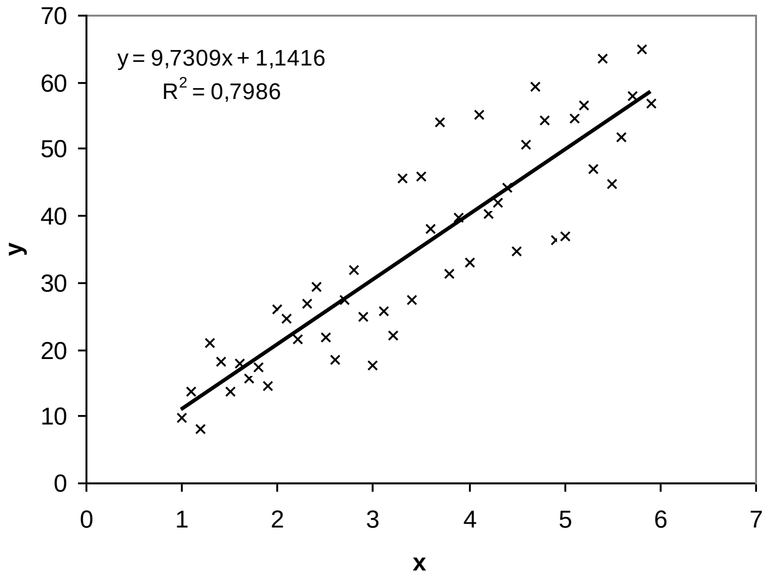

Fig. 2.6: Example of scatter diagram with a regression function.

2.8 CONTROL CHART

A control chart (see Fig. 2.7) is a graphical tool used to distinguish the process variability induced by assignable causes from the variability induced by random causes. This is very important if you want to find suitable improvement activities.

Random (natural) causes represent a wide range of single unidentifiable causes, where each of them contributes very little to the overall variability. Nevertheless, the overall effect of these random causes is measurable and is seen as a natural feature of every process. The effect of random causes is practically permanent and thus predictable, since the distribution of the monitored quality characteristic over time remains virtually unchanged as a result of their effect. The limitation of the overall effect of random causes is possible only through radical interventions in the production process, such as a change in the technology, changes in the production equipment, a change of the process control system, etc.

The assignable (special) causes induce variability, which manifests itself as the changing distribution of the monitored quality characteristic. The assignable causes can in principle be further divided into:

- unpredictable;
- predictable.

The unpredictable assignable causes do not represent the natural process behaviour. They operate irregularly and cannot be described by means of statistical laws. That is why they should be removed. Due to the fact that they lead to a real change in the process, they are generally identifiable and, in most cases, also removable. However, if no corrective actions of permanent nature are taken, these causes can appear again.

The predictable assignable causes are those causes whose effect can be described by physical laws and experimental research. These are, in particular, the causes the effect of which depends on the physical nature of the process. For example, machining is accompanied by a gradual wear of the tool, filtration is accompanied by a gradual clogging of the filter, production of steel is accompanied by a gradual wear of the lining, etc. The effect of these causes can be somewhat limited, but cannot be completely eliminated.

A process affected only by random variability causes is referred to as statistically stable process („in control” process). A process affected also by the assignable causes of variability is referred to as statistically unstable process („out of control” process).

A control chart is used for process analysis and it is a fundamental tool of statistical process control (SPC).

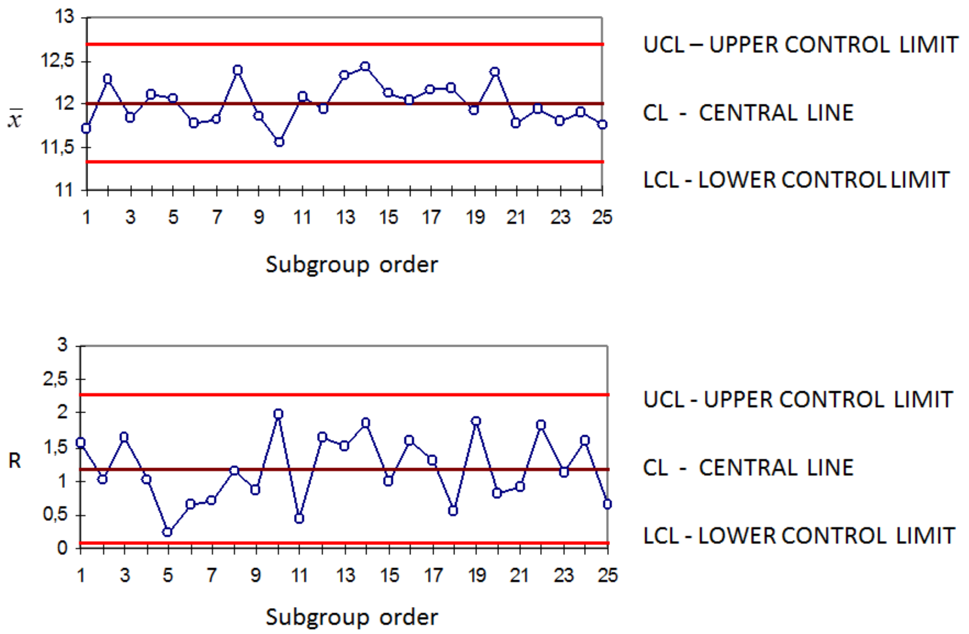

Fig. 2.7: Structure of $\bar{x}, R$ control chart.

2.8.1 Statistical process control (SPC)

Statistical process control is a feedback system, whose principal aim is to achieve and maintain a state in which the process runs at a stable level and consistently provides products that meet the required quality criteria. Statistical process control is based on a strategy of prevention, i.e. on a strategy which prevents the occurrence of non-conforming products. It focuses its attention directly on the processes, where the decisions about quality are made and where it can still be affected.

Depending on the nature of the monitored quality criteria, we distinguish between two types of control charts:

- control charts for variables;
- control charts for attributes.

Statistical process control for variables can be used only in cases where the monitored quality characteristic is measurable. It works with a pair of control charts; one monitors the changes of position depending on time and the other monitors the changes in variability of the observed characteristic (see Fig. 2.7).

Statistical process control for attributes is applicable universally, because its application only requires monitoring the occurrence of non-conforming products or non-conformities. Statistical proces control for attributes works with one control chart.

The process of implementation of statistical process control can be divided into four phases:

1) preparatory phase;
2) analysis and ensuring statistical stability of the process;
3) analysis and ensuring process capability;
4) actual statistical process control.

Procedure for the implementation of statistical process control for variables (control chart $\overline{x}, R$)

a) Preparatory phase

During the preparatory phase, it is desirable to create suitable conditions for the implementation of statistical process control and to set its basic parameters. The preparatory activities include:

1) *Selection of the controlled variable*

The most commonly selected controlled variable is the crucial product quality characteristic which directly reflects the success of the ongoing process. The selected controlled variables, however, can also include some of the critical process parameters, the level of which directly determines the quality of the resulting products.

2) *Process analysis and the selection of the measurement system*

A detailed analysis of the process should be performed to determine all the causes that may affect its course, including the selected controlled variable. The selection of the measurement system is directly related to the selection of the controlled variable. It is necessary to ensure such a measurement system, which enables you to determine the controlled variable in real time.

3) *Determination of subgroup size*

The standard procedure of statistical process control is to check certain number of products taken out of the process in conveniently selected control intervals. This sample is referred to as a subgroup. It should lead to the creation of the so-called logical subgroups, i.e., the characteristics of the products included in a subgroup should be affected only by random variability causes. This is usually achieved by taking certain number of products manufactured in succession out of the process.

In case of statistical process control for variables, we usually work with a constant size of subgroup, the ISO 8258 [4] standard recommends selecting four or five products in one subgroup.

4) ***Determination of the control interval***

A control chart works with subgroups of data obtained from the process at approximately regular intervals, and these intervals can be determined in the units of time (e.g., every hour) or quantity (e.g. after every 50 manufactured products). When you are selecting the control interval, you should consider the potential interference with the process and the economic aspects.

5) ***Selection of the type of control chart***

A suitable type of control chart should be selected as early as during the preparatory stage. A pair of diagrams is used in case of statistical process control for variables, where one evaluates the course of the selected measure of position of the monitored characteristic, while the other one evaluates the course of the selected measure of variability. The most commonly used control charts are those in which the measure of position is represented by average or a median, and the measure of variability is represented by a range or standard deviation.

b) Analysis and ensuring statistical stability of the process

This stage assesses whether the examined process is statistically stable, i.e. whether the variability of the monitored quality characteristic (controlled variable) is caused only by random causes. This analysis takes advantage of a control chart.

In the case of using control chart for the average and the range ($\bar{x}, R$), the processing takes place in the following steps:

1) ***Gathering data***

Gathering data about the selected quality characteristic in the controlled product subgroups should take place over a period of time the length of which affects all the normal changes of the parameters affecting the process. The analysis requires obtaining data on at least 25 subgroups with recommended size of 4 or 5 units.

2) ***Calculation of sample characteristics of the values in the individual subgroups***

Depending on the selected type of control chart, you have to calculate the relevant sample characteristics of the measured values in the subgroups that are drawn into a control chart. In case of $\bar{x}, R$ control chart, it is necessary to determine the mean values and the ranges of the values in the individual subgroups.

3) ***Calculation of central lines and control limits***

To make a control chart a real control chart, it must contain the lower control limit (LCL) level, the upper control limit (UCL) and the central line (CL).

The positions of these levels are calculated on the basis of average sample characteristics of the position and variability of the values in the subgroups. In case of $\bar{x}, R$ control chart, these values are calculated according to formulas:

$\bar{x}$ **- diagram:**

$$CL_{\bar{x}} = \bar{\bar{x}} = \frac{\sum_{j=1}^{k} \bar{x}_j}{k} \tag{2.3}$$

$$LCL_{\bar{x}} = \bar{\bar{x}} - A_2 \cdot \bar{R} \tag{2.4}$$

$$UCL_{\bar{x}} = \bar{\bar{x}} + A_2 \cdot \bar{R} \tag{2.5}$$

where:

$\bar{\bar{x}}$ - average of the averages in the subgroups

$\bar{R}$ - average of the ranges in the subgroups

k - number of subgroups

A_2 - coefficient depending on the subgroup size [4].

R-diagram:

$$CL_R = \overline{R} \tag{2.6}$$

$$LCL_R = D_3 \cdot \overline{R} \tag{2.7}$$

$$UCL_R = D_4 \, . \, \overline{R} \tag{2.8}$$

where:

D_3, D_4 – coefficients depending on the subgroup size [4].

4) ***Construction of a control chart and its analysis***

The values of the calculated sample characteristics in the subgroups and the levels of control limits and central lines are drawn into the pair of control charts.

The control chart analysis is based on an assessment whether the sample characteristic courses do not signal an activity of assignable variability causes. The signals showing the activity of assignable causes include the occurrence of points outside the control limits and the non-random patterns of points [2]. In the event of an indication of the occurrence of signals of assignable causes, the process is considered to be statistically unstable (“out of control”). To ensure it is statistically stable, it is necessary to apply the so-called "cleaning process" that takes place in the following steps:

a) identification of assignable causes

b) execution of corrective actions to permanently prevent the reoccurrence of these causes

c) exclusion of these subgroups from further evaluation

d) recalculating the control limits and central lines

e) analysis of the control chart with regard to the new (revised) control limits.

An analysis of the signals of the action of assignable causes is performed together with the "cleaning process" in both diagrams, until all points lie within the control limits. It should be emphasized that this elimination of subgroups affected by assignable causes is not done to "improve the process", but to establish the control limits characterizing the natural behaviour of the process, i.e. a condition where the process is affected only by random causes of variability.

5) ***Extension of the validity of the control limits for the next period***

If the final analysis of both diagrams has not identified any signals of the action of assignable causes and the process capability has been confirmed in the next step, you can use the set control limits for the actual statistical process control. If a larger number of subgroups was excluded during the "cleaning process", the determination of the control limits would requires you to collect a new data set and to repeat the analysis phase and to make sure the process is statistically stable.

c) Analysis and ensuring the process capability

If the process is statistically stable, you can evaluate its capability that characterizes the ability of the process to permanently provide products that meet the required quality criteria. In case the process is not found incapable, you have to take actions to achieve its capability. After a successful implementation of these actions, it is necessary to return to the stage of analysis and ensuring the statistical stability of the process.

d) Actual statistical process control

The initial state required for starting the actual statistical process control is a statistically stable and capable process. The actual statistical process control is based on drawing a control chart with the control limits drawn in advance. Subgroups of the manufactured products are taken out of the process at selected intervals and the values of the monitored quality characteristic are determined. These values are used to calculate the respective sample characteristics, which are drawn into the control chart. Once the data on each subgroup have been drawn, you can perform an analysis of the control chart in order to detect the occurrence of the signals of assignable causes. If such a signal appears, it is necessary to detect the cause and to remove it so that the process can return to the statistically stable state.

Summary of terms

PDCA cycle - a cycle consisting of four phases (Plan-Do-Check-Act) that should take place to improve quality.

Quality Journal methodology – quality improvement methodology which develops the PDCA cycle into seven specific steps.

Flow chart - a graphical tool showing the sequence and interrelationship of all steps of the given process.

Cause - effect diagram (Ishikawa diagram, fishbone diagram) - a graphical tool used to analyze all the possible causes of a particular effect (problem with quality).

Data form – a tool used for a systematic collection of data relevant for quality management.

Pareto chart - a tool allowing you to set the priorities in solving quality problems in order to achieve the maximum effect thanks to an effective use of the resources.

Histogram - a column chart expressing the frequency distribution of given quality characteristic in suitably selected intervals.

Scatter diagram – a tool for a graphical analysis of the relationships between two variables.

Control chart - a tool distinguishing the process variability induced by assignable (special) causes from the variability caused by random causes.

Questions

1. Name the individual steps of quality improvement according of the Quality Journal methodology.
2. What is the use of a flow chart?
3. What is brainstorming?
4. Name the most frequently used main categories of causes during the processing of a cause-effect diagram.
5. What are the advantages of preparing a data form?
6. Formulate the Pareto principle.
7. What information can be obtained by analyzing the shape of a histogram?
8. What does regression and correlation analysis deal with?
9. Characterize random and assignable causes of variability.

10. What process is referred to as statistically stable (“in control”)?
11. Name the examples of control charts for variables.

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