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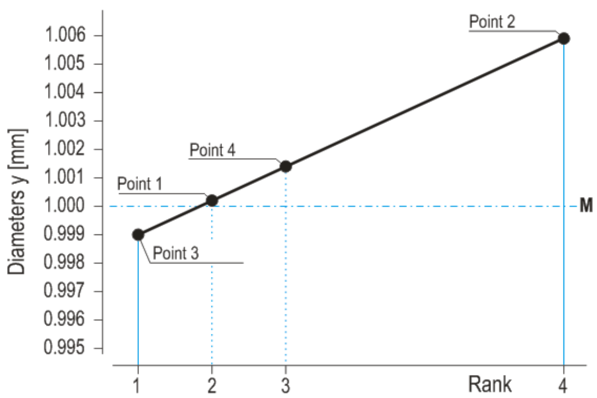
The FACTORY DIAGNOSIS DIAGRAM – An Efficient Tool for Quality Control

During electroplating or heat treatment operations parts are usually mounted on plating or charging racks, which can for practical purposes be described as position matrices. An optimized production process should exhibit no significant changes in the quality characteristics of the products after going through the production cycle regardless of the product's position within the matrix. Measurement results taken from a random sample of finished parts over a number of predetermined rack locations can be displayed easily in a Factory-Diagnosis-Diagram (FDD®), which is introduced in this paper. The descriptive nature of this type of diagram truly provides an "at a glance" display of essential quality related information. Weaknesses in a manufacturing process or a production line become evident, without the need for complex data analysis. The advantages of the Factory Diagnosis Diagram, highlighted in this paper can be applied beyond example application to nearly all areas of production.

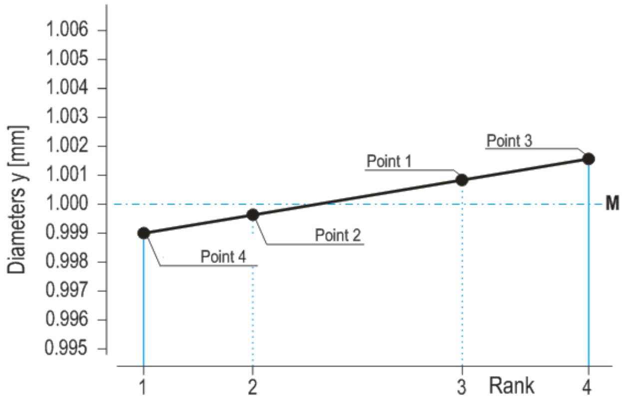
1 Introduction

As a rule, counting, measurement and experimental data of various origins are initially protocolled or stored in the order of their occurrence. For descriptive and/or analytical processing of such data, it is often advantageous, at times even mandatory, to sort the data in ascending or descending order according to their size, i.e., to bring them into a so-called rank order. In particular, in applied statistics, rank orders form the foundation for certain evaluation methods or graphical presentations, for example in probability charts, cf. [1-3].



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 1	Point 3
ø 0.9990 mm	ø 1.0002 mm	ø 1.0014 mm	ø 1.0059 mm

Fig. 1. Rank order of diameter values measured on four specified places of a defined pin



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 1	Point 3
ø 0.9990 mm	ø 0.9997 mm	ø 1.0008 mm	ø 1.0016 mm

Fig. 2. Analogous to Fig. 1: Rank order of a further pin after realizing a quality improvement

Apart from these special applications, such rank orders are most often expressed only in table format. Only rarely is use made of the remarkable possibilities of, for example, quickly acquiring additional valuable insights by displaying (simultaneously) the rank data in the form of so-called rank diagrams. This is surprising considering the manifold possibilities of applying such presentations in the broad field of quality management. Both in production control as well as in receiving, interim and outgoing inspections, they prove to be extremely efficient tools for quick, reliable and at the same time economical product and process evaluations ("quality diagnoses"), as shall be demonstrated below.

In this paper, the displaying of measurement results in the form of a special rank diagram type called Factory Diagnosis Diagram (FDD®[1]) is introduced and explained with regard to its significant advantages and characteristics. This type of diagram is applicable in many areas of application as a simple yet efficient instrument of quality management. Its distinctive feature is that the test results of a certain quality feature, which is demanded to be of the same value at several locations of a product, are fundamentally always reproduced as a plot in the form of a straight rank line. This simple presentation method allows the specialist to arrive at quick and remarkably reliable information regarding the current production quality without the need for additional evaluation steps.

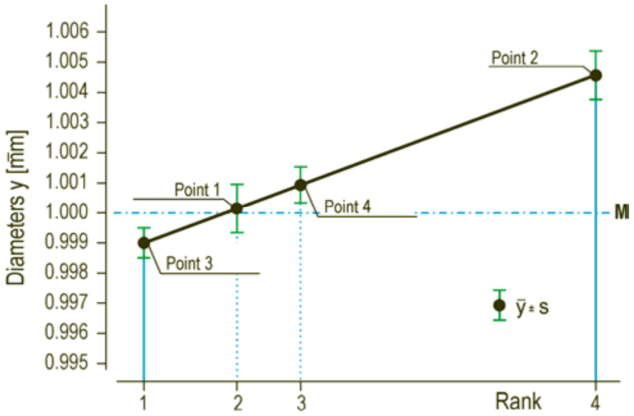
1 Ref. [4]

2 The Factory Diagnosis Diagram

2.1 Fundamentals

The Factory Diagnosis Diagram is a rank diagram type that presents a pre-specified number of measurement data or characteristic quantities in an ascending order *linearized* as points {y} over the assigned ranks {x}. To this end, it is simply necessary to establish on the abscissa (rank axis) a suitably selected distance (to be kept the same for comparative presentations) between the respective first and last rank (rank distance) of the examined group of data.

How to arrive at a Factory Diagnosis Diagram can be demonstrated in a simple manner using the manufacture of pins for needle bearings as an example: For a pin, (target length L = 20.00 mm; target diameter D = 1.000 mm) taken from a defined location, a diameter value is determined according to the test instructions at four equally spaced measurement locations, namely at 4 mm, 8 mm, 12 mm and 16 mm, with the reading carried out to 0.1 µm ("estimation point"); this provides the following result, Fig. 1. The diameter reading at 8 mm (2^{nd} measurement location) deviates in a "significant" (systematic) manner – here initially according to a subjective evaluation – and results, therefore, in the relative "steep slope" of the straight rank line. A readjustment of the production machine, carried out as a result, leads to a recognizably "better" result for the next pin, Fig. 2. The slope of the rank line is significantly less steep; in addition, the (changed) order and more uniform distribution of the measurement results over the rank distance suggest that the differences between local diameter readings are "purely coincidental". "At a glance" one is able to draw the conclusion of a "quality improvement".



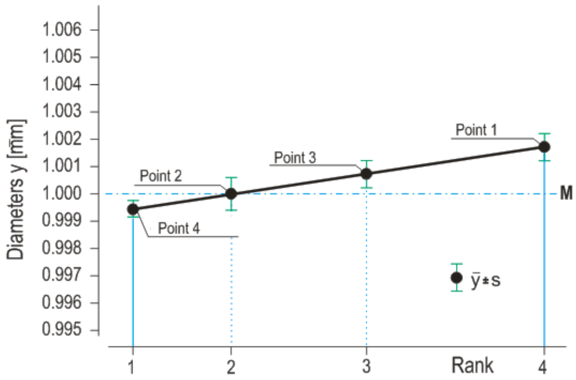
Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 3	Point 1	Point 4	Point 2
$\bar{y}$ = 0.9990 mm	$\bar{y}$ = 1.0001 mm	$\bar{y}$ = 1.0009 mm	$\bar{y}$ = 1.0046 mm
s = 0,0005 mm	s = 0.0008 mm	s = 0.0006 mm	s = 0.0008 mm

Fig. 3. Rank order of x, s-values (n = 4) obtained at four specified places of a defined pin

To increase the reliability of the information, the “testing accuracy” has been raised for this production by carrying out four diameter measurements at each of the four positions mentioned, each time advancing the angle by 45º. The four diameter values at each longitudinal position can be interpreted as random samples (circumference n = 4), because the advance in the angle was not carried out against a defined starting point. One can deduce from Fig. 3, again at a glance so to speak, that the diameter at the 2nd measurement location (i.e., at 8 mm) deviates significantly and not randomly from the other measurement locations. The measurement data scatter (“scatter bar”), visualized using the standard deviation (± s), does not indicate significant scatter differences between the four measurement locations.

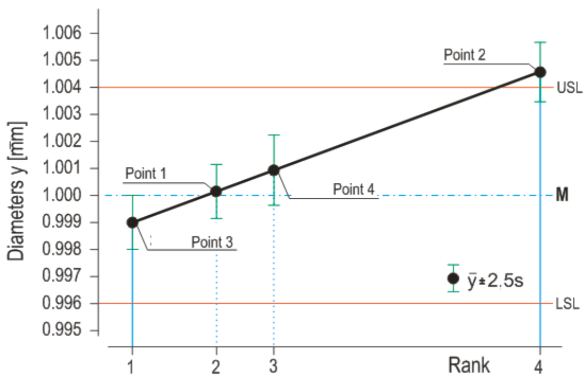
The necessary readjustment of the production machine provided a significantly “better” result, ref. Fig. 4. With a comparable scatter of the diameter values at the four measurement locations, the mean values are now distributed with a satisfactory uniformity across the length of the “gently” increasing rank line of the Factory Diagnosis Diagram.

In many cases, maintaining a tolerance is required for the quality feature under observation. In the example above, the specification limits for the pin diameters were determined with 1.004 mm (USL = upper specification limit) and 0.996 mm (LSL= lower specification limit).



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 3	Point 1
$\bar{y}$ = 0.9995 mm	$\bar{y}$ = 1.0000 mm	$\bar{y}$ = 1.0008 mm	$\bar{y}$ = 1.0018 mm
s = 0.0003 mm	s = 0.0006 mm	s = 0.0005 mm	s = 0.0005 mm

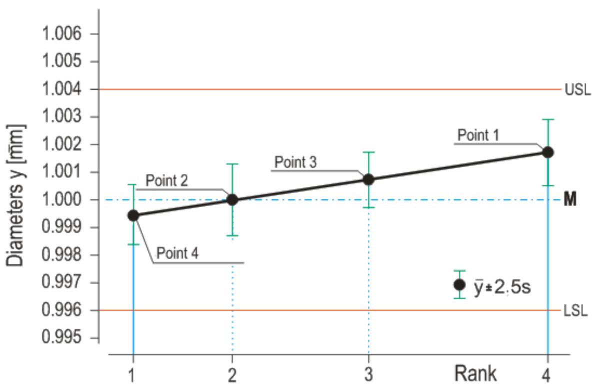
Fig. 4. Analogous to Fig 3: Rank order of a further pin after realizing a quality improvement



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 3	Point 1	Point 4	Point 2
$\bar{y}$ = 0.9990 mm	$\bar{y}$ = 1.0001 mm	$\bar{y}$ = 1.0009 mm	$\bar{y}$ = 1.0046 mm
2.5s = 0.0010 mm	2.5s = 0.0010 mm	2.5s = 0.0013 mm	2.5s = 0.0011 mm

Fig.5. Analogous to Fig. 4: Introduction of specification limits

A violation of specification limits cannot be excluded if – and this shall initially serve as a rough rule of thumb – in a Factory Diagnosis Diagram the end points of the one-sided scatter bar reach ($\bar{y}$ +2.5 s) the USL or ($\bar{y}$ -2.5 s) the LSL “from the inside” (tolerance). Fig. 5 shows that the tested pin not only exceeds the USL clearly at the 2nd measurement position but even with its mean diameter $\bar{y}$. This means that here several single readings are above the USL, which makes corrective measures (readjustments) unavoidable. In comparison to Fig. 5, Fig. 6 shows an overall satisfactory result for a sample pin that has been taken after the readjustment.



Ranking of pin diameters			
Rank no. 1	Rank no. 2	Rank no. 3	Rank no. 4
Point 4	Point 2	Point 3	Point 1
$\bar{y}$ = 0.9995 mm	$\bar{y}$ = 1.0001 mm	$\bar{y}$ = 1.0008 mm	$\bar{y}$ = 1.0016 mm
2.5s = 0.0011 mm	2,5s = 0.0013 mm	2.5s = 0.0010 mm	2.5s = 0.0012 mm

Fig. 6. Analogous to Fig. 5: Rank order of a further pin after realizing a quality improvement

The simple application example mentioned above already indicates the enormous potential inherent in the Factory Diagnosis Diagram. Today, for almost any measuring application, the employed measurement device is capable of providing the obtained measurement data directly (online, wireless) to a PC, where they can be evaluated in just a second and displayed in a clear fashion as a Factory Diagnosis Diagram. Position, slope and point arrangement of the rank line as well as the size and the uniformity of the associated scatter bars can be evaluated at a glance, so to speak; thus, it is often possible to do entirely without simultaneous analyses of measurement and evaluation tables. Thus, presentations in the form of Factory Diagnosis Diagrams enable the practioner to arrive at a quality diagnosis quickly and reliably, without requiring of him the often tedious use of complex statistical evaluation methods.

2.2 Factory Diagnosis Diagram: "Auto body coating"

2.2.1 Preliminary Remarks

For the application example (pin diameter) described in Section 2.1, “multi-sectioning” of the evaluated product was a result of the requirements (test instructions) to perform the diameter measurements at four measurement locations along the length of the pin. For this reason, four “ranks” each formed the foundation for the Factory Diagnosis Diagram. This is comparable, for example, to the conditions on boards (generally: Flat products) with certain dimensions, perhaps made of metal or plastic, where the same target value for a quality feature, which is measured only discretely (i.e., not continuously) due to metrological economic reasons, is required for all locations. Here, multi-sectioning is the result of the number of measurement locations (e.g., marked board areas), which are specified for specific cases by the quality requirements. This situation is often found when monitoring the material thickness or when verifying certain characteristic values at various kinds of coatings (mechanical, chemical, thermo-chemical). In particular in electroplating, product racks used for the transport through the bath are often divided into sections in order to recognize systematic differences that might occur in an often ambiguous manner at objects that have been removed from these racks specifically for this purpose after the coating process; this can be due to the position of the anode, the bath movement, a reduction in the field or even because of a power down.

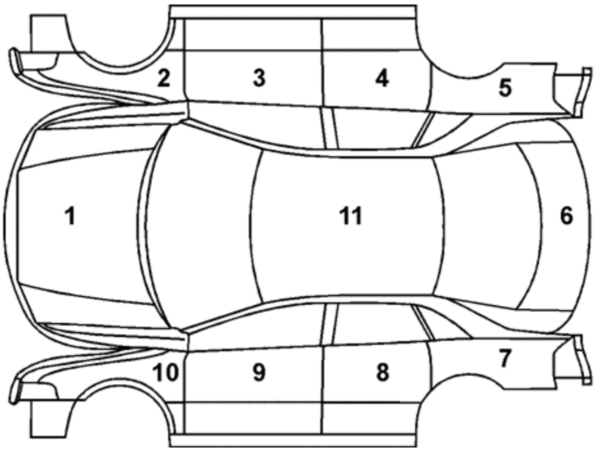


Fig. 7. Top view of an auto body (butterfly diagram)

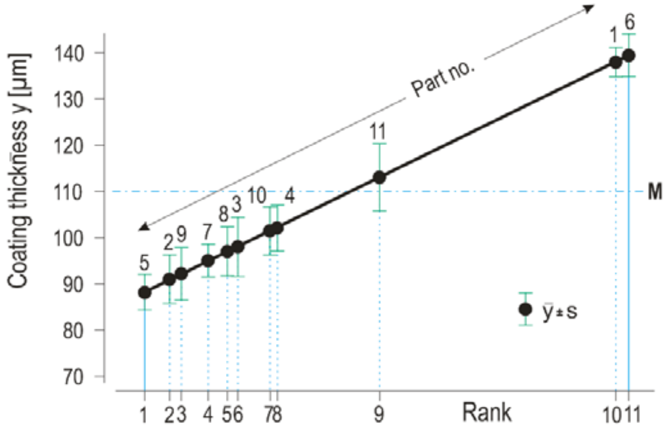


Fig. 8. Factory Diagnosis Diagram of an auto body based on the evaluation values of Table 1

The findings of such examinations then form the foundation for quality improvements for both products and process management. A corresponding practice offers itself in the field of technical heat treatment when examining the uniformity of certain furnace batches, where it is possible to evaluate quickly not only the batch quality itself but simultaneously the quality of the furnace system as well.

Even if different target values for the examined quality feature are specified for special products from one partial section to another, a normalization of the measurement results for differences (e.g., of the type: (local) target value minus measured value) would – in principle – not change anything for the presentation of the Factory Diagnosis Diagram.

2.2.2 Practical Example

For auto bodies, the multiple sections explained above arise practically "by themselves", ref. Fig. 7. For the k = 11 (essentially clockwise) consecutively numbered individual parts of the auto body evaluated here, the thickness of a new type of coating structure (target value d = 110 µm) was to be monitored in the course of a pilot trial; according to test instructions following a specified measurement plan, n = 5 measurements were to be performed for each individual part.

Coating thickness y in µm	Part designation	Part number	n	s	s	Rank*) i
137, 133, 139, 141, 140	Engine hood	1	5	138.0	3.16	10
95, 87, 86, 89, 98	Front end right	2	5	91.0	5.24	2
98, 95, 103, 89, 105	Front door right	3	5	98.0	6.40	6
107, 103, 95, 99, 106	Rear door right	4	5	102.0	5.00	8
90, 83, 86, 89, 93	Rear end right	5	5	88.2	3.83	1
137, 143, 140, 133, 144	Tailgate	6	5	139.4	4.51	11
97, 93, 100, 91, 94	Rear end left	7	5	95.0	3.53	4
98, 95, 103, 89, 100	Rear door left	8	5	97.0	5.34	5
90, 87, 96, 89, 99	Front door left	9	5	92.2	5.07	3
103, 100, 110, 98, 97	Front end left	10	5	101.6	5.22	7
111, 117, 125, 109, 107	Roof	11	5	113.8	7.29	9

*) Ranks: i = 1 to k = 11

Table 1. Coating thickness of an auto body – measurement and evaluation results

Table 1 shows the measurement and evaluation results for a certain auto body; Fig. 8 shows the corresponding Factory Diagnosis Diagram. From it, it can be deduced (subjectively) that the scatter is not characteristically different from one body part to the next, however, that the mean coating thickness deviates significantly upward for two ranks. The body parts represented by these ranks are, therefore, responsible for the relatively steep slope in the rank line. If one additionally inserts the specified coating thickness tolerance (USL = 140 µm; LSL = 80 µm) into the Factory Diagnosis Diagram, then it becomes immediately apparent (Fig. 9) that measures for improving the quality are recommended.

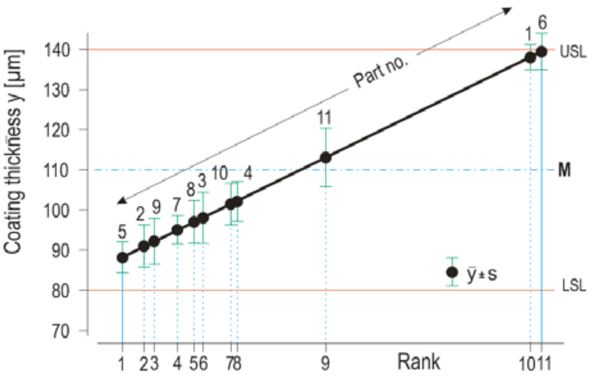


Fig. 9. Analogous to Fig. 8: Introduction of specification limits (USL / LSL)

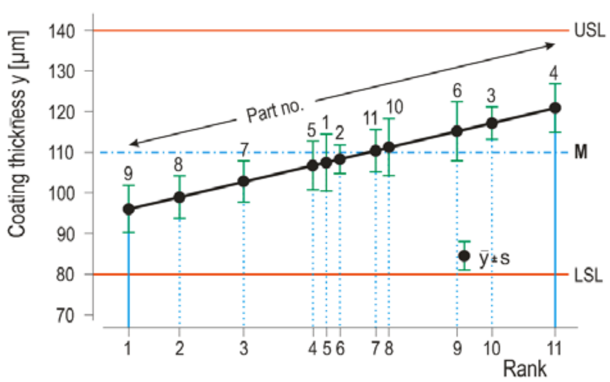


Fig. 10. Analogous to Fig. 9: Factory Diagnosis Diagram of a further auto body after realizing a quality improvement

At the end of these measures, the next auto body of this series provides the following Factory Diagnosis Diagram, ref. Fig. 10. The scatter of the coating thickness values of the individual parts has apparently not changed significantly. However, the rank line now runs very satisfactorily within the tolerance, with the upper/lower ranks at a sufficiently safe distance from the respective relevant specification limits (USL / LSL). With this now significantly gentler slope of the straight line, the mean values are distributed in a satisfactory uniform manner along the rank distance as well. Thus, it can be concluded (subjectively) that there are no noteworthy (systematic) differences between the parts of this auto body with regard to the coating thickness. This condition of the system is to be maintained for the future.

In particular with “multi-part" Factory Diagnosis Diagrams, the clarity can deteriorate by labeling the individual points of the rank line (cf. Fig. 10, for example). In such cases, it is advisable to provide the appropriate part numbers at the respective (fixed) positions on the abscissa instead of the rank numbers. Thus, the rank axis can be converted easily into a part number axis without any loss of information.

2.3 Statistical Background

An efficient use of the Factory Diagnosis Diagram can be implemented in quality management as long as the user has some basic experience with the worldwide customary characteristic random sample parameters mean value and standard deviation. Extensive knowledge in the field of technical statistics is expressly not an essential requirement for the successful use of this user-friendly quality tool. For by far the most applications, the fact that (plausible) conclusions drawn from a Factory Diagnosis Diagram still have some inherent residual subjectivity is not a disadvantage.

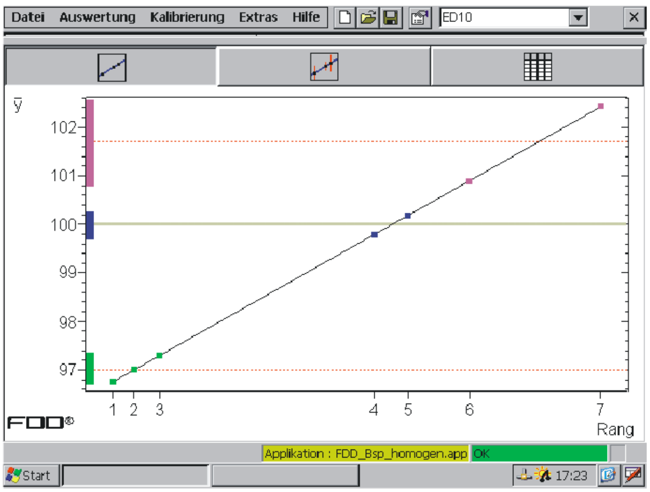


Fig. 11. Systematically differing point groups on Factory Diagnosis Diagram's straight line (statistically evaluated)

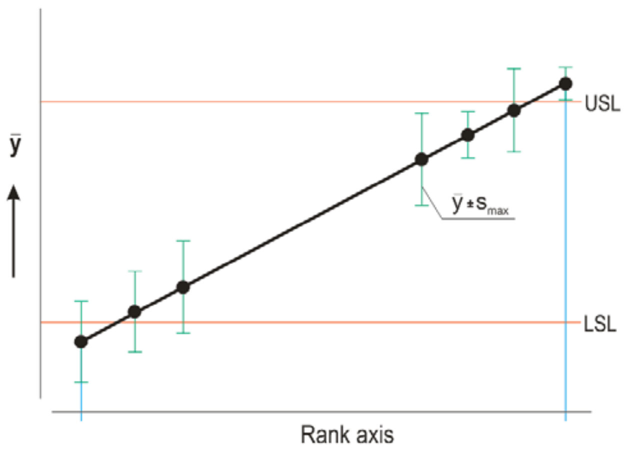


Fig. 12. Example of a Factory Diagnosis Diagram for a very inferior production quality diagnosis (schematically)

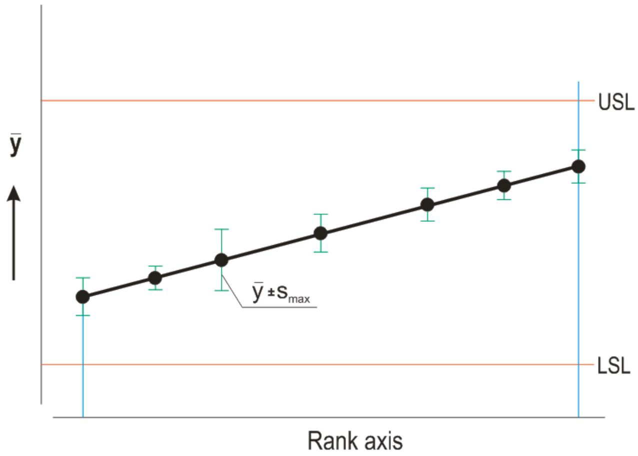


Fig. 13. Example of a Factory Diagnosis Diagram for an – on the whole – very satisfactory production quality diagnosis (schematically)

However, in some cases, in particular for Factory Diagnosis Diagrams with a large amount of data and at the same time very complex reasons for the data generation, it may be desired occasionally to objectify the decisions by applying suitable methods of analytical statistics. In this context, questions usually arise as to the type of distribution of the monitored quality feature (e.g., normal distribution, logarithmic normal distribution, etc.) as well as to the evaluation routines that are to be used as a result (e.g., tests for only adaptation, homogeneity of scatter, identical position, etc.). In some cases, the boundary conditions may also suggest utilizing so-called "distribution-free methods" in order to create viable conditions for objective decision making. However, since such methods are at times connected to significant calculation efforts, a suitable selection of a number of these methods has been made available as software programs[2]. Depending on the objectives and requirements, these methods can be used without any difficulties with the click of the mouse for the data sets that have been read into the memory from the measuring device. Figure 11 provides an example of an evaluation that examines for adjacent mean values the so-called null hypothesis (i.e., its traceability to an identical population). Following this path, several groups of points (identified by edge bars, ref. inside ordinate via assigned color or shading) may be separated on the rank line, as shown in Fig. 11; the technical conclusion could then be that the differences *within* these groups could be classified as *random,* and *between* these groups as *systematic.* The conclusion would be that the mean values of each group stem from separate populations.

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[2] Multi Measuring System FISCHERSCOPE® MMS® PC

Section 2.1 provides a rough rule of thumb according to which the scatter bar end points $y_{top} = \bar{y} + 2.5\ s$ must not exceed the upper specification limit (USL) of a tolerance range and $y_{bottom} = \bar{y} - 2.5\ s$ must not fall below the lower specification limit (LSL). Objectifying this statement is possible by determining the so-called "statistical coverage interval" for the respective ranks. If the distribution is (at least approximately) normal, but also if the distribution of the concerned data is not determined, i.e., for any distribution of adjacent data, the procedure suitable for it can be obtained from the literature [5, 6].

Finally, mention should be made of the interesting possibility of presenting the random sample standard deviations or variances separately as Factory Diagnosis Diagrams. In this case, the ordinate of the diagram would have to be set up correspondingly for s or optionally for s^2 instead of $\bar{y}$. From this display, one could again deduce, at a glance so to speak, based on an initially subjective evaluation of the point arrangement ("point clustering"?!), whether there is a satisfactorily similar scatter for all ranks or whether the characteristic scatter values differ (possibly significantly) between the ranks. In this case too, the answer can be determined easily by using statistical evaluation methods and – in case of relevance corresponding to Fig. 11 – visualized via associated edge bars (inside ordinate, ref. above).

With the background of quality control chart techniques – today typically called SPC (Statistical Process Control) – the idea suggests itself to plot the Factory Diagnosis Diagram that has been generated at certain time intervals on a time axis in the same way as is used for quality control charts. A correlation with the now seldom used control chart type Original Data Chart (or Extreme Data Chart, ref. for example [5, 7]), would not constitute a novelty in case of a one-piece product as defined above, because the readings were to be interpreted a priori as random samples. However, what would be new is the combination in particular of the type Factory Diagnosis Diagram ↔ x*,* s-chart for multi-part products, because in this manner the advantages of process control monitoring would be expanded by the remarkable information content of this efficient "quality tool" using a quality control chart.

3 Summary

The rank diagram type designated as Factory Diagnosis Diagram (FDD®) is understood as a succession of groups of measurement data or characteristic data, respectively, specified beforehand with regard to their contents, fundamentally presented in a linearized manner in ascending order in an x/y coordinate system.

From the deliberations in this paper, it becomes apparent that the use of this special rank diagram offers itself essentially always as a diagnosis tool when practical solutions for quality management associated with manufacturing are considered. The term *multi-part* is to be interpreted expressly in the figurative sense such that at a “whole” (i.e., single part) product, a certain quality feature must be monitored simultaneously at several locations (fictitious: Parts) based on the specified manufacturing processes. For example, the bearing seats of a shaft that is supported at several places can be understood in the context of the Factory Diagnosis Diagram but also as individual parts, like the teeth or even defined tooth zones (e.g., the flanks) of a toothed wheel, or certain areas of furnace batches in the field of technical heat treatment, or certain contact locations of a specific electronic component. In many cases, the multi-part configuration is essentially apparent through the interaction between the means of production and the required product quality, as has been demonstrated on the practical example auto body in Section 2.2.

With suitable computer support of the measurement process, Factory Diagnosis Diagrams can be displayed on the screen essentially instantaneously with a click of the mouse as visualized test documentation. In all cases, the production and quality diagnosis derived from such diagrams is rather overall negative (ref. Fig. 12) if

- The slope of the rank line is relatively steep and/or
- The rank points can be divided into groups and/or
- Tolerance violations occur or are beginning to show and/or
- The shown scatter bars are relatively great and/or
- The shown scatter bars are very irregular.

In all cases, the production and quality diagnosis derived from such diagrams is rather positive overall (ref. Fig. 13) if

+ The slope of the rank line is gentle

+ The rank points can be interpreted as *one* group,

+ No tolerance violations occur or are beginning to show,

+ The shown scatter bars are relatively small, and uniform.

In most cases, a practioner familiar with his manufacturing devices and quality features will quickly gain valuable insights simply based on a subjective evaluation of such Factory Diagnosis Diagrams that can help achieve significant and often sufficient progress in quality management. Through (optional) use of additional (statistical) evaluation routines it may, in some cases, be possible to gain additional significant insights. Such evaluation routines are already available as – user-friendly – software programs.

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