Implementation details of quality evaluation system for manufacturing enterprises of large piston compressors

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Abstract. In a former paper by the authors (Guangfan Gao et al., 2017), an evaluation system for Chinese manufacturing enterprises of large piston compressors was established for the proper evaluation of production quality. In addition to the first three levels, the fourth level indices are needed, and therefore introduced in this paper. There are 35 and 47 items for the two branches of "Man" and "Soft power" respectively. In addition to the four levels, potential faults and accidents are also an integral part of compressor quality. Piston rod, for example, has its complexity of fault factors illustrated. We put forward two ways for malfunction factors to participate in evaluation. One is weight allocation of each element in all levels based on the multi-factor malfunction correlation matrix. The other is a general first-level correction of malfunctions based on product accident statistics.

1. Introduction
Among the many types of compressors, such as centrifugal compressors, axial compressors, screw compressors, the piston compressor has the highest discharge pressure and can realize large discharge capacity [1]. Thus, the piston compressor is a leading type among all compressors. Large-scale piston compressors are generally considered to have the discharge capacity greater than 30 m\(^3\)/min, the shaft power greater than 250 kW, or the piston force greater than 80 kN. The large piston compressor is key equipment widely used in petrochemical processing, chemical and oil refining, and has great energy consumption.

The development of energy industry has led to the improvement of compressor research, design and manufacture levels in China [2]. Piston compressors are required in the processes of hydrofining, hydrogen production of coal gas, coal-made olefin, LNG and other processes. Some examples are 4M150 (8100kW) hydrogenation compressor, 6M100 coke oven gas compressor, 6M80 combined gas compressor, 2D100 circulating gas compressor, 6K-375MG natural gas labyrinth compressor, RTY3360 high speed shale gas compressor. Cases of major accidents often occur in the early stages of operation of compressors due to design reasons [3].
Establishment of a quality evaluation system for the manufacturing enterprises of large piston compressors is important for the proper evaluation of production quality, government decision-making and user selection. In [4], the authors introduced the quality evaluation system for manufacturing enterprises of large piston compressors. The evaluation system was constructed using the hierarchical analytic process. Weighted calculations at the top three levels were combined to obtain a comprehensive score. The design of software architecture of evaluation system was also introduced. Based on the previously described three levels, this paper introduces the needed fourth level indices with weight consideration based on fault factors.

2. Evaluation system and the required fourth level indices
The top three levels of indices in the quality evaluation system are shown in Table 1. There are two first level indices, "External effect" and "Intrinsic effect". "Malfunction correction" is a modified index for fault and accident factors (a total of 20 items). There are 13 second level indices, including 6 external effects and 7 intrinsic effects. There are 81 third level indices, including 31 external elements and 50 intrinsic elements. Only two branches, "Man" and "Soft power", have fourth level indices, there are 35 and 47 items respectively, as shown in Figure 1.

| 1st level indices | 2nd level indices | 3rd level indices |
|-------------------|-------------------|-------------------|
| External effect   | Man               | Responsibility; Technical ability; Skill; Physical & psychological; Steady state |
|                   | Machine           | Production capacity; Precision accuracy; Tooling precision; Maintenance; Steady state |
|                   | Method            | Processing technology; Operating instruction; Tooling selection; Steady state |
|                   | Environment       | Regulation; Policy; Temperature; Humidity; Lighting; Noise; Sanitation; Air; Steady state |
|                   | Measurement       | Measurement standard; Measurement method; Measuring equipment; Steady state |
|                   | Soft power        | Quality control; Performance; Technology R&D; Computer application |
| Intrinsic effect  | Capability        | Discharge capacity; Discharge temperature; Pressure; Power; Life span; Load; Noise; Critical speeds; Maintenance performance; Field performance |
|                   | Structure         | Cylinders; Cylinder accessories; Valves and unloaders; Piston group; Crankcases, crankshafts, connecting rods, bearings, crossheads; Distance pieces; Stuffing box, packing; Lubrication |
|                   | Material          | Material selection; Material standard; Casting; Weldment; Heat treatment; Forging; Repair |
|                   | Accessory         | Drivers; Shaft couplings, guards; Mounting plates; Controls and instrumentation; Pipeline, appurtenances; Coolers, separators; Pulsation and vibration control; Gas intake filters; Special tools; Outsourced parts |
|                   | Test              | Material inspection; Mechanical inspection; Hydrostatic and gas leakage tests; Mechanical running test; Other tests |
|                   | Data              | Drawings; Technical data; Installation manual; Recommended spares; Operating & maintenance |
The scores of the fourth level indices in the branch of "Technical ability" (stem from "Man" and "External effect"), represented as $S_{a121}$ to $S_{a123}$, were calculated by membership grade and the ascending semi trapezoidal distribution function model. The scores of the fourth level indices in the branch of "Performance", "Technology R&D", and "Computer application" (stem from "Soft power" and "External effect"), were calculated like the branch of "Technical ability". The scores for other than the above fourth level indices were calculated by questionnaires. The persons who filled the questionnaires include compressor manufacturing supervisors and professional and technical personnel.

The personnel of compressor manufacturing enterprises are divided into three categories and eight kinds, as shown in Table 2, which covers related production workers, technical developers and managers.
3. Influence of malfunction on manufacturing quality

The piston compressor has reciprocating moving parts (piston, piston ring, connecting rod, crosshead, etc.), rotating moving parts (crankshaft, balance weight, etc.), a plane moving part (connecting rod), and so on. Important pressure bearing parts are cylinders, cylinder heads, etc. Vulnerable parts include gas valves, piston ring, bearing bush, packing, etc. Additionally there are accessories for lubrication, cooling and driving.

An important performance measure for manufacturing quality of piston compressor is the failure caused by various defects. Failures in each specific structure are often related to multiple factors, which makes it difficult to disentangle contributing factors and their corresponding weights.

Table 2. The classification of enterprise technicians.

| Three categories | Eight kinds | Specific work |
|------------------|-------------|---------------|
| Production workers | Machining operators | Turning, milling, planing, grinding, boring, drilling, riveting, welding, benching, |

Figure 1. The fourth level indices and malfunction correction indices in quality evaluation system.
Taking piston rod as an example: its fracture can result from seven causes, material, design, manufacture, process, operation, maintenance, and others (Figure 2). In the first case, many surface cracks were found in piston rod 42CrMoE of a compressor after half a year of use. The reason was improper heat treatment in the manufacturing process [5]. In the second case, the piston rod of a 4M40 compressor was fractured after four months of operation when the material strength and hardness could not meet the relevant standards and technical requirements [6]. In the third case, the second stage piston rod of a piston air compressor DW-160/4.5 broke many times. One reason was that the radius of the corner was too small, thus resulting in serious stress concentration on the structure [7]. In the fourth case, after replacing some of the components in 2nd cylinder and working for a year, the piston rod of continuous reforming compressor fractured from the root of the piston locking nut owing to overload [8]. In the fifth case, the main reason of piston rod fracture in compressor unit RTY1030MH10.5×7.25 was thought to be improper pretightening force in manufacturing [9]. In the last case, long cracks were observed along the longitudinal direction on the surface of the commercial 17-4 PH stainless steel piston rod after heat treatment. Energy dispersive X-ray analysis (EDXA) revealed that the segregation of Cu and Ni should be responsible [10].

From these accident analysis reports and the summary in Figure 2, it clear that the quality of piston rod is affected by many factors. The same is true for other parts, such as connecting rods, pistons, crankshafts, etc. Reasonable manufacturing quality evaluation needs to be based on multi-factor correlation analysis and attention to the influence of malfunction.

4. Application of malfunction in evaluation

The quality evaluation of large piston compressor manufacturing enterprises is not the evaluation of a certain type of piston compressor, but the overall evaluation of the manufacturing quality of related enterprises. All influencing factors related to external effects and intrinsic effects should be considered, as listed in Table 1. This paper innovatively emphasizes the influence of fault factors on manufacturing quality and its proper introduction.

4.1. Weight allocation of each element

The distribution of all element weights at all levels needs to be modified by introducing fault factors on the basis of considering the proportion of performance and technical importance. Firstly, the degree of correlation between the malfunction and each element is established. Moreover, a multi-factor correlation matrix is formed to determine the strong and weak correlation of elements (example as Figure 3). Second, the degree of harm by malfunction of the element to the overall performance of the compressor is considered. For example, the damage of crankshaft fracture and piston rod fracture is
greater than that of gas valve fracture. Third, it is necessary to consider the frequency of each malfunction.

**Figure 2. The fault tree of the piston rod fracture.**

- N1-Inadequate discharge capacity
- N2-Pressure anomaly
- N3-Temperature anomaly
- N4-Vibration anomaly
- N5-Sound anomaly
- N6-Mechanical overheating
- N7-Gas leakage
- N8-Coke combustion
- N9-Liquid impact
- N10-Piston rod fracture
- N11-Cylinder cracking
- N12-Cylinder head cracking
- N13-Crankshaft breakdown
- N14-Fracture of connecting rod
- N15-Connecting rod bolt fracture
- N16-Piston stuck and cracking
- N17-Body fracture
- N18-Valve rupture
- N19-Burning of bearing liner

**Figure 3. Two cases of correlation degree between elements and malfunctions.**

4.2. General first-level correction of malfunctions

Fault and accident factors are corrected at the overall level. It is a minus item, which means the best result is 0 point. In the overall evaluation system, external effects and intrinsic effects compose the basic evaluation. On top of that, the malfunction correction amends and personalizes the evaluation.

There are 20 kinds of malfunctions (See Table 1 and Figure 1), which are based on the product accident statistics of large compressor enterprises in the past 6 years. The frequency of malfunctions is divided into "Frequent occurrence", "More occurrence", "Average occurrence", "Occasional occurrence", and "No occurrence". According to the frequency of malfunctions, the system calculates the deduction score of each item and combines with item weight to calculate the total deduction points.
5. Summary
To evaluate the manufacturing quality of compressor enterprises more reasonably, basing upon the top three levels, we present the needed fourth level indices under two branches of "Man" and "Soft power" respectively.

There is no doubt that the potential failure of the main parts directly affects the quality of compressor products. Moreover, the relationships between malfunction factors and the elements at all levels are very complicated. Therefore we introduced two methods for malfunction factors to contribute to evaluation. One is weight allocation of each element in all levels based on the multi-factor malfunction correlation matrix. The other is a general first-level correction of malfunctions based on product accident statistics.

Importantly, false data must be eliminated in the introduction of fault and accident factors evaluation. Rational prediction, verification, continuous correction and improvement of evaluation also cannot be overemphasized.

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