ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)

https://doi.org/10.17559/TV-20190404054849

Subject review

Study on Preventive Maintenance Strategies of Filling Equipment Based on Reliability-Cantered Maintenance

Pengfei ZENG*, Weiping SHAO, Yongping HAO

Abstract: In order to ensure normal operation of enterprise production activities and enhance the competitiveness of enterprise, equipment management and maintenance strategy formulation has always been one of important contents of daily management of enterprise. According to the actual requirement of a Chinese beer production enterprise, preventive maintenance strategy of filling equipment is put forward based on reliability-centred maintenance (RCM). Firstly, on the basis of analyzing RCM theory and equipment maintenance, the general process of failure analysis of beer production equipment is presented. Secondly, the general production process of bottled beer is analyzed, and the composition of major filling equipment is also introduced in the beer production line. With the help of key indicators of equipment reliability, such as mean time between failure (*MTBF*), mean time to repair restoration (*MTTR*) and availability *Ai*, the fault analysis of filling production line is carried out, and the relevant results are calculated. Then, process failure mode and effect analysis (PFMEA) of filling machine is implemented, and fault tree analysis (FTA) of potential failure modes with high risk priority numbers is also completed. Finally, preventive and maintenance strategies of filling equipment are established on the basis of RCM. Through the research in this paper, maintenance costs and unplanned breakdown hours can be significantly reduced.

Keywords: Beer filling equipment; Fault Tree Analysis (FTA); Preventive maintenance strategy; Process Failure Modes and Effects Analysis (PFMEA); Reliability-centred maintenance (RCM)

1 INTRODUCTION

With the continuous extension of enterprise production and the rapid development of industry technology, production equipments have become increasingly larger-scale, automatied and complicatied [1]. In order to keep up inherent reliability and stability of equipments in the design, equipment management and maintenance become one of important things of enterprise production activities [2, 3]. As the market competition is becoming fiercer, Chinese beer production enterprises have to consider some impacts of beer production equipment and its faults on production capacity, costs and product quality in order to improve product competitiveness. If fault prediction can be carried out to related equipment in the beer filling production line, corresponding preventive measures will be adopted before fault occurrences. Thus, the impact of enterprise production fault will be minimized to the lowest level. This will greatly improve opening rate of filling production line.

At present, most Chinese beer production enterprises still adopt traditional breakdown maintenance of fire-fighting mode. This strategy largely affects production rate, product quality and costs. Under this circumstance, the requirement and importance of preventive maintenance and predictive maintenance of production equipments are also increasingly prominent. Predictive maintenance is also called state maintenance, and it predicts impending fault of equipment by monitoring operation state. This method is very precise and timely, but its costs are high and implemention technology is complex so that it is unable to be applied in beer production for small and medium enterprises. Fortunately, enterprises are already aware of the significance of preventive maintenance to equipments and the promotion to enterprise production.

This paper takes filling production line of bottled beer as the research object from a certain Chinese beer production enterprise. The RCM theory and method are used to study reliability and fault analysis of filling equipments and to build related strategy about preventive maintenance, in order to reduce production line downtimes. This will be of certain help and will provide a guidance function in maintaining and repairing filling production line of bottled beer.

2 LITERATURE REVIEW

Maintenance is an important way to increase system dependability: timely inspections, repairs and renewals can significantly increase a system's reliability, availability and life time. At the same time, maintenance incurs costs and planned down time. Thus, better maintenance planning has to balance between these factors. Reference [4] studied the effect of different maintenance strategies on the electrically insulated railway joint, a critical asset in railroad tracks for train detection, and a relatively frequent cause of train disruptions. A fault maintenance tree modelled complex maintenance concepts to analyse the system reliability, number of failures, and costs, so as to predict the expected number of failures at system level. Reference [5] focused on the application of reliability centred maintenance with the aim to improve the reliability of a cone crusher. RCM technology involves failure modes and effects analysis and total time to test-Plot to assess the reliability of a cone crusher in a processing plant. Reference [6] proposed a risk-assessment methodology for preventive maintenance planning evaluation based on a reliability model for marine engine systems. The FMEA approach was chosen as a risk assessment methodology to synthesize the potential failure modes in order to identify early response and smoothly promote the preventive maintenance planning. Yan et al. addressed a reliability modelling method for preliminary hazard analysis of automated guided vehicles' critical components by the Failure Modes Effects and Criticality Analysis. FTA is adopted to model the causes of phase failure, enabling the probability of success in each phase and hence mission success to be determined [7]. Reference [8] had developed a method for predicting customer reliability of a distribution power system using the fault tree approach with customer weighted values of component failure frequencies and downtimes. The method directly incorporates customer disturbance information in component failure frequency and downtime calculations through weighting these parameters with information of customer interruption. It also significantly improves the prediction of customer reliability indices with fault tree and two-state Markov chain formulations. Gupta et al. [9] introduced fuzzy logic and failure mode and effect analysis to select the appropriate maintenance strategies for each failure mode of functionally significant item of conventional milling machine. On the basis of RCM with fuzzy logic integrating with fuzzy linguistic scale method, the criticality analysis of conventional milling machine was described. A critical step in FMEA is identifying potential failure modes for product sub-systems, components, and processes, for which component-failure mode knowledge is necessarily needed as an important source of knowledge. Reference [10] proposes a method to construct the component-failure mode matrix automatically by mining unstructured and short quality problem texts and mapping as well as representing them as component-failure knowledge. Reference [11] proposed a data-driven approach and a system design based on the approach for decision-making on equipment maintenance. The RCM process was improved to become data-driven to support the data requirements for the data-driven RCM process; a system framework for the proposed approach was established, and a prototype system was built and verified with end users.

3 RCM THEORY AND FAULT ANALYSIS PROCESS

3.1 RCM Theory

RCM is the reliability oriented maintenance management. Its purpose is to reduce maintenance costs under the premise of improving availability rate of equipment. The RCM theory is used in the aviation industry for aircraft maintenance initially. It has been widely applied in the field of equipment maintenance, at present [12]. Though the RCM itself is not maintenance technology and tool, it can use three kinds of information of criticality and fault mode of equipment parts, as well as most suitable maintenance scheme to guide maintenance process. It is currently used in a number of asset-intensive enterprises, such as Oil and Gas Industry, Nuclear Industry, Railway Industry, Petrochemical Industry, Power Industry, etc [13-15]. The maintenance plan is determined based on the results of reliability assessment and the need to maintain equipment functioning. This better avoids over-maintenance or under-maintenance problems. Not only maintenance costs are controlled, but also availability and reliability of equipment are both improved.

The RCM is built on the foundation of design characteristics, operation functions, and fault modes and results analysis of equipment, aiming at maximizing the operational reliability of equipment. The RCM applies available safety and reliability data to determine which subsystems and parts are in critical condition, which need to be repaired, improved and redesigned, and to determine the necessity and feasibility of maintenance, so as to evaluate the requirement of maintenance and to finally make practical and reasonable maintenance plan. The biggest difference between RCM and other maintenance ideas is based on determining maintenance mode of equipment by taking reliability and fault effect as safety, environmental failure and hidden failure, and by using economy and utilization rate as usability and non-usability consequence [16].

3.2 Fault Analysis Process of Beer Production Equipment

The requirements of beer production enterprises reduce downtime rate of corresponding equipment of filling production line are consistent with the goal of RCM theory. Thus, it is feasible to apply the relevant RCM theory to the practice of fault analysis of beer filling equipment. According to its related specifications, the standard analysis process of RCM is to get the distribution of downtime rate of equipment failure on the basis of failure fault report, and to indentify key equipment by operation data of equipment, and to compute reliability and maintainability index by function structure deployment of equipment, and to confirm the key equipment that need to be studied. Then the fault tree analysis is used to analysis the preventive maintenance plan of key equipment. Finally, the corresponding maintenance plan is continuously improved. The general workflow of fault analysis of filling production equipment based on RCM is shown in Fig.1.

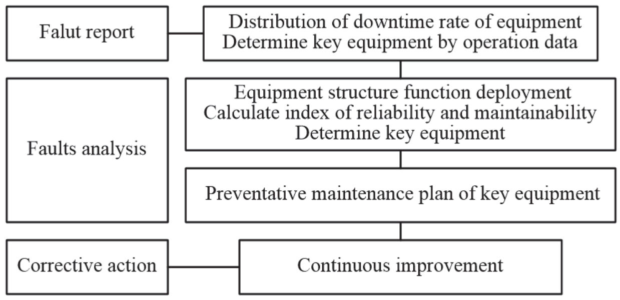

Figure 1 Fault analysis process of filling equipment based on RCM

4 RELIABILITY INDICATOR OF EQUIPMENT

Reliability is the ability of system, mechanical equipment or its parts to keep and perform required functions under specified work conditions and specified period of time [17]. In other words, it is the capacity of system or device to resist failure. Because reliability cannot be measured with an instrument, the measurement of reliability must be studied, tested and analyzed to make the correct estimation and evaluation. The main indicators of equipment feasibility are as follows:

(1) Mean Time Between Failure (*MTBF*):

MTBF is the average life parameter of maintainable system. A repairable equipment has N breakdown times during operation. It can continue to work as new after each failure repair. The measured working hours between each failure is t_1, t_2, and t_3, ..., et al., respectively. So its *MTBF* is expressed by:

$$MTBF = \frac{1}{N}\sum_{i=1}^{N} t_i = \frac{T}{N} \tag{1}$$

where T represents the total working time of equipment.

(2) Mean Time To Repair Restoration (*MTTR*):

MTTR is a parameter determined by the probability density of repair. Under prescribed time and conditions, equipment is at any specified maintenance level, *MTTR* is equal to the ratio of total hours of repairing maintenance to the total number of failures of repaired equipment in this maintenance level. *MTTR* describes the long-term statistical mean value of required hours that change equipment from a failure state to a normal state. In short, it equals the mean value of actual direct maintenance hours to eliminate failure, except delay hours of maintenance support, for example waiting spare parts.

$$MTTR = \sum_{i=1}^{N} \frac{t_i}{n} \tag{2}$$

where t_i represents the *i* th repaired hours, *n* is the repaired number of times.

(3) Availability:

Availability is a generalized reliability indicator that considers the reliability and maintenance of repairable equipment. Availability is defined as probability of a repairable equipment to have or maintain its specified functions at a normal state under specified conditions to use, under specified maintenance conditions to maintain, at a stated instant of time. Obviously, availability is a function between working hours *t* and maintenance hours τ, denoted as $A(t, \tau)$. Because of time difference, the characteristics of availability are also different. There are many different definitions and computational formulas about availability [18]. In engineering field, work availability is more applied by expressing with parameter *Ai* It is equal to the ratio of mean working hours to the sum of mean working hours and breakdown hours. It can be expressed as the ratio of *MTBF* of equipment to *MTBF* and *MTTR*. The work availability model is expressed by:

$$Ai = \frac{MTBF}{MTBF + MTTR} \tag{3}$$

where *Ai* represents the availability of *i*th equipment participates assessment, *MTBF* is a parameter from *i*th equipment participates assessment, *MTTR* is also a parameter from *i*th equipment participates assessment.

5 FILLING PRODUCTION LINE AND ITS FAULT ANALYSIS

5.1 Beer Filling Production Process

Beer filling process is of greatest importance to a beer production enterprise. The production of a kind of high quality beer must have perfect filling production line and related equipments in addition to good raw materials and advanced brewing technology. Their better running state will be able to reduce enterprise costs and to decrease consumption. Generally, there are three modes to filled beer. They are glass bottled beer, beverage can beer and barrel beer respectively. At present, most Chinese beer enterprises adopt glass bottled production to filled beer. Equipment configuration and type of beer production enterprises are different because of different production conditions of each enterprise. In general, however, beer production line includes Depalletizing Machine (DM), Unpacking Machine (UM), Bottle Washing Machine (BWM), Bottle Inspection Machine (BIM), Beer Filling Machine (BFM), Sterilization Machine (SM), Labeling Machine (LM), Packing Machine (PM1) and Palletizing Machine (PM2), as well as cap conveyer system, bottle conveyer system, pallet conveyer system and box conveyer system et al.

The technical process flow of packing production of bottled beer includes the depalletizing machine unloads of layered empty beer bottles from the plastic tray and pushing them to the plastic chain plate. These empty beer bottles are sent to the immersion bottle tank and are washed by the bottle washing machine. The bottle inspection machine checks these washed empty beer bottles. If these empty beer bottles pass the check, they will be sent to the filling production line. At the same time beer is filled and cap is pressed through the beer filling machine. These beer bottles filled, upon pass inspection, will be sent to the sterilization machine for sterilizing. These bottled beers are packed into warehouse after they are sent to the labeling machine and are labeled. The integrity work process of packing production of bottled beer is shown in Fig. 2.

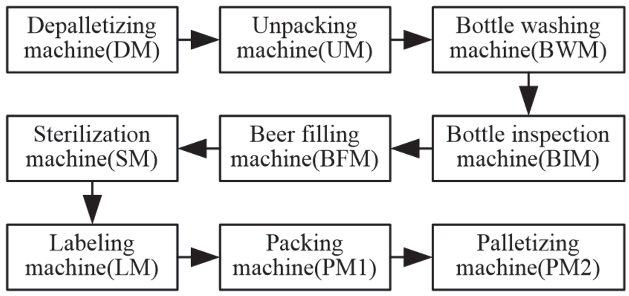

Figure 2 Production process of bottled beer

5.2 Product Structure of the Filling Machine

The filling machine is composed of two parts, a bottling machine and a capping machine. Component parts and function units of the bottling machine include machine housing, drive device, lifting unit, bottling system, assistive device, beer jar and electrical control device. Component parts and function units of the capping machine include machine housing, lifting unit, capping system and assistive device. The composition of beer filling machine is shown in Fig. 3.

The composition of the bottling machine and its main functions are as follows:

1) Centering cover: It with a guide frame has a positioning function to localize bottle mouth and to strengthen leak proofness. It plays a role in the transition of nature, thereby undertaking smoothly.

2) Idler wheel: It has a guiding role, and it can enable the guide frame to rise and fall according to specified requirements.

3) Gas-returning pipe: When beer arrives to the bottom of gas returning pipe, the beer valve is closed and filling work is stopped.

4) Control valve unit: It is composed of three valves, the 9 th valve, the 10 th valve and the 12 th valve. Fast filling process is completed when the 10 th and 12 th valves are opened. Pressure of filling beer is released when the 10 th valve is closed and the 9 th valve is open.

5) Pressure gage of CO_2: It shows the CO_2 pressure of beer jar.
6) Pressure gage of compressed air: It shows the pressure of compressed air.
7) Pipe distributor: It lies in the center position of the bottling machine. It is center connection part of all working pipes, including beer liquid, CO_2, pressure relief and vacuuming pipe.
8) Lifting gas cylinder: It contains bottle pad above it. It pushes bottle to make bottle mouth contact with the filling valve body with the help of the guide frame.

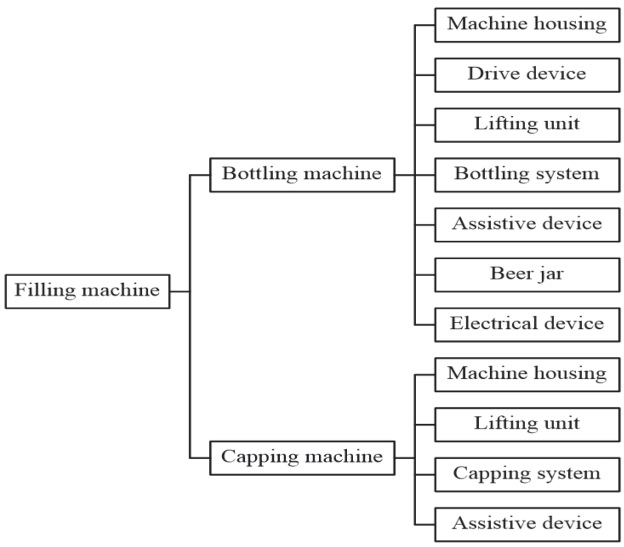

Figure 3 Structure of beer filling machine

The composition of the capping machine and its main functions is as follows:
1) Cap container: It caches beer bottle caps.
2) Cap turner: Disoriented caps are turned to the same required direction by it.
3) Cap slider: The bottle cap slides and enters the inlet of cap die from it.
4) Plunger chip: It is the key part of capping machine, and is responsible for pressing bottle cap on beer bottle mouth according to capping process requirement.
5) Cap die: A bottle cap enters the internal opening of cap die, and is pressed on the top of corresponding bottle.
6) Guider ring: It plays a role of orientation and location, centers bottle neck and bottle cap.

5.3 Fault Analysis of Filling Production Line

The relevant data of major equipments fault breakdown records and equipment maintenance records for 12 consecutive months are investigated and surveyed, at beginning of production from a filling production line of the beer enterprise. On the basis of these data, statistical indicators of different types of major equipments are organized and stored in the filling production line, such as breakdown hours, breakdown frequency, production hours and fault rate, et al., as shown in Tab. 1. and Tab. 2. respectively. Using computing Eq. (1), Eq. (2) and Eq. (3) related to reliability of equipment in Section 2, according to the data in the two tables above, the corresponding results of *MTBF*, *MTTR* and *Ai* can be calculated, as shown in Tab. 3.

Table 1 Downtime of major equipment of production line (min)

Equip. / Month	BFM	BIM	SM	BWM	LM	UM	PM1	DM	PM2	Total	Production hours	Fault rate
1	335	40	0	55	35	30	25	40	0	560	18720	2.99%
2	275	15	0	65	30	45	0	85	0	515	20160	2.55%
3	255	55	20	0	85	0	0	0	90	505	17280	2.92%
4	210	75	45	85	0	60	40	0	65	580	20040	2.89%
5	195	65	50	40	0	15	20	0	0	385	19680	1.96%
6	165	40	85	0	70	0	0	65	0	425	19200	2.21%
7	180	35	60	50	45	0	45	0	25	440	17460	2.52%
8	200	50	90	35	20	0	0	0	0	395	16440	2.40%
9	160	50	40	80	45	50	40	10	30	505	18960	2.66%
10	175	25	25	55	60	35	20	25	0	420	19440	2.16%
11	205	0	55	65	35	30	0	0	10	400	18720	2.14%
12	185	35	30	30	25	0	35	15	0	355	18840	1.88%
Total	2540	485	500	560	450	265	225	240	220	5485	224940	2.44%

Table 2 Number of breakdowns of major equipment from filling production line

Equip. / Month	BFM	BIM	SM	BWM	LM	UM	PM1	DM	PM2	Total
1	10	2	0	3	2	1	1	2	0	21
2	6	1	0	2	1	1	0	3	0	14
3	7	2	1	0	4	0	0	0	3	17
4	6	3	3	4	0	1	2	0	2	21
5	5	2	2	2	0	1	2	0	0	14
6	4	1	4	0	2	0	0	2	0	13
7	5	1	3	1	1	0	1	0	1	13
8	5	3	2	2	1	0	0	0	0	13
9	3	3	2	2	2	1	1	1	1	16
10	3	1	1	2	1	1	2	1	0	12
11	3	0	4	3	2	1	0	0	1	14
12	4	2	2	1	1	0	2	1	0	13
Total	61	21	24	22	17	7	11	10	8	181

Tab. 3 shows that *MTBF* is equal to 1212.46 min, and mean monthly failure frequency is 15.08, in the beer filling production line. Among them, the largest proportion is of the beer filling machine, its *MTBF* is 3597.62 min, and mean monthly failure frequency is 5.08. The beer filling machine occupies the most part of the reason of production line downtime whether its breakdown hours or breakdown frequency. Therefore, the beer filling machine is selected as research object to analyze its PFEMA and FTA in detail. This lays the foundation for formulation of preventive maintenance strategies related to the beer filling production line on the basis of RCM.

Table 3 Calculating results of *MTBF*, *MTTR* and *Ai*

Month	*MTBF*	*MTTR*	*Ai*
1	864.76	26.67	0.970
2	1403.21	36.79	0.974
3	986.76	29.71	0.971
4	926.67	27.62	0.971
5	1378.21	27.50	0.980
6	1444.23	32.69	0.978
7	1309.23	33.85	0.975
8	1234.23	30.38	0.976
9	1153.44	31.56	0.973
10	1585.00	35.00	0.978
11	1308.57	28.57	0.979
12	1421.92	27.31	0.981

6 PFMEA OF THE FILLING MACHINE

FMEA is a method of reliability analysis intended to identify failures affecting the functioning of a system and enable priorities for action to be set. FMEA is a qualitative analysis technique for advance prevention. From the beginning of design stage, FMEA analyzes and predicts potential failures of design and process, studies results and effects of failure, and takes necessary preventive measures, so as to reduce or avoid these potential failures, and improve the reliability of product and process. According to FMEA, the analysis related to design phase is a design failure mode and effect analysis (DFMEA) and FMEA related to process is PFMEA The main objective of PFMEA is to identify potential failures, evaluate causes and effects of these failures, and to propose solutions to prevent these potential failures [19, 20].

PFMEA with an emphasis on preventing failure improves the process as one of its primary objectives. So that the failures at high risk are determined according to the opinions of team members and an executable program is presented in order to prevent them [21]. Through the investigation and study of the beer filling production line of this enterprise, there are eight main potential failure modes of filling machine in the production process of bottling and capping, including input bottle dislocation, output bottle dislocation, beer overflow, irregular liquid level, oxygen increase in the bottling process, capping fault, broken bottle or bottle mouth damaged in the capping process, and bubbling after pressure reliefs. Through further investigation related to failure results, potential failure causes and current prevention and detection methods, combing with three kinds of scoring standards of PFMEA, according to the enterprise actual situation and relevant departments focused discussion, the PFMEA of filling machine is summarized, as shown in Tab. 4. The specified analysis process of PFMEA is not discussed due to limited space, the failure causes of maximum value are only discussed in this paper.

Table 4 PFMEA of beer filling machine

Process Step / Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Process Controls Prevention	Current Process Controls Detection	Detection	Risk Priority Number
Beer bottling and capping	Input bottle dislocation	Bottle can not enter the bottle pad accurately	6	Input bottle device fault	2	Maintain according to maintenance plan	Notify field maintenance personnel	5	60
	Output bottle dislocation	Bottle can not leave the bottle pad	6	Output bottle device fault	2	Maintain according to maintenance plan	Notify field maintenance personnel	5	60
	Beer overflow	Unable to seal	7	High beer temperature	3	Control temperature	Check beer temperature every 3 hours	4	84
	Irregular liquid level	Quality unqualified	8	Bottling machine fault	4	Maintain according to maintenance plan	Notify field maintenance personnel	3	124
	Oxygen increase	Shelf life shorten	7		2			2	
	Capping fault	Packing cannot be completed	9	Capping machine fault	3	Maintain according to maintenance plan	Gap check each production shift	2	124
	Broken bottle or bottle mouth damaged	Cannot meet packing requirement	9		3			2	
		Waste packing material							
	Bubbling	Packing cannot be completed	7	Bottle mouth damage	3	Weed out unqualified bottles	Examine each bottle	4	84

7 FTA OF THE FILLING MACHINE

The FTA is a kind of graphical deduction method to analyze fault, and is a kind of logical reasoning method related to fault events under specified conditions. In the FTA, various fault stats or abnormal conditions are called fault events for a studied system [22]. Various good stats or normal conditions are referred to as success events. The events studied by the FTA are known as top events, which are events that system does not want to happen or result events that are concerned in the FTA, which are located at the top of fault tree. Events that cause only other events in the FTA are known as bottom events, may be basic cause of event, and are located at the bottom of fault tree. FTA allows us to trace back the root cause of a system or mission failure by using a systematic top-down approach. FTA provides a straightforward and clear presentation of the logic between various undesired events and is regarded as an effective, systematic, accurate and predictive method to deal with the safety and reliability problems in complex systems.

FTA aims at the top event to search all possible causes through layer by layer down. Immediate cause is searched in each layer, so as to find out some logical relationships between hardware and software factors (bottom events) such as component failure, environment impact, and human factors and program processing and system faults (top events) in the system, and to describe causality relationship between various events by different symbols, thus forming an inverted tree shape. The tree graphic is called fault tree. When the fault tree has been constructed, combination mode and propagation path of impact of each bottom event on the top event will be qualitatively analyzed to identify possible system fault modes. For specific symbolic graphics and their significance in the method of FTA, please refer to some definitions in these references [7, 17]. Combing these analysis results of PFMEA, four kinds of intermediate top events which are most likely to fail are mainly analyzed in this paper.

7.1 Irregular Liquid Level during Bottling Beer

Irregular liquid level is mainly fault of bottling machine in the filling process. The fault tree of immediate top event of irregular liquid level is charted according to collected data, as shown in Fig. 4. The failure of rubber seal ring, the leakage of vacuum valve or relief valve, the gas-returning pipe too-short or curved, and the improper adjustment of gas valve are these direct bottom events of irregular liquid level during bottling beer.

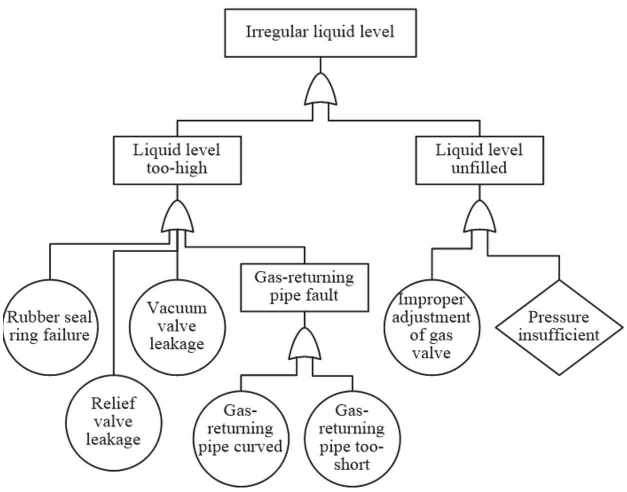

Figure 4 FTA of irregular liquid level

Failure of rubber seal ring: The friction between the sealing surfaces will generate heat, the temperature of sealing surface increase. The rubber ring has the risk of vulcanization, and eventually loses its elasticity and fails.

Leakage of vacuum valve or relief valve: Dirty impurities fall on the seal ring in the filling process, and pad the seal ring, there is a gap between core valve and core seat and that causes leakage.

Gas-returning pipe too-short or curved: The filling of beer can be affected when the gas-returning pipe curved or umbrella-shaped anti-bow ring is damaged above gas-returning pipe.

Improper adjustment of gas valve: Gas valve is easy to disable when dirty impurities were sandwiched between the sealing surfaces.

7.2 Broken Bottle or Bottle Mouth Damage during Capping

Broken bottle or bottle mouth damaged during capping is one of the main faults of capping machine in the filling process. The fault tree of immediate top event of bottle broken or bottle mouth damaged during capping is charted according to collected data, as shown in Fig. 5. Guided bottle component wear, unregulated travel height of capping machine, incorrect arrangement of each other among transmission gear, intermediate gear and capping reel wheel are main bottom events caused broken bottle.

Guided bottle component wear: Beer bottle enters into the capping machine through the guided bottle component. If the guided bottle component is to fail, it will cause the capping machine fail to aim at the bottle mouth, the phenomenon of broken bottle will occur.

Unregulated travel height: If the travel height of the capping machine is too high, it will lead to excessive capping force, the phenomenon of broken bottle and bottle mouth damaged will occur.

Incorrect arrangement among different gears and reel wheel: Incorrect arrangement will cause bottle body and the capping machine not on the same line, and result in broken bottle or bottle mouth damaged.

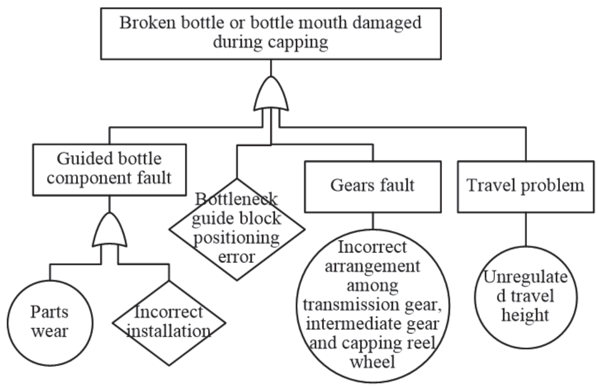

Figure 5 FTA of broken bottle or bottle mouth damaged

7.3 Deformity Cap Caused by the Capping Machine

Deformity cap caused by the capping machine includes straw hat cap, flattening cap, cap off paint in the cap margin or no capping, which are one of the main faults of the capping machine in the filling process. The fault tree of immediate top event of deformity cap during capping is charted according to collected data, as shown in Fig. 6. Bottom events cause deformity cap included in the spring of plunger chip is of insufficient elasticity or the spring fractured, the plunger chip severe wear, the cap die severe wear, the cap container severe wear or loose, the magnet of cap container wear or fall off, the guide plate of star wheel misalign or severe wear, the capping cam severe wear, and the bottle pedestal severe wear, et al. After a long period of use, some vulnerable parts of components of the capping machine fail to different types of deformity cap.

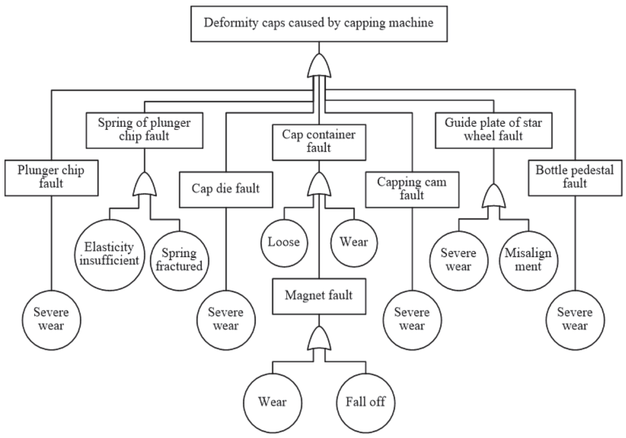

Figure 6 FTA of deformity cap

7.4 Oxygen Increase during Bottling Process

Oxygen increase is one of main faults of the bottling machine. In the bottling process, oxygen increase means carbon dioxide deficiency. Oxygen will accelerate the deterioration of beer and shorten the shelf life of beer. The fault tree of immediate top event of oxygen increase during filling process is charted according to collected data, as shown in Fig. 7. Bottom events of oxygen increase include the vacuum pump and its related components fault, the vacuuming rail wears, the beer valve wears and the vacuum valve stem severe wears, et al.

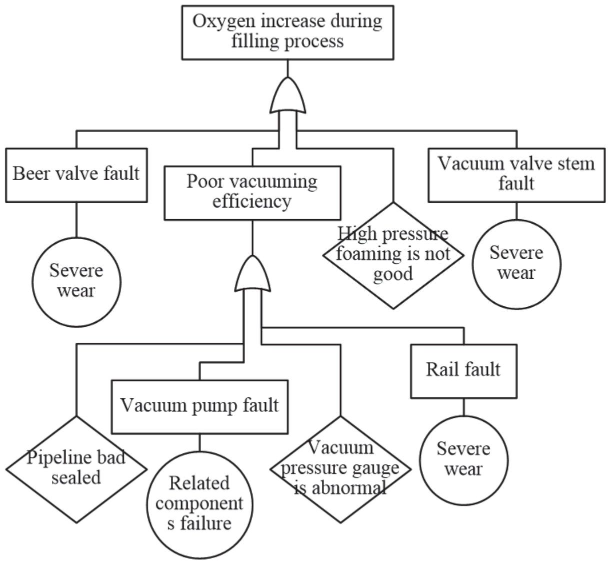

Figure 7 FTA of oxygen increase

Table 5 Maintenance strategies of beer filling equipment

Fault top event	Bottom event describe	Preventive strategy (cycle time)	Maintenance strategy
Irregular liquid level during filling beer	Rubber seal failure	6 months	Replace, safety stock 10
	Vacuum valve or relief valve leakage	week	Clean and adjust
		2 years	Replace, safety stock 5
	Gas-returning pipe too short or curve	week	Adjust
		6 months	Replace, safety stock 2
	Gas valve improper adjust	week	Check and adjust
Broken bottle or bottle mouth damaged	Guided bottle components wear	week	Clean and lubricate
		2 years	Replace, safety stock 2
	incorrect arrangement of each other among transmission gear, intermediate gear and capping reel wheel	3 months	Check and revise
Deformity cap caused by capping machine	Spring of capping plunger chip is insufficient elasticity or fractured	month	Check and lubricate
		6 months	Replace, safety stock 10
	Plunger chip severe wear	month	Check and lubricate
		2 years	Replace, safety stock 2
	Cap die severe wear	month	Check and lubricate
		2 years	Replace, safety stock 2
	Cap container severe wear or loose	3 months	Check, adjust and clean
		2 years	Replace, safety stock 2
	Magnet of cap container wear or fall off	3 months	Check and clean
		year	Replace, safety stock 5
	Guide plate of star wheel misalign or severe wear	3 months	Check and adjust
		2 years	Replace, safety stock 2
	Capping cam severe wear	2 months	Check and lubricate
		3 years	Replace, safety stock 2
	Bottle pedestal severe wear	6 months	Check and clean
		year	Replace, safety stock 2
Oxygen increase during filling process	Vacuum pump fault	month	Check and lubricate
		year	Replace, safety stock 2
	Vacuuming rail wear	month	Check, clean and lubricate
		9 months	Replace, safety stock 10
	Vacuum valve stem severe wear	3 months	Check, clean and lubricate
		2 years	Replace, safety stock 2

The vacuum pump and its related components fault:
(1) Operation abnormal: These reasons may be that component assembly does not meet requirement, the entrance pressure is too high or overloaded, the lubricating oil is lacking, and bearing is worn, et al.
(2) Limit of pressure cannot meet the rated pressure: The cause of this situation may be the leakage of pump, lubricating oil contamination or oil seal damage.
(3) Pumping speed down: It is possible reason that pipeline is too thin.

(4) Motor overload: It is possible that the overload situation may be excessive inlet pressure or the friction between the end face and the end cover of the rotor is too large.
(5) Overheating: The cause may be friction between the rotor and the pump body.
(6) Wear: The main factor leading to the wear of parts is lack of lubricating oil, high temperature, sundries in the rail gap.

8 PREVENTATIVE MAINTENANCE STRATEGIES OF THE FILLING MACHINE BASED ON RCM

Maintenance analysis based on RCM is mainly based on the reliability requirement of equipment to make a decision on maintenance type of equipment, so as to provide the basis for the preventive maintenance of equipment. This is basic work to prepare preventive maintenance program of equipment. This section uses the previously completed PFMEA and FTA of the filling machine to develop preventative maintenance strategies of the filling machine by the RCM theory. For each failure reason of key equipment in the filling production process, analysis and decision-making should be made according to the logic decision diagram of RCM, so as to provide preventive maintenance work and working interval for cause of the failure. On the basis of above countermeasure analysis of various bottom events of fault tree, this paper summarizes preventive maintenance strategies of filling equipment based on RCM, as shown in Tab. 5.

9 CONCLUSION

Strategy problems of preventive maintenance of major and key beer filling equipments are researched on the basis of RCM for a Chinese beer production enterprise. Failure problems of beer filling production line are analyzed, main fault equipments resulting in breakdown factors are found through computing *MTBF*, *MTTR* and *Ai*. Using PFEMA method, statistics and analysis of main potential failure modes related to beer filling equipments are carried out, and corresponding risk priority number (RPN) is computed. With the help of FTA method, main fault modes of the filling machine are analyzed, such as irregular liquid level during beer filling, broken bottle or bottle mouth damaged during capping, deformity cap and oxygen increase, et al. Maintenance strategies of the filling machine are established based on RCM as well. The application of this research approach in equipment management of beer filling production can significantly reduce maintenance and repair costs of production line, and lower hidden failure probability and unplanned downtime. The next step is to develop aided decision management software to construct reliability database of enterprise equipments, and to realize probability of reliability computing and failure risk assessing automatically, and to improve efficiency and accuracy of maintenance strategy analysis of key equipment for beer production enterprise.

Acknowledgement

This research work was partially supported by the National High-Tech. R&D Program of China under Grant No. 2014AA041603 and the Guided Plan Project of Natural Science Foundation of Liaoning Province under Grant No. 20180550932.

10 REFERENCES

[1] Wu, Y., Jia, X. S., Wen, L., Son,g W., & Guo, C. M. (2016). A review of reliability centered maintenance development and application. *Journal of Ordnance Engineering College*, *48*(4), 13-21.
[2] Jiang, X., Duan, F., Tian, H., & Wie, X. (2015). Optimization of reliability centered maintenance scheme for inertial navigation system. *Reliability Engineering and System Safety*, *140*, 208-217. https://doi.org/10.1016/j.ress.2015.04.003
[3] Bartkowiak, T. & Pawlewski, P. (2016). Reducing negative impact of machine failures on performance of filling and packaging production line–a simulative study. *Proceedings of the 2016 Winter Simulation Conference*, IEEE, Washington, DC, USA, 2912-2923. https://doi.org/10.1109/WSC.2016.7822326
[4] Ruijters, E., Guck, D., Noort, M., & Stoelinga, M. (2016). Reliability-centered Maintenance of the Electrically Insulated Railway Joint via Fault Tree Analysis: a Practical experience report. *Proceedings of 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks*, IEEE, Toulouse, France, 662-669. https://doi.org/10.1109/DSN.2016.67
[5] Sinha, R. S. & Mukhopadhyay, A. K. (2015). Reliability centered maintenance of cone crusher: a case study. *International Journal of Systems Assurance Engineering and Management*, *6*(1), 32-35. https://doi.org/10.1007/s13198-014-0240-7
[6] Cicek, K., Turan, H. H., Topcu, Y. I., & Searslan, M. N. (2010). Risk-based preventive maintenance planning using failure mode and effect analysis for marine engine systems. *Proceedings of 2010 Second International Conference on Engineering Systems Management and Its Applications*, IEEE, Sharjah, United Arab Emirates, 1-6.
[7] Yan, R., Dunnett, S. J., & Jackson, L. M. (2016). Reliability modelling of automated guided vehicles by the use of failure modes effects and criticality analysis, and fault tree analysis. *Proceedings of 5th Student conference on operational research*, Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany, 1-11.
[8] Rahman, F. A., Varuttamaseni, A., Kintner-Meyer, M., & Lee, J. C. (2013). Application of fault tree analysis for customer reliability assessment of a distribution power system, *Reliability Engineering and System Safety*, *111*, 76-85. https://doi.org/10.1016/j.ress.2012.10.011
[9] Gupta, G. & Mishra, R. P. (2017). A failure mode effect and criticality analysis of conventional milling machine using fuzzy logic: case study of RCM. *Quality and Reliability Engineering International*, *32*(2), 347-356. https://doi.org/10.1002/qre.2011
[10] Xu, Z., Dang, Y., Munro, P., & Wang, Y. (2020). A data-driven approach for constructing the component failure mode matrix for FMEA. *Journal of Intelligent Manufacturing*, *31*, 249-265. https://doi.org/10.1007/s10845-019-01466-z
[11] Ma, Z., Ren, Y., Xiang, X., & Turk, Z. (2020). Data-driven decision-making for equipment maintenance. *Automation in Construction*, *112*, 103103. https://doi.org/10.1016/j.autcon.2020.103103
[12] Fuentes-Huerta, M. A., Gonzalez, D. S., Sifuentes, M. C., & Prage-Alejo, R. J. (2018). RCM implementation on plastic injection molding machine considering correlated failure modes and small size sample. *International Journal Advanced Manufacturing Technology*, *95*, 3465-3473. https://doi.org/10.1007/s00170-017-1402-y

[13] Yssaad, B. & Abene, A. (2015). Rational Reliability Centered Maintenance Optimization for Power Distribution Systems. *Electrical Power and Energy Systems*, 73, 350-360. https://doi.org/10.1016/j.ijepes.2015.05.015
[14] Biswal, G. R., Maheshwari, R. P., & Dewal, M. L. (2012). System reliability and fault tree analysis of SeSHRS-based augmentation of hydrogen: dedicated for combined cycle power plants. *IEEE Systems Journal*, *6*(4), 647-656. https://doi.org/10.1109/JSYST.2012.2192065
[15] Souza R. Q. & Alvares A. J. (2008). FEMA and FTA analysis for application of the reliability centred maintenance methodology: case study on hydraulic turbines. *ABCM symposium series in mechatronics*, *3*, 803-812.
[16] Mendes A. A. & Ribeiro J. L. D. (2015). A study of the quantitative methods that support RCM operation. *Proceedings of 2015 Annual Reliability and Maintainability Symposium*, 1-6. https://doi.org/10.1109/RAMS.2015.7105162
[17] Ben-Daya, M., Duffuaa, S. O., Raouf, A., Knezevic. J., & Ait-Kadi, D. (2009). *Handbook of Maintenance Management and Engineering*. Springer-Verlag London Limited, UK. https://doi.org/10.1007/978-1-84882-472-0
[18] Braaksma, A. J. J., Klingenberg, W., & Veldman, J. (2013). Failure mode and effect analysis in asset maintenance: a multiple case study in the process industry. *International Journal of Production Research*, *51*(4), 1055-1071. https://doi.org/10.1080/00207543.2012.674648
[19] Banduka, N., Veza, I., & Bilic, B. (2016). An integrated lean approach to process failure mode and effect analysis: a case study from automotive industry. *Advances in Production Engineering & Management*, *11*(4), 355-365. https://doi.org/10.14743/apem2016.4.233
[20] Baghery, M., Yousefi, S., & Reazee, M. J. (2016). Risk measurement and prioritization of auto parts manufacturing processes based on process failure analysis, interval data envelopment analysis and grey relational analysis. *Journal of Intelligent Manufacturing*, *1*, 1-23. https://doi.org/10.1007/s10845-016-1214-1
[21] Rausand, M. & Hoyland A. (2004). *System Reliability Theory: Models, Statistical Methods, and Applications, 2nd edition*. John Wiley & Sons Press, New Jersey, USA.
[22] Li, Y. F., Huang, H. Z, Liut, Y., Xiao, N. C., & Li, H. Q. (2012). A new fault tree analysis method: fuzzy dynamic fault tree analysis. *Eksploatacja i Niezawodnosc-Maintenance and Reliability*, *14*(3), 208-214.

Contact information:

Pengfei ZENG, associate Professor and PhD
(Corresponding author)
School of Mechanical Engineering,
Shenyang Ligong University, Shenyang 110159, P. R. China
E-mail: pfzeng@163.com

Weiping SHAO, Professor and PhD
School of Mechanical Engineering,
Shenyang Ligong University, Shenyang 110159, P. R. China
E-mail: wpshao@126.com

Yongping HAO, Professor and PhD
R&D Center of CAD/CAM Technology,
Shenyang Ligong University, Shenyang 110159, P. R. China
E-mail: yphsit@126.com