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Reliability, availability and maintenance optimisation of heat exchanger networks

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Abstract

A new methodology is proposed to use comprehensive up-to-date commercial software tools for Heat Exchanger Network (HEN) reliability modelling and optimisation. The idea behind this proposal is that to apply the combination of specific HEN optimisation and reliability software packages has several advantages over the commonly used approach. There is a variety of features that need to be taken into account to choose the right software tool. The HEN design has a significant impact on reliability issues and this should be considered. There are many related issues and features - the robustness, the type of welding, the increment of maximum mechanical resistance, the impact on manufacturing costs, reduction of lost opportunity costs caused by exchanger outages, troubleshooting of heating exchanger problems by operators etc. Fouling should be analysed as it has a significant impact on maintenance issues. Up to 30 % decrease of maintenance costs can be achieved annually by applying advanced reliability results and determining heat exchanger failure causes. These analyses include the investigation of failure causes, prediction of future probabilities of failures, cleaning planning and scheduling and the calculation of reliability and maintainability.

Keywords: reliability; availability; maintenance; Heat Exchanger Network; RAMS; optimisation

1. Introduction

A heat exchanger network is an important part of many processing and power generating plants. In most cases the HEN synthesis and design are assuming steady-state and non-variable operating conditions. In practice they can change and disturbances may occur.

Operational maintenance, availability and cost are some of the most important factors of HENs. All heat exchangers must be able to provide a specified heat transfer
while maintaining a pressure drop across the exchanger. The propensity for fouling must be evaluated to assess the requirements for periodic cleaning. Fouling affects nearly every plant relying on heat exchangers for its operation. It is the accumulation of undesired solid material at the fluid or solid interface. Fouling introduces various costs, e.g. increased capital expenditure, and increased maintenance, loss of production, quality control problems, cleaning costs, additional hardware, and energy losses [1].

Fouling of individual heat exchangers has been the subject of intensive research in recent decades. However, HEN fouling has even more issues. Maintenance considerations in the scheduling of continuous and batch plants have recently received increasing attention. Muller-Steinhagen [2] proposed an integrated approach for developing alternative fouling mitigation strategies based on both experimental and modelling work. Georgiadis et al. considered the short term cleaning scheduling in special classes of HENs [3].

A wide variety of approaches are not limited to mathematical models and practical methodologies. The lifetime of heat exchangers varies with the application. A common practice to fouling mitigation is the implementation of Cleaning-In-Place (CIP) operations. Special heat exchangers exists which eliminate cleaning scheduling and maintenance activities by a self-cleaning mechanism. There are advanced materials, such as the hyper-duplex stainless steel, that designed and developed to increase operating performance and to extend service life in severely corrosive heat exchanger applications.

Reliability estimation is a useful tool to improve HEN design subject to uncertainties in the operating conditions. The efficiency of the technique has been proved by Tellez et al. [4]. The analysis of the design constraints has been performed for different possible variations in the operating conditions.

Failure analysis contains Fault Tree Analysis (FTA). An FTA of a coolant supply to Heat Exchanger has been described as an example by Lazor in the reliability handbook of Ireson et al. [5].

Although several approaches and methodologies have been studied in the field of heat exchanger and HEN fouling, Reliability, Availability and Maintenance (RAM) issues of HENs should be further studied, especially for optimisation purposes. Scheduled and unexpected shutdowns should be differentiated. Maintenance times should be optimised. The characteristics of units should be considered. Another important issue is the mean time between maintenance and the reduction of efficiency to certain levels.

Present paper focuses on the possibilities of advanced software tools that support this field. The paper introduces a methodology for effective modelling and optimisation of HEN maintenance and reliability.

2. Problem statement

Market pressures drive management to achieve higher and higher levels of availability and reliability. However, the motivation to improve reliability is more complex than simply to reduce maintenance costs. There is a need to control reliability for best economic performance. In fact, least cost maintenance is not recommended when a plant strives to achieve high reliability. Maintenance costs are relatively low when compared with loss opportunity costs. HEN reliability issues can be effectively handled with RAMS software. The reliability issues of HENs deserve much more attention. Most designers mainly focus on HEN capital and operation cost optimisation
only. The reliability issues of HENs should be properly analysed and improved by relevant software tools. All relevant features affecting availability, reliability and maintenance should be considered while modelling and optimising HENs. One of these factors is the interaction between heat exchangers in the HEN. The main task of optimisation is the appropriate scheduling of cleaning interventions of the individual exchangers in the HEN. It can be based on a priori knowledge of the time behaviour of the thermal resistance of fouling [6]. Further tasks to be optimised are the operating costs of the HEN. The estimation of current and future failure probabilities are required to make the decision for equipment replacements performed at the right time to eliminate unnecessary shutdowns caused by unexpected faults. The simple cases, including series and parallel HENs, and the complex arrangements (block HENs) should be differentiated as their fouling factors are different. The detrimental effect of fouling can be reduced by adopting appropriate measures in HEN design [7]. Important is the choice of local parameters and the HEN structure [8].

Enhancing heat exchanger reliability has many advantages. Cost effectiveness can be increased; plant assets management can be improved. Component lifetime can be extended, and leakages can be detected prior to shutdown. Improved reliability results in reduced maintenance costs and a better economic performance.

2.1. RAM of Heat Exchanger Networks

Reliability is the probability that the HEN will perform satisfactorily for at least a given period of time when used under certain conditions [5].

The availability of a Heat Exchanger Network represents the capability to manage heat and power streams continuously in a usual and regular way. The cause of failures varies, including mechanical failures, corrosion, fouling, and sealing problems.

Maintenance has an important role in plant design. Optimum maintenance planning is a key factor in modern HENs. Maintenance covers the activities undertaken to keep the HEN operational (or restore it to operational condition when a failure occurs).

A measure of ease and speed a system can be restored to operational status after a failure occurs can be expressed as a percentage. It is called maintainability, i.e. the probability of performing a successful repair action within a given time.

Analysing failures is an important way to determine availability and reliability issues of a system, including component failures, service failures, mechanical failures, control system failures (or malfunction), the failures to detect faults, changeover failures, lack of manpower, operator errors, and instrument failures.

The most important failure characteristics can be expressed by mean times. The widely used is the Mean Time Between Failures (MTBF), i.e. the reciprocal of failure rate. Further types of mean times are the Mean Time Before Maintenance Actions, the Mean Time Between Repairs, and the Mean Time To Failure.

Two types of fouling-induced effects should be identified in HENs [7]:

(i) Changes in outlet temperature of process streams caused by the thermal resistance of fouling in an exchanger;

(ii) Changes in inlet temperature of process streams caused by the thermal resistance of fouling in other exchangers (“antecedent exchangers” serving the same process streams).

Some problems to be handled are the interaction between heat exchangers within the HEN and the optimisation of online cleaning.
3. Heat Exchanger Network system analyses

HEN analysis can be approached from various angles.

3.1. HEN design analysis

HEN design depends significantly on the types of the heat exchangers used. Several factors should be considered when selecting the heat exchanger type [9].

Determining the list of system components is one of the first steps in availability and reliability analysis. The calculations require different kind of data of each component that build up the system. The component table could be useful to describe these data, because the majority of parts have different characteristics. The next step is to build up a system tree (either as a drawn tree structure or as a table).

3.2. Failure analysis

Failure Analysis (FA) or Root Cause Analysis (RCA) is a detailed examination of failed items to determine the root cause of failure and to improve product reliability. It helps with developing tests focused on problematic failure modes and with selecting better materials and/or designs and processes, and with implementing appropriate design changes to make products or processes more robust [10]. FA is strongly supported by reliability software tools.

3.3. RAM analysis

Availability analysis identifies the items that can affect system operation. It can be extended by considering the combination of maintainability and reliability data. System Reliability Analysis with Reliability Block Diagrams (RBDs) can be used for testing systems via component reliability and overall system reliability. Weak points can be identified. Different designs can be compared. Maintainability analysis provides data for the optimisation of maintenance and repair actions. These analyses can be performed in all major RAMS software packages.

4. Comprehensive software for modelling

The significance of the latest approaches of modelling the behaviour of the heat transfer surface by using the fouling resistance factor increased recently. As a result of intensive research, some of the classical theories are either being validated or modified to suit current design and optimisation techniques.

Various types of modern software packages are used for modelling the different issues of HENs. Fouling mitigation strategies can be effectively modelled by Fuzzy-Logic Expert Systems (FLES) and Computational Fluid Dynamics (CFD) software. General MILP solvers can be used for optimisation of processes.

However, another kind of software can be used for modelling and optimising the reliability related issues of HENs: Reliability, Availability, Maintainability and Safety (RAMS) software. The proper choice of RAMS software depends on many factors (e.g. the place of application, the amount of provided data, calculation precision). Availability can be treated together with reliability and life cycle cost modelling as they are influenced by each other.

Some examples of RAMS packages are BlockSim and Weibull++ (ReliaSoft [11]), Reliability Studio (Relex Software Corp. [12]), Item ToolKit (ITEM Software [13]). Most of them can be tested as a trial version for free. A more detailed description was
introduced by Sikos and Klemeš [14]. There are specific CAD approaches as well, e.g. process design software tools applied for capacity increase and advance of distillation units, performing predictions of fouling layer structure or improving design [15]. Prototype software ‘FiltraDynaSim’ for the analysis of the fouling layer properties in microfiltration was introduced by Tung et al. [16] It can be used both to design a membrane filtration system and to predict or monitor its performance during plant operation. Nordman and Bernstsson presented a graphical method to determine heaters and coolers for retrofit in HENs [17]. They used advanced composite curves to describe the potential amount of heat that could be saved. They can serve as a monitoring tool to identify heat recovery targets and show the order of units to be targeted for rearrangement. Bertolini et al. determined an algorithm that allows a methodical, automatic approach for management of failure data in oil refineries [18]. It seems to be a significant potential to make substantial improvements in task organisation and decision-making processes. The aim of the Risk-Based Inspection and Maintenance (RBI&M) method proposed is to solve two important problems of reliability of refineries: (i) The personnel available for the analysis of critical items and events is limited and it is not able to assess in detail all the events occurred; (ii) Once defined the critical level of an item or event, reliability department has to decide the best maintenance actions and work orders to carry out. Kim et al. introduced a systematic methodology for designing wastewater and heat exchange networks [19]. Based on cost estimation, networks for water and heat exchange were optimised simultaneously. Their proposal is a useful guideline for wastewater and heat exchanger network design with greater cost efficiency and environmental performance. The method employed a specific strategy to address mixed integer non-linear programming (MINLP) formulations. The mathematical formulation was based on water-pinch analysis and an expanded transhipment model. Bulasara et al. [20] addressed a revamp study of the crude distillation unit (CDU) heat exchanger network (HEN) of a typical refinery with and without the consideration of the free hot streams available in the delayed coking unit (DCU). Two sub-cases of revamp study have been considered: (a) Installation of new heat exchangers for the entire network; (b) Reutilisation of existing heat exchangers. They demonstrated the relevance of the consideration of DCU free hot streams in CDU revamp and retrofit design choices.

5. A suggested methodology

The proposed methodology suggests a combination of specific HEN optimisation tools with reliability software packages to improve the effectiveness of reliability optimisation in heat exchanger networks. A structure to conduct reliability, availability and maintainability analyses is presented as well. The reliability analysis of HENs can be performed manually or using reliability software packages. The main advantages of using RAMS software in HEN reliability modelling and optimisation are:

(i.) Prediction of replacement times can eliminate costs via failure analysis. Performing Weibull analysis on the failure data yields an estimation of MTBF and provides parameters that can be used to estimate future probability of failure. Based on Weibull parameters, it can be determined if exchangers in the HEN will probably survive until the next scheduled outage. If not, what is more cost effective: to replace now or to wait for the next scheduled outage? The answer if it is worth to wait until the next outage is delivered.
(ii.) Estimation of current probability failure with failure probability calculator.

(iii.) Realization of the establishment of new reliability culture at the plant.

(iv.) Improvement of system reliability.

(v.) Reduction and optimisation of maintenance costs.

(vi.) Reduction of loss opportunity costs.

(vii.) Optimisation of the balance between maintenance costs and loss opportunity costs via cost benefit analysis.

(viii.) Control over equipment reliability.

(ix.) Cohesive modelling modules. System tree, FMEA table, fault tree table, subdiagrams/mirrored blocks/multiblocks, LCC, Weibull tree, throughput analysis, downtime distributions, parts table, prediction data, FMEA worksheet, maintainability data, maintenance policies, RBD, fault tree diagram, event tree diagram, Weibull graph.

(x.) Simultaneous analyses. This feature can be used to handle Availability, Reliability and Maintenance together.

(xi.) Combining series and parallel subsystems. HENs can be analysed by calculating the reliabilities of individual series and parallel sections and combining them in the appropriate manner.

(xii.) A wide variety of distributions. The standard definition of maintainability

\[ M(t) = 1 - e^{-\mu t} \]

can be easily expanded to different distributions. In case of the Weibull distribution, for example, \( MTTR \) should be modified from \( 1/\mu \) to

\[ MTTR_{\text{Weibull}} = \eta \cdot \Gamma \left( \frac{1}{\beta} + 1 \right) \]  

with the scale (\( \eta \)) and shape (\( \beta \)) Weibull parameters.

Thus maintainability becomes

\[ M(t)_{\text{Weibull}} = 1 - e^{-\left( \frac{t}{\eta} \right)^\beta} \]  

while with lognormal distribution it can be expressed as

\[ M(t)_{\text{Lognormal}} = \int_{0}^{t} \frac{1}{\sigma_r \sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{t' - \mu}{\sigma_r} \right)^2} dt \]

where \( t' = \ln(t) \), where the \( t \) values are the times to failure,

\( \sigma_r \) = standard deviation of the natural logarithms of the times to failure.

RAMS software packages allow total system approaches in analyses of individual system components. This contributes to the optimisation of design targets for plants to improve equipment selection, replacement, maintenance, as well as to increase system reliability.

5.1. The reliability program

When making the decision which tube bundles to replace, reliability groups should look at the reliability engineering principles and applying their results. The heat exchanger reliability could be supported by specification of the scope of the reliability analysis, which should contain:

- The total number of failures
- \( MTBF \)
- Fluid velocity
• Years of service
• The current age of heat exchangers.

From them further requirements are recommended to investigate operation classes, date of installation, date of last replacement, tube age factor table, remaining life factor table, production criticality factor, service conditions, bundle replacement costs, and other considerations (e.g. corrosion mechanism).

5.2. Data requirement
Numerous data required to perform reliability and maintainability calculations. They can be classified in three groups.

First, general characteristics needed, including the general description of the plant, HEN usage, the period of continuous HEN operation, system structure, HEN arrangement. Data collection time interval need to be settled for further experiments. Features to be considered include but not limited to the list of equipments, units, flow streams of the HEN, the heat duty, the heat transfer area, heat transfer coefficients, shell and tube passes, the number of tubes, and design $\Delta T$. The main groups of candidate variables are: operational (tube/shell inlet temperatures, flowrates, and integral flows), maintenance (peak efficiency), scheduling (crude/condensate in blend), and predicates (shell/tube side outlet temperatures).

Availability and reliability calculations are in the second group. They require failure history, durations of failures and shutdowns. Three classes of heat exchanger operation modes should be differentiated both for forced (unplanned) shutdowns (e.g. tube leakage) and scheduled maintenance actions. Equipments of Class A require total unit shutdown. In Class B, production cutback is required by a certain percentage. Class C equipments have no impact on system output (run-to-fail).

The optimisation of maintenance actions need variables depending on the system to be analysed. In a crude oil plant, for example, the ones that affect HE fouling required, including operational variables (inlet and outlet variables, flow rates of the crude, fluid temperatures, wall temperature of tubes, tube side and shell side flow rates), maintenance variables (e.g., peak efficiency), scheduling variables (crude/condensate in blend), as well as crude property variables.

Analyses can be more easily understood if a figure of the HEN is provided.

Process data are required as well, including inlet and outlet, mass flowrate (both for shell side and tube side), the exchanged heat, and the heat transfer surface.

5.3. System reliability analysis with RAMS software
System reliability analysis can be divided into parts. Firstly, the required reliability approach should be decided. The steps for conducting reliability analysis of HENs are:
(i) Data collection: gather specific bundle failure history.
(ii) Conduct Weibull analyses on the failure data.
(iii) Failure probability calculations to estimate current probability of failure. During this step, the various operation classes of heat exchangers should be differentiated.

Both the maintenance activities that ensue after a failure and the failure mechanisms at work affect the way of conducting the Weibull analyses of heat exchangers. For tube failures caused by process corrosion, failures are expected to reveal a wearout pattern, represented by $\beta > 1$. If the Weibull analysis results in $\beta < 1$, the heat exchanger is failing due to lack of quality or some other process that occurred during manufacturing.
To control heat exchanger reliability, the probability of failure should be accurately predicted. Estimating tube bundle reliability should account for the age of each individual tube that failed. Each tube lifetime is estimated from the installation date of the bundle to the failure date, at which time the failed tube is plugged.

6. Case study

The proposed methodology is suitable for optimising maintenance issues of HENs. A HEN of a petroleum refinery plant has been selected to demonstrate its capabilities. The MOL (Magyar Olaj- és Gázipari Nyrt.) plant is located in Százhalombatta, Hungary. The refinery has a conventional Crude Preheat Train which consists of a set of shell and tube heat exchangers. Fouling of this unit reduces heat input (Fig. 1). Based on experience, energy consumption is 10-20 % higher due to fouling. Fouling level is mainly depends on the properties of the crude blends being processed, the operating temperature, and flow conditions. Online cleaning is not applied.

The analysed subsystem contains 36 heat exchangers and 2 desalters (Fig. 2). The estimations and calculations (Table 1) were based on the failure data of the last two years (2007/2008) provided by the company (Table 2). There were no large unexpected faults in 2007. Because of the small problems occurred during in various parts of the year, the Mean Time Between Failures increased through 2008, when two considerable faults happened. However, the downtimes caused by these events were not as much as can be expected, thank to the spares available at the right time [21].

The measured failure data were inserted into the spreadsheets of Relex Reliability Studio. The fault tree diagram was generated based on the failure tables (Fig. 3.). The advantage of this approach is the inclusion of their impacts on each other.

Weibull analysis and the estimation of future probability of failure were performed by Reliasoft Weibull++. There were four main types of system events in the analysed subsystem: normal events that do not have impact on downtimes, scheduled outages such as repairing or cleaning, unexpected faults and outages caused by special orders. The most important events of them are the unexpected faults that should be reduced or even eliminated.

Predictions performed through failure analysis are efficient to make suggestions to this field. Mean Time To Repair has become approximately four times larger in 2008 than it was previous year, i.e. the repair rate decreased to one forth. The further result is the most important from our point of view: maintainability has fallen significantly within the examined period. The time needed to restore the system to fully operational status varies from a few minutes to some days due to the complexity of repair and maintenance tasks. In 2007, maintainability reached 100% within less than 1 day. In 2008, the plant achieved the same level of maintainability within a maximum of four days (Table 3).

The software tools proved that the examined subsystem of the plant runs in a nearly optimal way. However, small corrections could improve RAM issues, depending on probable investments.

Inherent availability was 99.539 % in 2007 and 98.530 % in 2008. The plant had high system reliability, too (97.307 % and 96.003 % in the last two years).

Class B operating mode is preferred in the plant so the production efficiency becomes lower continuously. Total shutdowns are not required for maintenance actions.
(eliminating Class A mode). However, production cutback does not performed by a fixed threshold. Instead, cleaning is done during major scheduled outages as preventive maintenance.

The plant has high maintainability. Maintenance, repair and replacement actions are well organised and scheduled. Many actions do not cause more than a few minutes outage due to spares. Failures are rare and mainly caused by heat exchanger breakdowns, leakages, problems in the steam production, and the burnout of the tube furnace. Maintainability cannot be increased significantly by simply increasing the frequency of cleaning interventions. However, the failure causes mentioned above are strongly related to availability and reliability and thus they can be optimised via total system approach supported by reliability software.

A longer period should provide more detailed picture because of the large intervals between main scheduled cleanings of up to four years. However, based on the performed study, some recommendations still can be added and the weak points highlighted. In the worst cases, fouling reduced the diameter of tubes by one third. At the same time, heat transfer coefficient went down because of fouling. A threshold should be applied to prevent very high fouling levels, especially where rapid fouling occurs. Scheduling of major outages should be improved while still considering costs. Supervisions should be done more frequently. However, total shutdown was not necessary and total downtimes were not significantly longer than the sum of the short downtimes in 2007. The most sensitive points in the system from the point of maintainability are the frequency of cleaning to avoid the effects of fouling, the failed heat exchangers and the efficiency of repairs (e.g. the repair of tube furnace burn control).

7. Conclusions

The proposed software modelling and optimisation methodology provides a way to reduce future losses in HENs and reach these aims through optimum maintenance. Several new approaches have been reviewed. The proposed methodology focuses on HEN maintenance through the influence of availability and reliability rather than the optimisation of cleaning schedules only. It has been shown that the failure analysis is capable to predict heat exchanger bundle replacement times, leading to significant savings. All major failure types are taken into account, including heat exchanger breakdowns, fouling, and leakages. Units of HENs are classified through operating classes and the most specific maintenance characteristics of fouling. This can reduce or even eliminate the need for total unit shutdowns required for cleaning. Reliability culture of plants or subsystems can be developed via total system approach, considering antecedent exchangers, HEN structure, local parameters, spares, and cost. The case study demonstrated that the RAMS software approach is capable to find the weak points in HEN maintenance, and emphasize the small corrections that could improve these issues towards optimality.

Acknowledgements

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References


Figure Captions

Fig. 1. Effects of HE fouling in the plant

Fig. 2. Technological scheme of the subsystem

Fig. 3. Fault tree diagram and fault tree table (generated in Reliability Studio and extended manually in CorelDraw)


Nomenclature

Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CIP</td>
<td>Cleaning-In-Place</td>
</tr>
<tr>
<td>CPT</td>
<td>Crude Preheat Train</td>
</tr>
<tr>
<td>FA</td>
<td>Failure Analysis</td>
</tr>
<tr>
<td>FLES</td>
<td>Fuzzy-Logic Expert Systems</td>
</tr>
<tr>
<td>FMEA</td>
<td>Failure Modes and Effects Analysis</td>
</tr>
<tr>
<td>FTA</td>
<td>Fault Tree Analysis</td>
</tr>
<tr>
<td>HE</td>
<td>Heat Exchanger</td>
</tr>
<tr>
<td>HEN</td>
<td>Heat Exchanger Network</td>
</tr>
<tr>
<td>LCC</td>
<td>Life Cycle Cost</td>
</tr>
<tr>
<td>RAM</td>
<td>Reliability, Availability and Maintenance</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reliability, Availability, Maintainability and Safety</td>
</tr>
<tr>
<td>RBD</td>
<td>Reliability Block Diagram</td>
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<tr>
<td>RCA</td>
<td>Root Cause Analysis</td>
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Quantities

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_i$</td>
<td>Inherent availability [%]</td>
</tr>
<tr>
<td>$A_o$</td>
<td>Operational availability [%]</td>
</tr>
<tr>
<td>$M$</td>
<td>Maintainability [%]</td>
</tr>
<tr>
<td>$M(x)$</td>
<td>Per cent maintainability in $x$ hours [%]</td>
</tr>
<tr>
<td>$MCT$</td>
<td>Mean Cycle Time [h]</td>
</tr>
<tr>
<td>$MDT$</td>
<td>Mean Downtime [h]</td>
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<tr>
<td>$MTBF$</td>
<td>Mean Time Between Failures [h]</td>
</tr>
<tr>
<td>$MTBMA$</td>
<td>Mean Time Between (or Before) Maintenance Actions [h]</td>
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<td>$MTBR$</td>
<td>Mean Time Between (or Before) Repairs [h]</td>
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<tr>
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<td>$Q$</td>
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<tr>
<td>$R$</td>
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<tr>
<td>$t$</td>
<td>Time duration analysed [h]</td>
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<td>$TDT$</td>
<td>Total downtime [h]</td>
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<tr>
<td>$TUT$</td>
<td>Total uptime [h]</td>
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<tr>
<td>$U_i$</td>
<td>Unavailability [%]</td>
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Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Weibull shape parameter (slope)</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Temperature difference [°C]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Weibull scale parameter</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Mean Time Between Failures ($MTBF$) [h/failure]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Failure rate [failure/h]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Repair rate [failures/unit time]</td>
</tr>
</tbody>
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Table 1
Main characteristics of the subsystem as the outputs of the performed analyses

<table>
<thead>
<tr>
<th>Measure</th>
<th>Quantity</th>
<th>2007</th>
<th>2008</th>
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<tbody>
<tr>
<td>Mean uptime (MUT)</td>
<td>h</td>
<td>221.681</td>
<td>287.905</td>
</tr>
<tr>
<td>Mean downtime (MDT)</td>
<td>h</td>
<td>3.861</td>
<td>6.178</td>
</tr>
<tr>
<td>Mean Cycle Time (MCT)</td>
<td>h</td>
<td>225.542</td>
<td>294.083</td>
</tr>
<tr>
<td>Failure rate ((\lambda))</td>
<td>failure/h</td>
<td>0.005</td>
<td>0.003</td>
</tr>
<tr>
<td>Mean Time Between Failures ((\theta))</td>
<td>h/failure</td>
<td>221.681</td>
<td>287.905</td>
</tr>
<tr>
<td>Mean Time To First Failure (MTTF)</td>
<td>h</td>
<td>220.653</td>
<td>283.608</td>
</tr>
<tr>
<td>Mean Time To Repair (MTTR)</td>
<td>h</td>
<td>1.028</td>
<td>4.297</td>
</tr>
<tr>
<td>Inherent availability ((A_i))</td>
<td>%</td>
<td>99.539</td>
<td>98.530</td>
</tr>
<tr>
<td>Operational availability ((A_o))</td>
<td>%</td>
<td>61.462</td>
<td>66.005</td>
</tr>
<tr>
<td>Unavailability ((U_i))</td>
<td>%</td>
<td>0.461</td>
<td>1.470</td>
</tr>
<tr>
<td>Reliability ((R))</td>
<td>%</td>
<td>97.307</td>
<td>96.003</td>
</tr>
<tr>
<td>Unreliability ((Q))</td>
<td>%</td>
<td>2.693</td>
<td>3.997</td>
</tr>
<tr>
<td>Maintainability ((M))</td>
<td>%</td>
<td>100.000</td>
<td>100.000</td>
</tr>
<tr>
<td>Repair rate ((\mu))</td>
<td>failure/unit time</td>
<td>0.973</td>
<td>0.238</td>
</tr>
</tbody>
</table>
Table 2
Input values

<table>
<thead>
<tr>
<th>Measure</th>
<th>Quantity</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time duration analysed (t)</td>
<td>h</td>
<td>8119.500</td>
<td>7058.000</td>
</tr>
<tr>
<td>Total uptime (TUT)</td>
<td>h</td>
<td>7980.500</td>
<td>6909.718</td>
</tr>
<tr>
<td>Total downtime (TDT)</td>
<td>h</td>
<td>139.000</td>
<td>148.282</td>
</tr>
</tbody>
</table>
Table 3
Maintainability of the subsystem

<table>
<thead>
<tr>
<th>Notation</th>
<th>Maintainability [%] 2007</th>
<th>Maintainability [%] 2008</th>
<th>Required time to reach that level</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(1)</td>
<td>62.204</td>
<td>20.764</td>
<td>1 h</td>
</tr>
<tr>
<td>M(2)</td>
<td>85.714</td>
<td>37.217</td>
<td>2 h</td>
</tr>
<tr>
<td>M(3)</td>
<td>94.600</td>
<td>50.254</td>
<td>3 h</td>
</tr>
<tr>
<td>M(4)</td>
<td>97.959</td>
<td>60.583</td>
<td>4 h</td>
</tr>
<tr>
<td>M(5)</td>
<td>99.228</td>
<td>68.768</td>
<td>5 h</td>
</tr>
<tr>
<td>M(10)</td>
<td>99.994</td>
<td>90.245</td>
<td>10 h</td>
</tr>
<tr>
<td>M(24)</td>
<td>100.000</td>
<td>99.624</td>
<td>1 day</td>
</tr>
<tr>
<td>M(48)</td>
<td>100.000</td>
<td>99.998</td>
<td>2 days</td>
</tr>
<tr>
<td>M(72)</td>
<td>100.000</td>
<td>99.999</td>
<td>3 days</td>
</tr>
<tr>
<td>M(96)</td>
<td>100.000</td>
<td>100.000</td>
<td>4 days</td>
</tr>
</tbody>
</table>
Top event

OR gate

01 - System event
  OR gate
  02 - Normal event (without downtime)
    OR gate
    06 - Unit start
      OR gate
      07 - State change
      OR gate
      17 - Source change
      OR gate
      18 - Quantity change
    20 - Quantity decrement
    21 - Quantity increment
  19 - Quality change
  03 - Scheduled outage
    OR gate
    08 - Repairing
    OR gate
    09 - Cleaning
    OR gate
    10 - Supervision
    OR gate
    11 - Avoidance of fatigue
  04 - Unexpected fault
    OR gate
    12 - Leakage
    OR gate
    13 - Fouling (Class B equipments)
    OR gate
    14 - Equipment stoppage
    OR gate
    15 - Material processing fault
    OR gate
    16 - Tube furnace burnout
    OR gate
    05 - Other outage (special order)

ID# and description
Gate/event type

01 - System event: OR gate
02 - Normal event (without downtime): OR gate
06 - Unit start: Basic event
07 - State change: OR gate
17 - Source change: Basic event
18 - Quantity change: OR gate
20 - Quantity decrement: Basic event
21 - Quantity increment: Basic event
19 - Quality change: Basic event
03 - Scheduled outage: OR gate
08 - Repairing: Basic event
09 - Cleaning: Basic event
10 - Supervision: Basic event
11 - Avoidance of fatigue: Basic event
04 - Unexpected fault: OR gate
12 - Leakage: Basic event
13 - Fouling (Class B equipments): Basic event
14 - Equipment stoppage: Basic event
15 - Material processing fault: Basic event
16 - Tube furnace burnout: Basic event
05 - Other outage (special order): Basic event