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Probability of Failure Assessment in District Heating Network

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Abstract: The aim of this paper is to present works performed in HTC (Heat-Tech Center), Research & Development Centre of Veolia Group located in Warsaw regarding assessment of probability of failure in DHN (district heating network). This work is a part of a project dedicated to develop a software which objective is to increase reliability of DHN. The research methods consisted of three approaches. First, using database of failures which happened in Warsaw DHN and repairing protocols from past 10 years, a statistics approach was applied to perform first analysis. The result was that pipelines with nominal diameter DN (nominal diameter) ≤ 150 had higher failure rate per km, than pipelines with DN > 150. The next step of research was to study influence of internal (corrosion caused by heat carrier, quality of materials) and external (stray currents) factor in order to assess its individual influence on failure rate of pipe and explain reasons of differences in failure rate. To end a FMEA (failure mode and effects analysis) will aim to identify the main failures modes appearing on DHN, to estimate the main causes of these failures and to propose the best solutions regarding the causes, the costs and the means available.

Key words: DHN, failures, failure analysis, Warszawa, Warsaw.

1. Introduction

DHN (district heating network) like any other industrial system ages and is more likely to fail due to worsening of mechanical properties of used materials. DHN issues are more complicated because most of pipelines are installed in duct channels and there are a few possibilities to monitor condition of assets. Better knowledge about condition of assets may allow to better plan investments in replacement of old part of network and reduce cost of repair and increase security of supply for customer. Therefore, HTC (Heat-Tech Center) has started a Research & Development Project dedicated to develop a software which aims to increase reliability of DHN.

The main criteria which leads to positive decision of renovation of a segment of pipeline is risk of destabilizing operation of DHN if given segment has a malfunction. Such a risk criteria has two main components: a probability of occurrence of failure, and consequences caused by a failure. This paper will put more attention to part related to probability of failure, whereas, part related to consequences will be covered in narrower scope.

The subject of study is Warsaw DHN owned by Veolia Energy Warszawa, presented in Fig. 1. The history of Warsaw's post-war DHN starts in 1952. Currently, it is the biggest centralized DHN in Poland and one of the biggest in Europe. DHN has radial-ring structure, with 100 rings and length of about 1,691 km. It supplies 19,000 buildings, and covers 80% of city's demand for heat. Annually 38 PJ of heat are delivered to customers. Heat losses of network are about 10% [1]. DHN is supplied from two base heat sources and two peak heat sources owned by company PGING Termika (polskie górnictwo naftowe i gazownictwo) which have installed capacity of 4,635 MWt.

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Fig. 1 Map of Warsaw DHN.

Table 1 Length of pipelines per each technology.

Technology	Length (km)	Share (%)
Pre-insulated	691	41
Traditional—in building	152	9
Traditional—duct channel	816	48
Overhead	31	2

The technology of construction of pipelines in Warsaw DHN can be divided into three main groups: pre-insulated, traditional (which consist of pipelines installed in duct channels, in buildings) and overhead. The corresponding lengths are given in Table 1.

2. State of the Art/Methods/Methodology

2.1 Modernization of Warsaw DHN

Until mid 80s' technical condition of Warsaw DH (district heating) system was unsatisfying. Corrosiveness of network water on internal surface of pipelines (Fig. 2 [2]), bad condition of devices (especially shut-off valves), poor quality of pipes, flawed workmanship, and difficult external conditions of duct channel pipelines are main shortcomings of Warsaw's DH network from this period of time. All those factors had significant influence on increasing failure rate. In 1980's, failure rate was systematically growing [3].

Since 1989, failure rate in Warsaw's DH network was slowly decreasing, what was caused by applying pipes with thicker steel wall since 1986. Nevertheless, annual number of failures was high, what was burdensome for customers. Modernization of Warsaw's DH network started in 1992, when a loan from World Bank was given. In May 1995, a process of reverse osmosis and demineralization was applied in heat sources for water treatment. This lowered aggressiveness and corrosiveness of network water.

Change of water quality and pipe renovation for pipes with thicker walls, installation of pre-insulated pipes, and exchange of armature caused significant drop of failure rate in Warsaw's DH network (from 5,470 in 1988 to 380 in 2012). Fig. 3 [4] presents the change of failure rate in years 1978-2012.

The part of data presented in Fig. 3 was collected from paper failure protocols which have been filled in

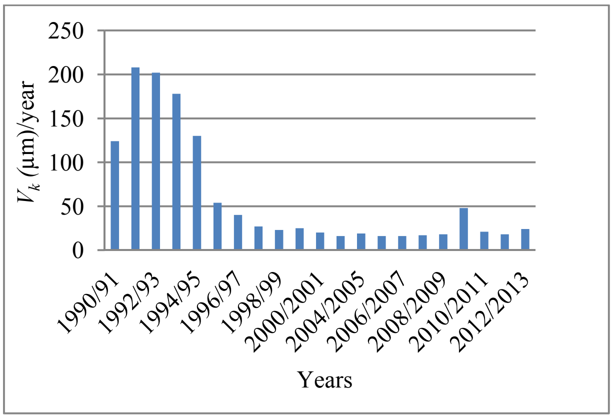

Fig. 2 Average surface corrosion rate of DH pipelines (supply + return) in years 1990-2002 and 2004-2013 determined with use of gravimetric method in μm/year.

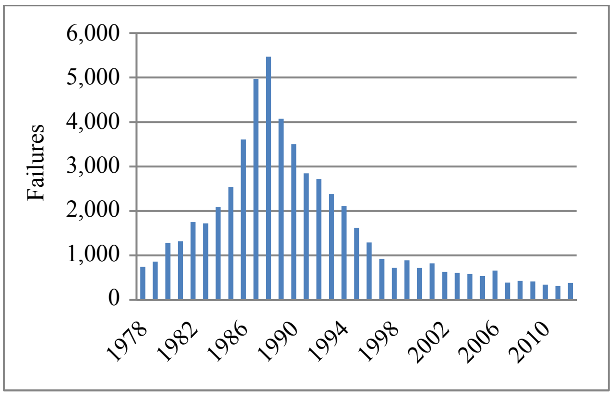

Fig. 3 Failures in Warsaw DHN in years 1978-2012.

by workers after removing each failure starting from year 2003. Until year 2012, 4,616 failure protocols have been recorded. Such a failure protocol included following data: address of failure, time of disconnection, time of start-up, type of damaged element, DN (nominal diameter) of element, type of damage, method of repair, cause of failure, etc. Therefore, the data about the failure were quite accurate, however, information about the damaged pipeline (ID of pipeline, type of pipeline, age of pipeline, etc.) were not sufficient.

The previous works in Veolia Energy Warszawa regarding failures consisted only of statistical analysis of number of failures per different categories (DN on which failure occurred, DHN administration zone, cause of failure, etc.). Moreover, failure rate (failures/km/year) was calculated for the whole DHN and administration zones.

In this paper, the same set of data is used to assess probability of failure. Such an information can allow operator of DHN have greater knowledge about condition of assets and make better decisions regarding renovation of pipelines.

To be complementary with failure rate approach, we decide to also use FMEA (failure mode and effects analysis) to make better decisions regarding renovation of assets on the DHN.

2.2 Failure Rate Methodology

In 2013, a new process of data treatment started. Recorded failures were manually added to Warsaw's GIS (geographical information system) and linked with the ID number of pipeline on which given failure occurred. However, not all failures could be identified in GIS. Some of failures have happened on pipelines which were replaced before 2013 and due to lack of historical data, it is not possible to make such a link. Other failures had poor data in the failure protocol and it is not sufficient to identify exactly where they happened. Therefore, the study concerns only the set of identified failures. Fig. 4 shows shares of failures with

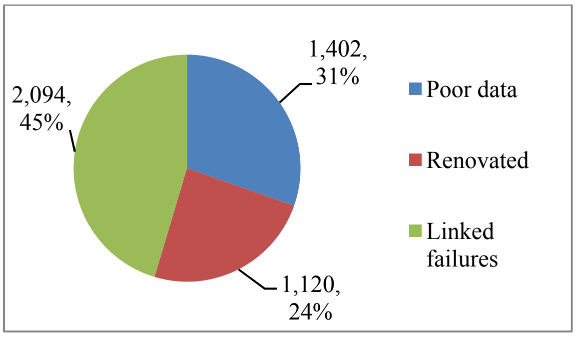

Fig. 4 Quality of data regarding 4,616 recorded failures in years 2003-2012.

poor data, which occurred on replaced pipelines, and linked failures.

This allowed to have accurate data about pipelines on which failures happened. Moreover, it was possible to quickly extract information how many failures occurred per one segment of pipeline (segment of pipeline in GIS is defined as part of network with homogenous characteristics) in any time period between 2003 and 2012.

The methodology of study consisted of analysis of occurrence of failures depending on different characteristic of pipeline and different characteristic of failure.

The first step (A) was to determine what was the change of failure rate (failure/km/year) in Warsaw DHN in order to investigate what is the trend. This was obtained by dividing the number of failures which happened during a given year by the total length of the DHN. Due to lack of consistent historical data about pipelines, the total length of DHN in given year is the same and assumed to be equal to 1,691 km, which is the current length. Such an assumption is valid because the size of Warsaw DHN is very big and changes of total length which occurred during last 10 years are relatively small and can be neglected.

The next step (B) was to study how often failures occur on one segment of pipeline. To obtain such information the GIS data base of pipelines with unique ID numbers was linked with data base of failures which had ID numbers of pipelines on which failures happened. This way each segment of pipelines had assigned number of failure which occurred on it. This information allowed to make statistics how many segments had one or more failures.

The third step (C) was to determine which characteristic have greater influence on failure rate. With use of the same approach, the number of failures per each group of selected characteristic was determined and divided by the corresponding length and time in order to obtain failure rate (failure/km/year).

The first studied characteristic was technology of construction of pipeline (C1). As it was mentioned, Warsaw DHN has used three technologies for construction of pipelines: pre-insulated, traditional (which consist of pipelines installed in duct channels, in buildings) and overhead. In total they give four different groups.

The next characteristic that was investigated was DN (C2). In Warsaw DHN, DN can be between values from 15 on up to 1,200. However, to make results easier to interpret, the three groups of DN were considered: connections—DN 15-150, distribution—DN 200-350, and main-line DN 400-1,200.

The third studied characteristic was the year of construction of pipeline (C3). The oldest pipelines in Warsaw DHN are from 1950, however, there is a small share of such an old pipelines. Most of the pipelines were built in 70s' and 80s'. Sadly, Warsaw GIS has quite many missing records regarding the year of construction. About 634 km of pipelines (37% of length) have assigned date of construction as Jan. 1st, 1980 and Jan. 1st, 1995, what was by default set for pipelines with missing date. The reason why those dates were selected as default for missing record is that they correspond to average construction date of traditional pipelines (January 1st, 1980) and pre-insulated pipelines (January 1st, 1995). Therefore, there is some inaccuracy, however, it can be partially dealt with by analyzing this characteristic by setting some groups. The groups are as follows: before-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2014. This way, even if a pipeline with unknown year of construction (with set default value, for example, 1995) was build a few years earlier or later, it will still be classified in the same group.

The fourth investigated characteristic was stray current effect on pipelines (C4). On a basis of study conducted by Instytut Elektrotechniki [5], 42 zones in Warsaw were determined, in which there is a higher risk for underground infrastructure of being exposed to stray currents produced by trams. With use of the GIS, the pipelines in those zones were assigned to them. That allowed to calculate how many failures occurred and what was the total length of pipelines in each zone. With this data failure rate was calculated. Moreover, Warsaw DHN is equipped with cathodic protection, which protects parts of network from electrochemical corrosion caused by stray currents. Therefore, failure rate was calculated for: zones equipped with cathodic protection, zones near cathodic protection, zones without cathodic protection and the rest of pipelines outside zones.

The last part of the methodology consisted of investigation of cause of failure on failure rate (D). As it was mentioned, the records of failure protocols have information about the most probably cause of failure: surface corrosion, pitting corrosion, corrosion around the circumferential weld, perforation at the seam of the pipe or nearby, other, and unspecified. By dividing the number of failures of each group of cause of failure by the total length and time, the failure rate was obtained.

3. Failure Rate Approach Results

The step (A) of analysis allowed plotting the change of failure rate in time, what is shown on Fig. 5. In 2006, there was a peak of failure rate, its value was 0.17 (failure/km/year). Such a peak in 2006 was also observed in other DHN networks in Poland. It can be explained by some external global factor like very cold winter [6] which caused extreme operational conditions and forced more failures. Therefore, the failure rate

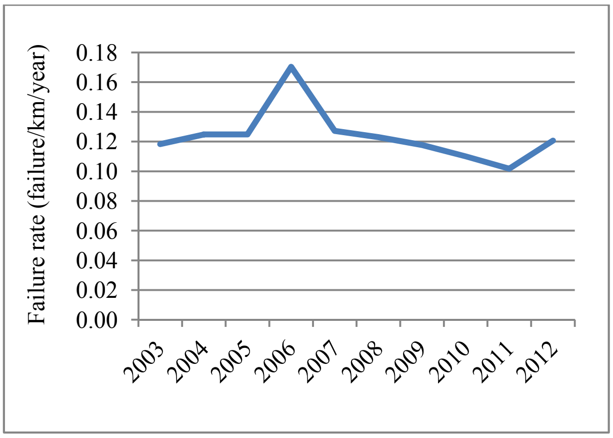

Fig. 5 Change of failure rate in time in years 2003-2012.

Table 2 Number and share of damaged segments of pipeline in years 2003-2012.

Number of failures	Number of segments	Share of damaged segments (%)
9	1	0
8	1	0
7	1	0
6	0	0
5	4	0
4	11	1
3	63	4
2	234	14
1	1,350	81
Total	1,665	

in Warsaw DHN in last 10 years is quite stable and is 0.12 (failure/km/year) on average. Moreover, failure rate for 2012 was also equal to 0.12 (failure/km/year). If Warsaw DHN replaces old pipelines with new ones with the same place as it was in this period of time, and operational conditions will be kept on the same level, it can be expected that, the failure rate will follow this trend.

The part (B) of the analysis showed that, only 1665 (2%) of segment of DHN out of 82,688 had failures between 2003 and 2012. The total length of damaged segments of pipelines was 67 km, what corresponds to about 4% of length of Warsaw DHN. Table 2 shows that the majority (81%) of pipelines which had failure had it only once. Moreover, if one failure have already happened on segment of pipeline there was 14% chance that this segment will have one more failure, and 5% that it will have two or more additional failures (there were only three extreme case which had 9, 8 and 7 failures, respectively). Therefore, the more attention should be put to determining the probability of such an incident.

The results of part (C1) are presented in Table 3. The lowest result which was obtained for overhead pipelines, however, this result should be neglected, because overhead pipelines consist of only 2% of total length of Warsaw DHN and this category is not representative for this network. Therefore, in fact the lowest result was for pre-insulated pipelines and it was equal to 0.02 (failure/km/year). Traditional pipelines have 0.19 and 0.31 (failure/km/year) for pipelines installed in duct channels and in buildings, respectively. This is 10 and 15 times higher than for pre-insulated pipelines, and 1.6 and 2.6 higher than average value for Warsaw DHN. Moreover, traditional pipelines have the highest share of length in Warsaw DHN.

Table 4 contains the values of failure rate for different DN groups (C2). As we may observe the smallest rate was for the main-line and was equal to 0.04 (failure/km/year). Twice higher result was obtained for distribution pipelines, and 4 times higher for the connection pipelines. What is more, the connection pipelines have the highest share of length. It means that, the probability and number of failures for this group is the highest.

Results of part (C3) of analysis are shown in Table 5. Surprisingly, the oldest pipelines do not have the highest failure rate. The highest failure rate is for pipelines build in 70s' due to poor quality of material and poor quality of workmanship, and the value is 0.26 (failure/km/year). Pipelines were built after 1990 have very low failure rate 0.05 and 0.01 (failure/km/year).

Table 3 Failure rate (failure/km/year) per different technology of construction.

Technology	Number of failures	Failure rate
Pre-insulated	111	0.02
Traditional—in building	467	0.31
Traditional—duct channel	1,513	0.19
Overhead	3	0.01

The rest of them are close to the average value for the whole DHN.

Table 6 presents the values of failure rate depending on the influence of stray current (C4). The pipelines outside the zones have the failure on the same level as the average value for the whole Warsaw DHN—0.12 (failure/km/year). Whereas, pipelines in the zones without cathodic protection have slightly higher failure rate—0.13 (failure/km/year). Nevertheless, the pipelines in the zones with cathodic protection have value 0.08 (failure/km/year) and that is significantly lower the average value.

Table 7 contains values of failure rate for different causes of failure (D). As we may observe, the surface corrosion has the highest result 0.07 (failure/km/year). Whereas, pitting corrosion is about half of that value and is equal to 0.03 (failure/km/year), other causes of failure are rather marginal and are 0.01 (failure/km/year) or smaller.

4. Failure Mode and Effects Analysis State of the Art

To better assess failures on the DHN, the idea is to try to use FMEA.

4.1 FMEA Principle

FMEA is an industry recognized tool to plan inspection activities based on relative risk. There are several methods for developing a risk analysis. Whatever method is chosen, it is based largely on feedback from the network operator and, if applicable, the specific characteristics of the assets and their environment.

Table 4 Failure rate (failure/km/year) per different group of DN.

Group of DN	Length (km)	Share of length (%)	Number of failures	Failure rate
Connection	1,090	64	1,780	0.16
Distribution	307	18	209	0.07
Main-line	294	17	105	0.04

Table 5 Failure rate (failure/km/year) per different group of year of construction.

Year of construction		Length (km)	Share of length (%)	Number of failures	Failure rate
From	To				
Before	1970	78	5	110	0.14
1971	1980	550	33	1,409	0.26
1981	1990	251	15	296	0.12
1991	2000	486	29	241	0.05
2001	2013	327	19	38	0.01

Table 6 Failure rate (failure/km/year) for different stray current influence.

Cathodic protection	Number of failures	Length (km)	Failure rate
No	290	217	0.13
Yes	26	32	0.08
Near	22	26	0.08
Outside zones	1,756	1,422	0.12

Table 7 Failure rate (failure/km/year) for different causes of failure.

Cause of failure	Number of failures	Failure rate
Surface corrosion	1,234	0.07
Pitting corrosion	534	0.03
Corrosion around the circumferential weld	75	0.00
Perforation at the seam of the pipe or nearby	27	0.00
Other	139	0.01
Unspecified	85	0.01

The FMEA method includes:

- Analysis of the causes and effects of failure of the various components of a system. Each intervention is listed as a FC (failure case);
- Evaluation of the criticity of different failure modes according to their probability of occurrence and the severity of their effects in the absence of safety barriers;
- Identification and evaluation of the effectiveness of existing safety barriers or implementation such barriers which reduce the criticity of failure modes to a level considered as acceptable. There may be barriers to prevent the occurrence of the event generating the hazard and/or barriers to limit, reduce or avoid the consequences of this event.

Among the Fedene-SNCU (Syndicat National du Chauffage Urbain et de la Climatisation Urbaine) [7], the occurrence and criticity scores are define as follow in Table 8 but can also describe using other more quantitative criterions as in oil and gas industry (Tables 9 and 10).

In France, a new policy implies to use FMEA method with design rules from January 1st, 2014 for DHN [8].

A RPN (risk priority number) can be define multiplying occurrence and criticity scores (Eq. (1)) and is estimated for each FC.

$$\text{RPN} = \text{Occurrence} \times \text{Criticity} \quad (1)$$

Indeed, in this method, occurrence and criticity of failure are considered simultaneously as shown in Fig. 6. Thus, for each failure case, RPN is placed on a four by four matrixes (Fig. 6) which visually represents on which assets focus effort and on which assets inspections can be reduced. Fedene-SNCU considers that the risk is acceptable if RPN ≤ 4 [7].

We propose to add another acceptance criterion in order to be less critical. Thus, as shown in Fig. 6:

- If RPN ≤ 4, the risk is acceptable;
- If 4 < RPN ≤ 8, the risk is high but can be acceptable depending if the failure mode only led to an economical loss and don't include human injuries or death;
- If RPN ≥ 9, the risk is very high and not acceptable.

4.2 FMEA Methodology

Before to start to develop FMEA, occurrence and consequences seen in Table 8 should be refined by project team (Tables 9 and 10 [9]) according to mean time between failure, Probability, economic loss, health and safety, environment. Each parameter depends on network size.

Then, the main different steps in a FMEA study are listed below:

- Standardize database: first of all, technical team

Table 8 Probability and criticity scores.

Score	Occurrence	Criticity
1	Not known or low occurrences (relatively few failures) on similar assets	Low: no impact or low impact on the distribution of heat
2	Moderate (occasional failures)	Major: no distribution
3	High (repeated failures)	Critical: no distribution and degradation of surrounding facilities
4	Very high (failure is almost inevitable)	Catastrophic: no distribution and endangering workers or the public

Table 9 Example of occurrence scores regarding number of failures.

Score	Occurrence	
	Mean time between failures	Probability
1	> 50 years	Unlikely: < 1%
2	10-30 years	Possible: 1%-5%
3	3-10 years	Probable: 5%-10%
4	< 3 years	Expected: > 10%

Table 10 Example of criticity scores regarding impact of failures.

Score	Criticity		
	Economic loss	Health & safety	Environment
1	< 0.5 k€	First aid	Neglecting impact
2	0.5-1 k€	Lost time accident	Spill contained
3	1-10 k€	Permanent disability	Inside fence damage
4	> 10 k€	One or several fatalities, life-threat illness	Off-site damage, long time effect

Table 11 FMEA results on valve family.

Failure case Nb	Date	Asset	Criticity	Occurence	Criticity rate	Occurence rate	Priority risk number
FC1	2009	Ball valves	Major	High	2	3	6
FC2	2009	Valve	Catastrophic	Moderate	4	2	8
FC1	2010	Ball valves	Major	High	2	3	6
FC2	2010	Valve	Critical	Very high	3	4	12
FC3	2010	Valve vents	Low	Low	1	1	1
FC1	2011	Ball valves	Catastrophic	Moderate	4	2	8
FC4	2011	Valve flange	Major	Moderate	2	2	4
FC3	2011	Valve vents	Major	Moderate	2	2	4
FC5	2012	Drain valve	Major	High	2	3	6
FC2	2012	Valve	Catastrophic	Low	4	1	4
FC6	2013	Stop valve	Catastrophic	Moderate	4	2	8

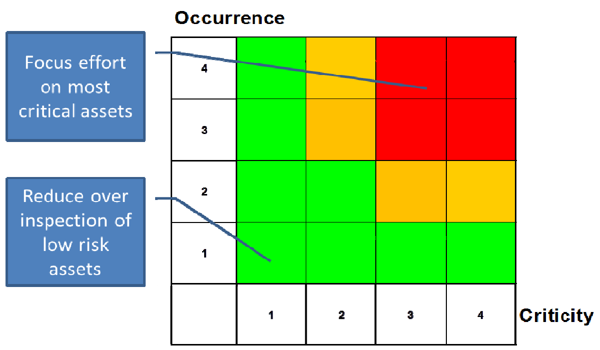

Fig. 6 Occurrence and criticity of failure's matrix.

needs to standardize database with same vocabulary for assets, failure modes, causes, solutions and numerical data;

- Identify and quantify failure cases: engineers identify and quantify main failure cases using failure modes, causes and solutions;
- Identify and benchmark solutions applied: engineers and managers identify best solutions to fix failures and evaluate long term impact of the solutions applied.

4.3 FMEA Results

First of all, the engineer identifies with his team all the scenarios which happened during the operating period and assign a FC number for each one. But the more failure cases are listed the more accurate and the better interpretation of FMEA results will be.

Here, only FC on valve family from 2009 to 2012 coming from a failure case database are represented. Using the database, FMEA is established on a first year before to evaluate the solutions impacts on the following years (Table 11). Then, we put the RPN in different FMEA grids which show risk for all valves and the evolution along the years (Fig. 7).

In this case, solution applied is replacement for all assets but seems to not have such a positive impact on RPN. Indeed, in 2010, the RPN for FC1 does not decrease furthermore the RPN for FC2 increase and a third FC appears. It is interesting because it means that solutions applied were not efficient. In 2011 and 2012, even if some new FCs appear (FC4, FC5 and FC6), the solutions decrease the RPN for previous FCs (FC1 and FC2).

5. Outlook

We present some methodologies and first results on

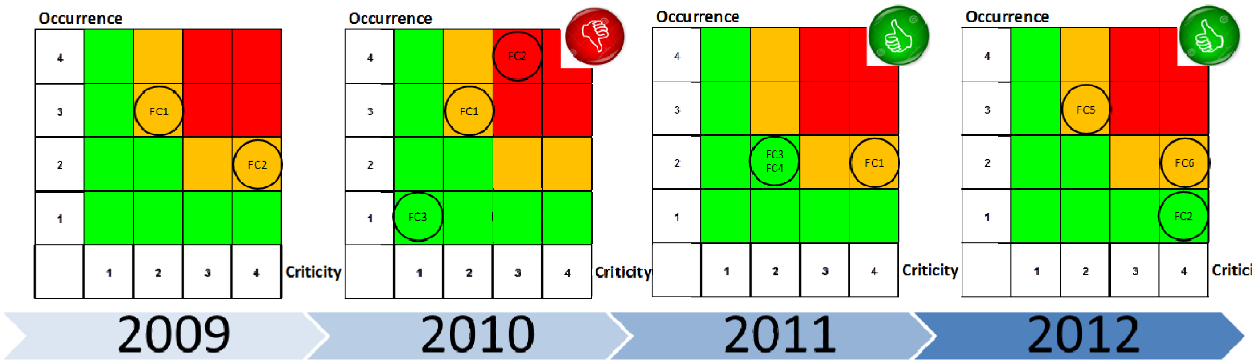

Fig. 7 RPN evolution on valve family.

how to assess DHN. This is only the first part of a bigger study in which we will use these tools to try to make more reliable DHNs.

6. Conclusions

DHN is constituted of both pipes and assets which age and need to be repaired or replaced during their operating life.

In order to invest time and money as wise as possible, it is very important to choose were and how plan interventions on the DHN.

Failure rate give quantitative information about network evaluation along the years whereas FMEA leads to make some priority between asset families.

The key to better manage DHN is to find the best criteria to evaluate efficiency of solutions applied to fix asset for each DHN regarding their own parameters.

Thus, FMEA dynamic approach is very interesting to see impact of solutions applied to fix asset all along the years. As seen in this study, FMEA is clearly adapted to DHNs because it aims to focus on risker equipments and to benchmark solutions in the past to find the best solutions for the next interventions according:

- cost;
- water and energy loss;
- others key performance indicators.

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