FMEA for hydropower:
Lessons learned and future advancements

Davide Cazzago
Frosio Next S.r.l.
Via Corfù, 71
25124 Brescia
Italy

Luigi Lorenzo Papetti
Frosio Next S.r.l.
Via Corfù, 71
25124 Brescia
Italy

Beatrice Baratti
Frosio Next S.r.l.
Via Corfù, 71
25124 Brescia
Italy

It was 2018 when Frosio Next (at that time, Studio Frosio) started developing a *failure mode and effect analysis* (FMEA)-based approach for risk assessment of hydropower components. It was the first time that the well-known FMEA methodology, widely used throughout the aeronautical, automotive, software, food services, health care and many other industries which have a huge set of data concerning the failure mode of their products, was applied to the hydropower sector. Frosio Next has used the FMEA methodology, combined with more than 40 years of experience in the hydropower field, and it has devised a procedure aimed at programming and scheduling the maintenance activities of civil and hydraulic works and infrastructures as well as the mechanical and electromechanical components of an hydropower plant, based on the risk assessment. The target was to provide a general overview of the plant with a focus on the management issues and on the level of risk through the identification of the most critical plant components and the intervention priorities, the plant components to be monitored over time and those that do not need maintenance.

During the last four years, this method has been applied to two real cases: the first one, unfinished, performed at the very beginning of the challenge and the second one, successfully completed last year.

The definition of the method, the degree of detail of the analysis and the ranking adopted for the parameters of the model in the two case studies are presented and critically compared in the paper. The methodology of action adopted that made it possible to overcome the criticalities that drowned the first attempt are presented and discussed as well as the compromises that we had to accept are clearly stated and analysed.

The proposed method revealed quite easy to implement and not too time consuming.

The method proved to be a valid decision-making tool, well accepted by the plant's owners. On the other hand, the subjectivities of the methods are still a critical open issue. The outcomes of the case studies allowed for the critical review and for a further optimization of the proposed method.

1. The methodology

The proposed method is based on the well-known FMEA (Failure Mode and Effects Analysis) methodology.

The FMEA methodology is widely used in several industries in order to assess the failure modes of a process, a product or system. For each identified failure mode, the potential effects, the causes and the detection controls are identified. The potential effects, the causes and the controls associated to each failure mode are expressed by means of three different parameters, respectively: the severity (how severe the effects are), the occurrence (how frequently the causes happen) and the detection (how easily the failure can be detected). These parameters are quantified by means of a score, from 1 to 10. The product of these 3 parameters leads to the computation of the Risk Priority Number (RPN) index, by means of which the level of risk is identified.

The RPN is computed for each cause of each failure mode. Then, the global risk level of a specific failure mode is associated to the maximum RPN computed. Therefore, the FMEA methodology is particularly suitable for quantifying the risk associated to a potential failure mode within a complex system such as a hydropower plant.

In fact, a hydropower plant is a set of components functionally connected to transform the water resource into energy. The scope of the method is to analyze each component of the plant and to identify the failure modes which could affect the way they work and their interconnection with the other components of the plant. Thus, for each potential failure mode, the effects it could produce, the causes which lead to the failure and the existing controls which are able to foresee the failure before it happens (or to detect it once it has happened) will be quantified.

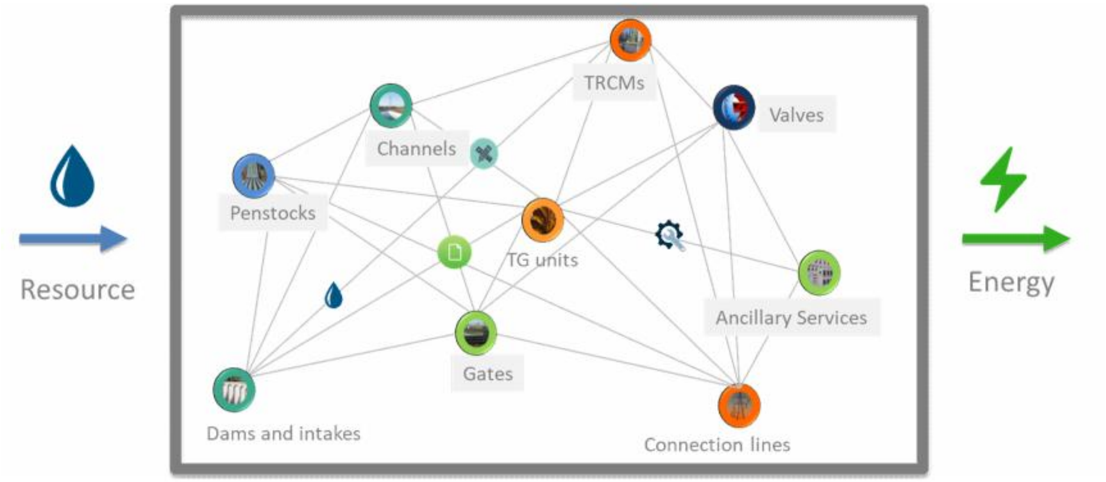

Fig. 1. Scheme of a hydropower plant

By means of the computation of the Risk Priority Number (RPN), based on objective indicators and criteria, the method leads to the evaluation of the priority of action to be undertaken on the hydropower plant in order to improve the efficiency, reliability and safety of the entire energy production process.

1.1 The structure

The service is based on the following steps.

- **Plant's visit**:
  In this preliminary phase, the target is to perform an in-deep analysis of the plant's scheme, identifying its components and their interconnections.
- **Data analysis**:
  Taking into consideration the information gathered during the plant's visit, as well as the information coming from the literature, the identification of the potential failure modes is performed. Furthermore, for each identified failure mode, the potential effects, the causes and the detection controls are identified.
- **Preliminary RPN computation**:
  The potential effects, the causes and the controls associated to each failure mode are ranked by means of a score, from 1 to 10 for the parameters related to occurrence, severity and detection. The RPN is computed as the product of these 3 parameters.
- **Plant personnel involvement**:
  Within this stage, the outcomes are shared with the plant's personnel in order to take the expertise coming from the plant's management into consideration. In this regard, the preliminary values of occurrence, severity and detection are reviewed.
- **Definition of the alert thresholds**:
  The thresholds of alert are defined beyond which the risk associated to a possible failure mode leads to the need to carry out monitoring campaigns in order to keep the status of the component under control or to undertake actions to reduce the risk according to the priority set by the RPN.
  According to the resulting risk level, either some corrective actions could be taken in consideration in order to lower the global level of the risk associated to the failure mode, or the risk associated to the failure mode could lead to the need to carry out monitoring campaigns, with the aim of better knowing the status of the component.

1.2 The decision-making parameter

The RPN (Risk Priority Number) is the quantitative decision-making parameter used for the categorization of the failure modes and for the identification of the priority of the potential actions.

For each cause of failure mode considered, the RPN index is computed as the product of Occurrence, Severity and Detection:

$$\mathbf{RPN = O \cdot S \cdot D}$$

The risk associated to a specific failure mode is the maximum value of RPN computed for each cause.

1.2.1 Parameters' scores

The attribution of a score to each parameter is based on quantitative and semi-quantitative indicators.

Severity

The severity of the effects of each failure mode is evaluated taking into consideration the following indicators:

- Production losses
- Safety of the plant and of third parties
- Need and urgency of the maintenance

Occurrence

In the hydropower sector, a consistent lack of information regarding failures can be experimented due to the inclination of owner, constructor and manufacturer not to share information regarding failures in their plant. Additionally (fortunately), the number of failures in the hydropower sector are not so many as to provide a solid sample that could justify a statistical analysis.
The lack of these information affects the determination of the occurrence which is generally performed according to statistical analysis based on the number of failures over the number of pieces realized. To overcome this problem for each of the identified causes, the occurrence has been computed according to the following indicators:

- Plant's personnel reactions
- Previous knowledge of similar events (occurred in the past or descripted in literature)
- Maintenance status
- Service life of the component

Detection

Detection is linked to the effectiveness of the controls to detect the conditions that lead to the activation of the failure mode.
The quantification of this parameter is based on the probability that the existing controls are able to detect the failure mode before it happens or once it has happened.

1.3 Alert's thresholds

The need to undertake actions to increase safety, efficiency and reliability conditions is evaluated through the introduction of two thresholds - Attention and Warning – based on the RPN (Risk Priority Number) values.
The flexibility of the model allows to set the thresholds according to the plant's owner perception to the risk (e.g. bounded by a lack of production) without affecting the safety of the plant which is always preserved.

Attention's threshold: below the attention's threshold, the risk associated to the possible failure mode is acceptable. It is not necessary to investigate the state of the component.
Above this threshold, and until the warning threshold is reached, the risk associated to the failure mode leads to need to carry out continuous or spot monitoring campaigns, with the aim of better knowing the status of the component.
Warning's threshold: once this threshold will be exceeded, the risk level associated to the possible failure mode is not acceptable, and it is necessary to carry out actions aimed at reducing the risk level.

Fig. 2. RPN's thresholds

2. Case studies

The method described in the paragraphs above has been applied to two different case studies. The main difference in the application of the method concerns the degree of detail of the analysis.

- Case study no. 1: in 2019, the first application of the method took place for an hydropower plant located in Northern Italy. The first experience didn't lead to the expected results due to the fact that the plant has been analyzed going into too much detail (***Fig. 3***). It means that it has been subdivided into macro sub-systems (i.e. intake's weir), subsequently for each macro sub-system, all its components (e.g. flap gate) have been analyzed in a very thorough way up to the identification of each single element (e.g. hydraulic power unit). Furthermore, the functional interconnections among the elements have been taken into consideration. This in-depth analysis led to the identification of a huge number of potential failure modes (**570**). The identification of these failure modes, as well as the investigation of their causes, effects and detection systems has required copious and specific information concerning the plant's elements assessed and their interconnections. It resulted in a huge amount of data, too difficult to manage, which affected the global overview of the plant's problems. On the other hand, the specificity of the information required made it difficult to obtain it, due to the fact that even the plant's owner doesn't have such detailed information.

Another aspect which made this application hard to be carried out concerns the data management. For the first application of the method, the collected data have been managed by means of Excel sheets which proved to be unsuitable to manage such a huge amount of data.

Finally, in order to preserve the objectivity of the method, the client has been minimally involved. This fact led to a loss of focus on the real plant problems.

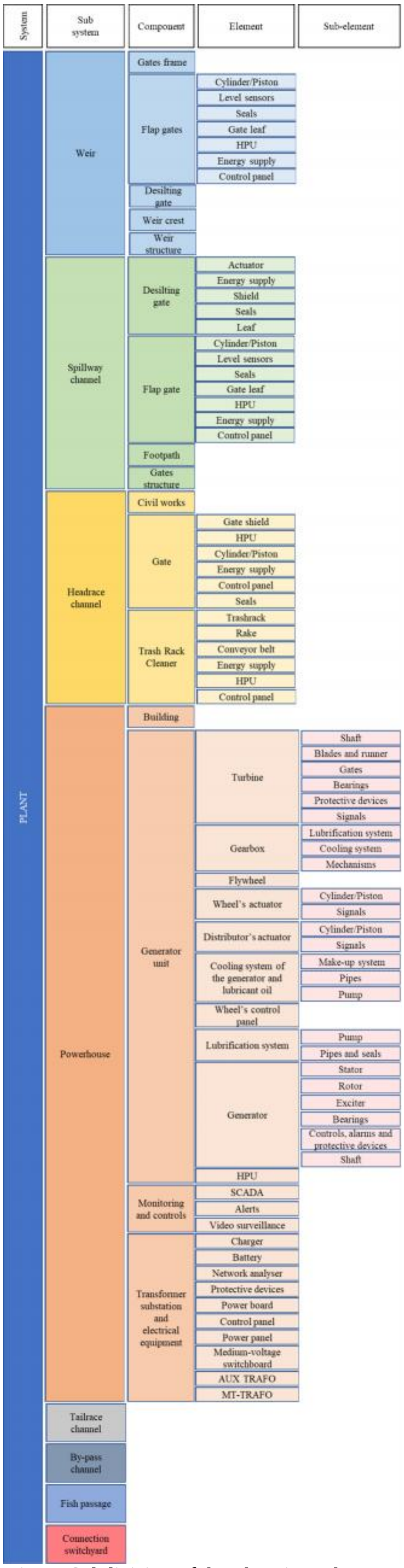

Fig. 3. Subdivision of the plant into elements

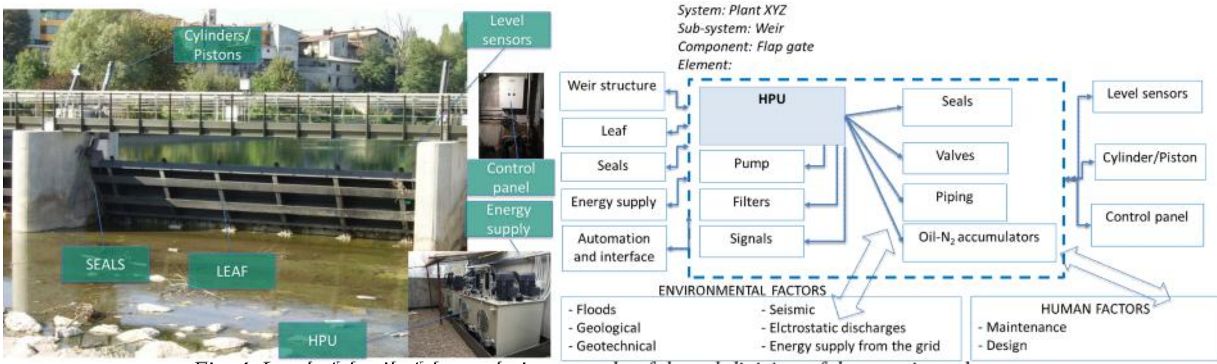

Fig. 4. Level of detail of the analysis: example of the subdivision of the gate into elements

- Case study no. 2: in the same year (2019), the application of the method for another plant located in Northern Italy has been performed.

Following the previous experience, the degree of detail with which the plant has been analyzed, has been reduced (***Fig. 5***): the macro sub-systems have been identified in a more general way (e.g. intake) and the analysis stopped with the identification of the components which make up the macro sub-systems (e.g. weir) while the elements which make up the single component haven't been taken into considerations. As for the first case study, the functional interconnections among the components have been analyzed.

During this task, the plant's owner has been involved starting from the early stages, in order to focus on the real plant's problems leading to the identification of the plant's components which could really be affected by failures, as well as the identification of the real events which potentially could happen on the plant. Once the components have been identified, for each of them the potential failure modes have been selected according to the plant's owner. The potential failure modes assessed were **194**.

Additionally, the parameters' ranking has been set according to the risk perception of the plant's owner, always complying with safety requirements.

Of course, the advantage of this approach is related to the fact that the expertise of the plant's owner can direct the expert's efforts to the real plant problems. Therefore, the subdivision of the plant into components has been less detailed, leading to a best global overview of the plant. Less components to be analyzed means, as a consequence, less data to be managed. This approach has led to the identification of the most critical components of the plant. Subsequently, a further step of the analysis could be the assessment of all the elements which make up the most critical component of the plants. It means to consider the elements of the most critical component only, not all the elements of all the components. And it allows to have a limited amount of data to be managed.

Finally, thanks to the experience of the first application, an adequate tool for the implementation of the FMEA methodology has been purchased. It allowed to easily manage the amount of data coming from the analysis of the plant. Moreover, this reduced the working time and led to a clearer overview of the plant's problems.

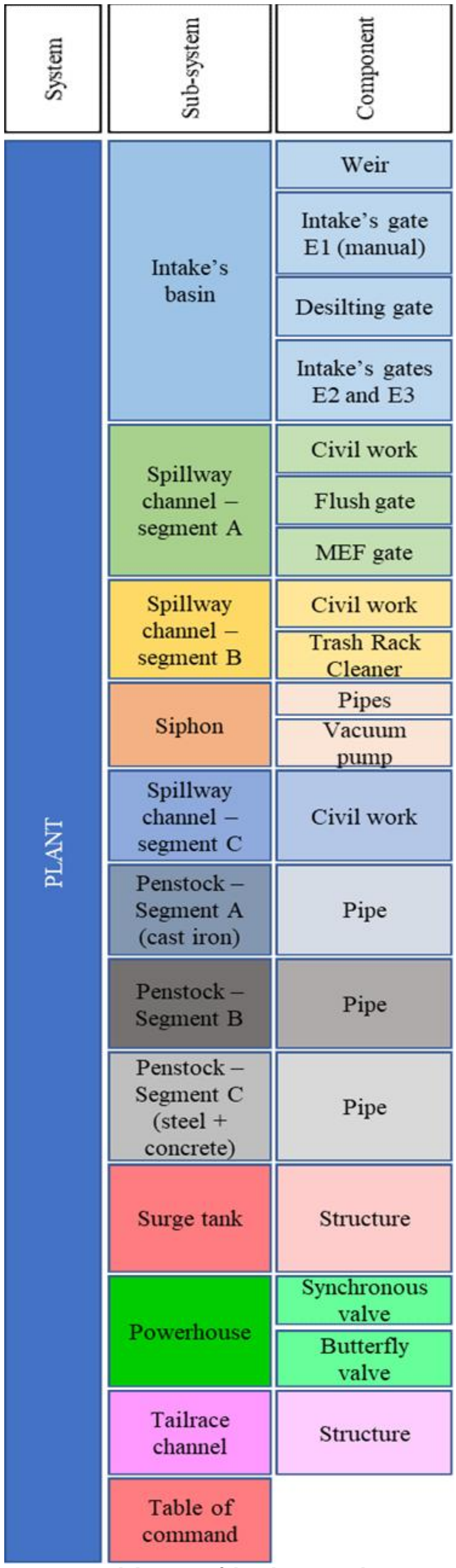

Fig. 5. Subdivision of the plant into elements

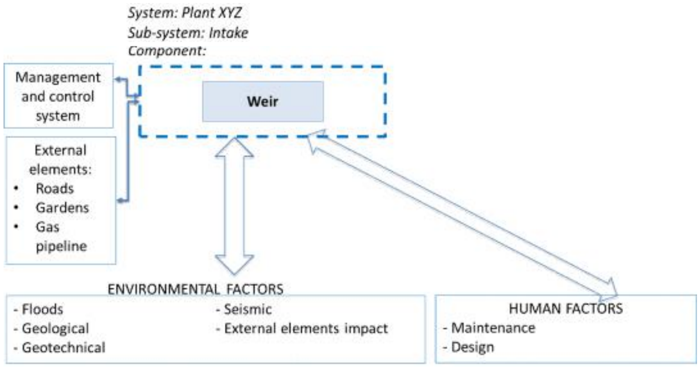

Fig. 6. Level of detail of the analysis: example of the subdivision of the intake into components

3. Conclusions

The main differences between the two applications of the method are listed in Table 1.

	1st application	2nd application
Analyzed plant's parts	75	20
Computed RPNs	570	194
Tool used for the analysis	Excel	Adequate tool for the implementation of the FMEA methodology
Owner's involvement	Only at the end	Starting from the beginning

Table 1 Main differences between the two applications of the method

Even if the first application of the method reflects most the FMEA methodology, the subdivision of the plant up to the identification of the specific elements which make up each component requires to gather a huge amount of data, too specific and hard to find due to the fact that in most cases such data are only available to the constructor of the element who barely allows to share them. Furthermore, this huge amount of data which is hard to manage, especially without a specific tool for data management, diverts the focus from the real problems of the plant.

The second application of the method, thanks to the more suitable degree of detail, led to several advantages which made this application a success. Firstly, since the subdivision of the plant went less into detail, the amount of data required is less than the amount of data needed in the first attempt. This results in an easier management of data. On the other hand, the required data are less specific, since they refer to macro components of the plant, and their information are easily retrievable from the plant's owner. Additionally, in order not to lose the focus on the real plant's problems, this application shows the importance to involve the plant's owner since the preliminary steps, starting from the subdivision of the plant. This allows to take into consideration the events which most likely occur on the plant and to identify the failure areas and the failure modes, avoiding wasting time and efforts on improbable events.

These two examples of application of the method clearly shows the need to have a suitable tool of data management, especially in case of a huge amount of data.

Another important aspect to be taken into consideration is the time needed in order to perform the analysis. In the first case, the identification of all the elements which make up the components of the whole plant and subsequently the collection of the required information took a long time. As well as the definition of the failure modes, the effects, the causes and the detection controls were very time-consuming. Finally, the elaboration of the data required time and efforts. And time and experts' efforts stand for money, leading to consider the service not suitable for the market. On the other hand, the degree of detail used in the second case led to a decrease in terms of time for carrying out the service, which made it affordable. As a further proof of this fact, currently this method is going to be applied for two other hydropower plants.

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The Authors

B. Baratti: graduated in Hydraulic Engineering from the Polytechnic University of Milan and joined Frosio Next (originally, Studio Frosio) in 2019. She has been involved in pre-assessment of hydropower plant components in Northern Italy. She is currently involved in an international project funded by the European Commission as project manager for Frosio Next.

D. Cazzago: Mr Cazzago is a Civil and Environmental engineer specialized in hydraulic and hydrology. In Frosio Next he developed extended experience in design and construction of small hydropower plants.
He held the position of hydraulic specialist performing analysis on hydrological data, hydraulic simulations (1 and 2D) and hydraulic design of hydropower plants. Later, he held the position of project manager and coordinator being responsible of several project, in Italy and abroad, especially in Georgia, Africa and in the Balkan areas.
Recently he carried out several due diligence and risk assessment on hydropower project and existing plants.
Currently he is Business Developer of Frosio Next and responsible for New Products focusing his activity mainly on foreign market. From 2018 he is also student assistant at the University of Brescia for hydrology courses from 2018.

L.L. Papetti: Mr. Papetti is a long-time member of Frosio Next (formerly Studio Frosio) since 1990. Holding a M. Sc. degree in hydraulic engineering and being specialized in hydropower plants and hydraulic works, he is currently CEO and CTO of Frosio Next. During his career he gained a wide experience both in the refurbishment of existing plants and in the design of new ones. As ELMEC expert he prepared hundreds of technical specifications.