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A Concept of Risk Prioritization in FMEA Analysis for Fluid Power Systems

Joanna Fabis-Domagala [1], Mariusz Domagala [1,*] and Hassan Momeni [2]

[1] Faculty of Mechanical Engineering, Cracow University of Technology, Al. Jana Pawla II 37, 31-864 Cracow, Poland; joanna.fabis-domagala@pk.edu.pl
[2] Department of Mechanical and Marine Engineering, Western Norway University of Applied Sciences, N5020 Bergen, Norway; Hassan.Momeni@hvl.no
* Correspondence: domagala@mech.pk.edu.pl

Abstract: FMEA analysis is a tool of quality improvement that has been widely used for decades. Its classical version prioritizes risk of failure by risk priority number (RPN). The RPN is a product of severity (S), occurrence (O), and detection (D), where all of the factors have equal levels of significance. This assumption is one of the most commonly criticized drawbacks, as it has given unreasonable results for real-world applications. The RPN can produce equal values for combinations of risk factors with different risk implications. Another issue is that of the uncertainties and subjectivities of information employed in FMEA analysis that may arise from lack of knowledge, experience, and employed linguistic terms. Many alternatives of risk assessment methods have been proposed to overcome the weaknesses of classical FMEA risk management in which we can distinguish methods of modification of RPN numbers of employing new tools. In this study, we propose a modification of the traditional RPN number. The main difference is that severity and occurrence are valued based on subfactors. The detection number remained unchanged. Additionally, the proposed method prioritizes risk in terms of implied risk to the systems by implementing functional failures (effects of potential failures). A typical fluid power system was used to illustrate the application of this method. The method showed the correct failure classification, which meets the industrial experience and other research results of failures of fluid power systems.

Keywords: FMEA; risk analysis; fluid power systems

Citation: Fabis-Domagala, J.; Domagala, M.; Momeni, H. A Concept of Risk Prioritization in FMEA Analysis for Fluid Power Systems. *Energies* **2021**, *14*, 6482. https://doi.org/10.3390/en14206482

Academic Editors: Ryszard Dindorf, Jakub Takosoglu and Piotr Wos

Received: 19 August 2021
Accepted: 2 October 2021
Published: 10 October 2021

1. Introduction

Fluid power systems find wide industrial applications as drive or control systems. Due to their advantage, they can perform various functions, including those that may directly impact human safety or as a crucial component in applications that require high reliability. They have been used in aerospace applications as a vital component of aircraft, rockets, and spaceships to actuate critical flight components: actuating flaps, brakes, and landing gears, opening/closing doors, etc. The marine industry uses hydraulics for controlling ships and deck appliances such as winches, cranes, or hatch covers. They found applications in metal making machinery, in production lines, as presses, or other machine tools. They are broadly used in mobile machinery such as cranes, excavators, earth-moving equipment, and automobiles. The mining industry utilized hydraulics in drilling equipment for oil and gas extraction. The energy industry employs hydraulic systems in control systems of wind and water turbines and other processes. Depending on the applications, they can have different levels of complexity and use purely mechanical–hydraulic or electromechanical–hydraulic systems. High power density and almost unconstrained flexibility are the main advantages of these systems, making them peerless to mechanical or electrical power systems. Fluid power is not a new technology, but, complemented with the electronic control system [1], it offers new possibilities and can be one of the leaders among drive systems. Fluid power systems and their components must be highly reliable, their potential failures must be recognized early and investigated, and corrective plans must be prepared. Research on their failures and reliability is conducted using qualitative and quantitative tools and methods individually or together [2–4]. One of the widely used methods is the FMEA (failure modes and effects analysis). The origin of the FMEA analysis is dated to the 1950s when it was formalized in the military standard [5]. It found practical application during the NASA Apollo mission and in the automotive industry in the 1980s and finally became a part of international standards: ISO 9000 and SAE 1793 [6]. The FMEA method was an inspiration for other methods and tools such as RCM (reliability center management), concept FMEA and FMEDA [7].

One of the steps of FMEA analysis is a risk evaluation, which, in its conventional form, is calculated using three risk factors: severity (S), occurrence (O), and detection (D). Severity is defined as the ranking of the end effect of failure mode to the system. Occurrence is defined as the likelihood of failure occurrence. Detection is the possibility of failure detection. These risks factors are quantified by experts with integer numbers from 1 to 10 each. The risk of individual failure mode is evaluated using risk priority number (RPN), which is a product of the aforementioned risk factors. A higher RPN value defines a higher risk of related failure modes. However, this approach is widely questioned due to several limitations. The equally weighted risk factors may produce the same RPN number for various combinations of S, O, and D, which may have different risk implications. The utilization of only three factors and related failure modes is also criticized as ineffective. Another problem of conventional FMEA is data uncertainty and subjectivity. All information in FMEA analysis is delivered by a group of experts who have to assign linguistic terms to exact numbers and rely on their own knowledge and experience. All shortcomings of traditional FMEA analysis are widely summarized in previous work [8]. To overcome the FMEA drawbacks, alternatives methods are implemented. The systematic literature review of employed methods was presented by Liu et al. [9]. The main trends which are observed to overcoming drawbacks of traditional FMEA are:

1. Modification of classical RPN by implementing customer perspective [10], performing risk evaluation in terms of risk factors and their implication to risk scenario [11], other factors [9].
2. Extension of S, O, D with new factors e.g.:
   - expected cost [12];
   - corrective actions [13];
   - maintainability criticality index [14];
   - division of the main risk factors into subfactors [15].
3. Implementing risk factors weights: [16,17].

Risk assessment is performed by different methods and with the utilization of various tools. The most common methods that concurrently resolves problems with information uncertainty are:

1. Fuzzy set theory: [18–20];
2. Reasoning theory: [21,22];
3. Linguistic theory: [23,24];
4. Grey theory: [25,26].

The FMEA is a hierarchical multicriteria decision-making (MCDM) process that can utilize decision-making tools. Literature review indicates that the following methods mainly find application in risk analysis:

1. Distance-based methods:
   - distance operator;
   - technique for order of preference by similarity to ideal solution (TOPSIS) [27];
   - multiattributive border approximation area comparison (MACBAC) [28];
   - shortest distance algorithms [29].
2. Piecewise comparison method (analytical hierarchy process: AHP and others).

3. Aggregation operator-based methods.
4. Relation analysis methods.

The drawbacks of FMEA analysis were not only recognized by scholars but also by industry, which led to employing ACP (action priority number) in FMEA analysis in the latest automotive standard [30].

Although many attempts have been made and new methods implemented to defeat the weaknesses of classical RPN, a risk assessment in FMEA is still a challenge. All information used in FMEA is delivered by experts who have to rely on their knowledge and/or experience what along with linguistic evaluation methods that can lead to a high level of uncertainty and subjectivity. It also implies that the results of FMEA analysis are unique for specific problems and can not be extended on similar cases. Methods proposed by scholars are too complex or computationally intensive to be employed in the practice. To overcome the aforementioned shortcomings, we proposed a method that combines known methods as a division of severity and occurrence into subfactors and risk prioritization based on associated risk to the system. The severity in the proposed method is calculated based on component importance, failure effect, and factor, which define a relationship to the other failures. The occurrence number was replaced by a failure predictor, which uses a base failure rate, and modification factors, which take into account the influence of size, load, working conditions, and operating time. The detection number is estimated in the traditional way. Risk is evaluated for classified functional failures that directly correspond with system risk. The proposed method is analogous to the conventional FMEA, easy to use, and can reduce uncertainties of severity and occurrence caused by expert subjectivities.

2. Methodology

2.1. Assumptions

The primary purpose of this study was a qualitative analysis of failure modes, failures, and their end effects for fluid power systems. Failures in fluid power components are complex, and primary failure may only trigger the final failure. In this method, only primary forms of failures were assumed. The analysis was carried out only for primary mechanical failures. The electrical components were omitted.

Investigated fluid power system utilizes typical components for mobile fluid power systems without any diagnostic systems. The primary form of failure detection is a visual inspection. Additionally, access to system components is relatively easy and can be compared to a hydraulic system for mobile machinery (e.g., excavator).

We assume that investigated system already exists and only a few essential data are available.

2.2. Method

In the presented method, we define criticality C_R in a similar way to traditional risk priority number (RPN) as a product of severity S, a failure predictor P, and detection D:

$$C_R = S \cdot P \cdot D \tag{1}$$

where $S = c_i \cdot c_e \cdot f_i$, $P = \lambda_b \cdot m_f \cdot t_f$. All three are valued with numbers from 1 to 20.

We can calculate severity S as a product of component importance c_i, failure which can appear in the component f_i and modification factor c_e:

$$S = c_i \cdot c_e \cdot f_i \tag{2}$$

Component importance c_i defines how an individual component is important to the system for a specified criterion. It can be safety or ability to perform the specific function. We assumed that components are valued in the way similar to that which was presented in our previous study [31]:

- Main components. They are essential for performing the intended function.

- Major components. They ensure the proper operation of the system. Their possible failures may cause the system to malfunction, but its main task is still maintained.
- Additional components. Their failure has little effect on the main task of the system.

The component importance c_i reaches values 1–4, where 1 is the lowest importance.

Failure f_i describes the final effect that failure brings in the component. Potential failures were classified and valued in the following way:

- Catastrophic: major damages with component destruction–4.
- Critical: component malfunction with severe damages–3.
- Marginal: component malfunction with minor damages–2.
- Minor: less than minor damages–1.

Modification factor c_e is an influencing factor that tells which component may influence others in the system in case of failure. It reaches value 1–1.25, where value 1 means that potential failures in the component do not influence others. Failure predictor P is expressed as:

$$P = \lambda_b \cdot m_f \cdot t_f \tag{3}$$

where λ_b is a base failure rate, m_f is failure modification factor, t_f is a time factor.

$$m_f = s \cdot p \cdot t_e \cdot w_e \tag{4}$$

We utilize the failure rate value that is commonly used in reliability and maintainability to rank components in the system. We assumed that the failure rate for individual components is the estimator of its possible failure. The real value of base failure rates for the system components [32] were assigned to individual components and renormalized to scale 1–5. Value 1 indicates a component that unlikely fails, while 5 indicates a component with highly expected failure. The value of failure rate for fluid power components according to handbook [32] depends on the following:

- Size (s).
- Operating pressure (p).
- Leakage value (t_e).
- Temperature.
- Fluid contamination.

Factors "Temperature" and "Fluid Contamination" were joined to one factor, "Environment" (w_e), which considers working conditions as an equivalent of both. Besides primary and internal (in-operation) oil contamination, the ingressed (or external) contamination is also recognized as one of the main sources as states by industry [33–35].

To include the above factors, we implemented an equivalent scale defined in the following way:

- Very high.
- High.
- Moderate.
- Minor.

Due to components' different structures and performed functions, we can not use one uniform evaluations scale. However, the scale mentioned above was adapted to the individual features of the components. Factor "Size" for hydraulic pumps depends on their volumetric displacement:

- Very high, volumetric displacement > 125 dm^3.
- High, volumetric displacement 80–125 dm^3.
- Moderate, volumetric displacement 21–79 dm^3.
- Minor, volumetric displacement 1–20 dm^3.

Factor "Size" for hydraulic actuators depends on their piston diameter:

- Very high, piston diameter > 200 mm.
- High, piston diameter 160–200 mm.

- Moderate, piston diameter 41–159 mm.
- Minor, piston diameter < 40 mm.

Factor "Size" for valves depends on their nominal size:

- Very high, nominal size > 16 mm.
- High, nominal size 12–16 mm.
- Moderate, nominal size 6–10 mm.
- Minor, nominal size < 6 mm.

Factor "Size" for accumulators depends on their nominal volume:

- Very high, nominal volume > 50 dm^3.
- High, nominal volume 24–49 dm^3.
- Moderate, nominal volume 6–23 dm^3.
- Minor, nominal volume < 6 dm^3.

Factor "Size" for pipes and hoses depends on their nominal or outside diameter:

- Very high, pipe outside diameter > 30 mm, hose nominal diameter > 38 mm.
- High, pipe outside diameter 22–30 mm, hose nominal diameter 20– 32 mm.
- Moderate, pipe outside diameter 12–20 mm, hose nominal diameter 10–16 mm.
- Minor, pipe outside diameter <12 mm, hose nominal diameter <10 mm.

Factor "Operating pressure" was defined in the following way:

- Very high, operating pressure > 50 MPa.
- High, operating pressure 21–49 MPa.
- Moderate, operating pressure 6–20 MPa.
- Minor, operating pressure < 6 MPa.

Factors "Leakage" is directly connected with manufacturing aspects (tolerances, surface quality, manufacturing methods, materials) and is described as:

- Very high, very high tolerances and surface finishing for providing internal tightness: piston pump, slide-type valves.
- High, high tolerances and surface finishing: gear and vane pumps, poppet-type valves, hydraulic actuators.
- Moderate, higher than typical manufacturing requirements: pipes, hoses, accumulators.
- Minor, typical manufacturing requirements: tanks, filters.

The factor "Environment" is defined in the following way:

- Very high, extreme dusty or chemically aggressive environmental conditions with large temperature variations.
- High, dusty environment, temperature variations.
- Moderate, moderate environmental conditions.
- Minor, small influence of environmental conditions.

In general, we can calculate the failure rate for the system based on the failure rate of system components [36]. For a serial system, the total reliability is a sum of the failure rate for individual components:

$$\lambda_b = \sum_{i=1}^{n} \lambda_i \tag{5}$$

For a parallel system, it is a product:

$$\lambda_b = \prod_{i=1}^{n} \lambda_i \tag{6}$$

For the majority of fluid power components, base failure rate λ_b is available [32]. The failure rate for the accumulator can be calculated as a sum of individual components (as a serial system):

$$\lambda_b AC = \lambda_{bSSE} + \lambda_{bSP} + \lambda_{bPC} + \lambda_{bV} + \lambda_{bCW} \tag{7}$$

where λ_{bSSE} is a failure rate for static sealing, λ_{bSP} is a failure rate for spring, λ_{bPC} is a failure rate for piston–cylinder interface, λ_{bV} is a failure rate for valve, and λ_{bCW} is a failure rate for cylinder wall.

For a diaphragm-type accumulator, the failure rate can be simplified to the following formula:

$$\lambda_b AC = \lambda_{bSSE} + \lambda_{bV} + \lambda_{bCW} \tag{8}$$

For hydraulic actuator, the flow rate can be calculated from the following formula [32]:

$$\lambda_{bHC} = \lambda_{bPC} + 2\lambda_{bSD} \tag{9}$$

where

$$\lambda_{bPC} = \frac{10 \times 10^6}{N} \tag{10}$$

and λ_{bSD} is a failure rate for a dynamic seals. N is a number of wear cycles.

The number of cycles was estimated assuming that the equipment pressure should withstand the number of infinite fatigue strength, which is 2×10^6 according to [37]. Research shows that fatigue failures may occur much sooner [38,39]. Another reported failure is leaking due to the sealing failure [40]. The values of base failure rates (in failures/million cycles) for other hydraulic components is presented below [32]:

1. Valves:
   - spool type: $\lambda_{bVS} = 3.75$;
   - poppet type: $\lambda_{bVP} = 3.9$.

   The values mentioned above are addressed to direct-operated valves. For pilot-operated, we can calculate failure rate as a sum of the pilot valve and main valve. In the simplest case (pilot and main valve are the same types), we can assume that the pilot-operated valve failure rate is twice more than a direct-operated value.
2. Seals:
   - static: $\lambda_{bSS} = 2.4$;
   - dynamic: $\lambda_{bSD} = 22.8$.
3. Pumps:
   - piston: $\lambda_{bPP} = 1.05$;
   - gear: $\lambda_{bPG} = 0.75$;
   - vane: $\lambda_{bPV} = 0.4$.
4. Pipe: $\lambda_{bP} = 0.57$.
5. Hose: $\lambda_{bH} = 1.95$.
6. Accumulator (diaphragm type): $\lambda_{bAC} = 3.81$.
7. Hydraulic oil: as a common practice, hydraulic oil has to be replaced much sooner than any failure in components may occur. Therefore, the value of the failure rate was set as maximal from other components in the system.

All of the above-mentioned factors were evaluated using the below scale:

- Very high: 9–10.
- High: 6–8.
- Moderate: 3–5.
- Minor: 1–2.

and then were renormalized to new scales according to Formula [41]:

$$x_{norm} = a + \frac{x - min(x)(b - a)}{max(x) - min(x)} \tag{11}$$

The "Size" (s) factor value is 1–1.25, the "Operating pressure" (p) factor value is 1–1.25, the "Leakage" factor (t_e) value is 1–1.12, and the "Environmental" factor (w_e) is 1.14. The range of factors range is not equal because operating pressure and size plays more important role than leakage and environmental conditions. The time factor (t_f) allows for distinguishing components with different operating time regimes. The range is 1–2. To make all data easier to identify and recognize, we prepared a practical chart presented in Figure 1.

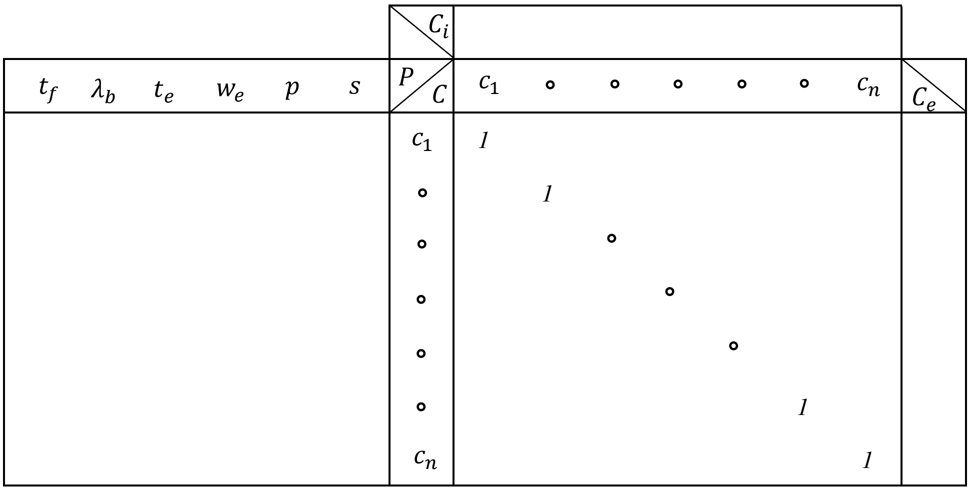

Figure 1. Data chart.

The chart above includes the pairwise comparison matrix, which is used to evaluate component modification factor c_e. The weights factors were calculated in the following way:

$$w_{ij} = \sum_{k,l=1}^{n} c_{kl}, k = 1 \ldots n \quad (12)$$

were next renormalized to range 1–1.25.

We evaluated the detection D in a similar way to classic FMEA analysis with values 1–20:

- detection of failure is almost certain: 1–2
- detection is very high: 3–5
- detection is high: 6–8
- detection is moderate high: 9–11
- detection is moderate: 12–13
- detection is very low: 14–15
- detection is remote: 16–17
- very remote: 18–19
- detection is nearly not possible: 20.

3. Case Study

An example of typical hydraulic system, presented in Figure 2, that includes typical fluid power components was used in this study. It is a hydraulic system that utilizes an accumulator as an auxiliary power source.

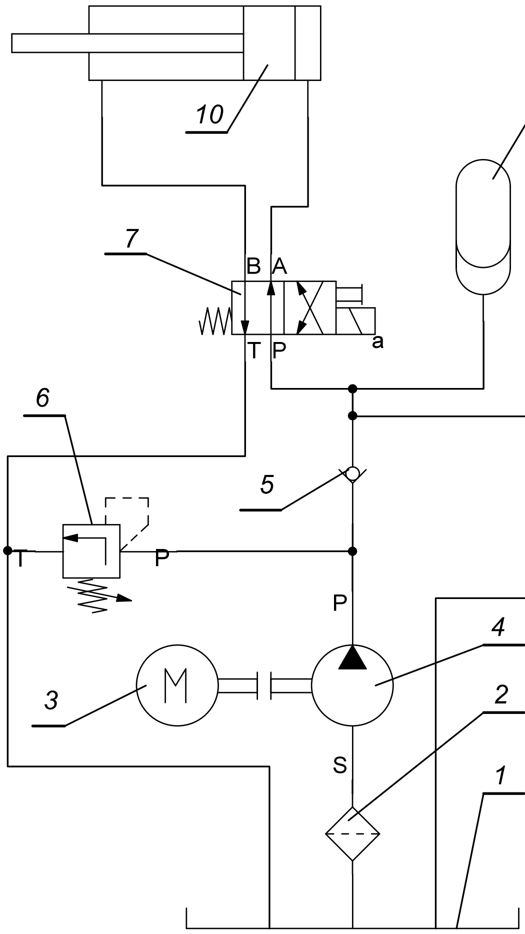

Figure 2. Hydraulic circuit: 1—reservoir; 2—filter; 3—motor; 4—pump; 5—check valve; 6 and 8—relief valve; 7—four way, two position directional control valve; 9—accumulator; 10—hydraulic cylinder.

The presented system's main task is to convert pressure energy into linear displacement of the hydraulic cylinder and actuate the component of a mechanical system (e.g., boom or arm of an excavator). The motor (3) drives a pump (4) and sucks hydraulic oil from the reservoir (1). Before passing the pump, the fluid is cleaned in the filter (2). The pump displaces the liquid to the hydraulic cylinder (10) through the check valve (5) and the directional control valve (7). The check valve (5) secures the system against the back flow. The hydraulic cylinder is a double-action actuator in which fluid acts on both sides of the piston. One side is connected with the supply line (with the pump) while the other is the drain (reservoir). Both ports can be alternatively connected to the supply line by switching a spool position of the control valve (7). In that way, the direction of piston rod movement is determined. The relief valve (6) plays a role of a safety valve in the system and secures the pump against excessive pressure. The other relief valve (8) sets the working pressure. The accumulator (9) is connected parallel to the supply line and is an auxiliary power source. During each operating cycle, the accumulator is charged and release fluid on power demand. Fluid is delivered to all components via rigid pipes or hoses, or both. The directional control valve (7) and relief valve (8) are components of the control system. Reservoir (1), filter (2), and pump (4) are components that generate pressure energy. Pipes or/and hoses transmit energy to the hydraulic cylinder (10), where fluid energy is converted into mechanical energy.

The following components were used in further analysis:

1. tank (reservoir) c_1 (item 1);
2. filter c_2 (item 2);
3. pump c_3 (item 4);

4. check valve c_4 (item 5);
5. relief valve (direct-operated) c_5 (item 6);
6. relief valve (pilot-operated) c_6 (item 8);
7. directional control valve (spool type) c_7 (item 7);
8. pipe c_8;
9. hose c_9;
10. accumulator c_{10} (item 9);
11. actuator (hydraulic cylinder) c_{11} (item 10);
12. oil (as a component of energy transfer) c_{12}.

Failures that can occur for the above-mentioned components are as follows [42]:

1. fracture f_1;
2. deformation f_2;
3. loosening f_3;
4. extreme contamination f_4;
5. properties f_5;
6. wear f_6;
7. corrosion f_7;
8. ageing/hardening f_8;
9. aeration f_9;
10. contamination f_{10};
11. properties changes f_{11};
12. cavitation f_{12}.

At the next step, we defined the system functional failures ff_i. The functional failure is understood as a system state (failure) that is categorized in the following way:

1. System is not able to perform intended function ff_1.
2. System is partially able to perform intended function. Major failure occurs ff_2.
3. System is able to perform intended function. Minor failure occurs ff_3.

Symptoms, failure modes, and failures matched with components corresponding to the above-mentioned functional failures were used to create relation tables presented below on Tables 1–3.

Table 1. Functional failure (ff_1): System is unable to perform intended function.

Symptom	Failure Mode	Failure	Components
Actuator: no motion	Loss of oil fm_1	Fracture f_1	Tank c_1 Pipe c_8 Hose c_9 Pump c_3 Valves c_4, c_5, c_6, c_7 Actuator c_{11} Accumulator c_{10}
	No output at pump fm_2	Fracture f_1	Pump c_3 Relief valve c_5
		Deformation f_2	Pump c_3
		Loosening f_3	Pump c_3
		Extreme level of contamination f_4	Oil c_{12}

Table 1. *Cont.*

Symptom	Failure Mode	Failure	Components
		Properties f_5	Oil c_{12}
	Fluid not delivered to actuator fm_3	Fracture f_1	Pipe c_8 Hose c_9 Accumulator c_{10} Valves c_4, c_5, c_6, c_7
		Deformation f_2	Valve c_7
	Blocked actuator fm_4	Fracture f_1 Deformation f_2	Actuator c_{11} Actuator c_{11}

Table 2. Functional failures (ff_2): System is partially able to perform the intended function.

Symptom	Failure mode	Failure	Components
Actuator: insufficient speed or force	Component malfunction fm_5	Wear f_6	Valves c_4, c_5, c_6, c_7 Pump c_3 Actuator c_{11}
		Corrosion f_7	Valves c_4, c_5, c_6, c_7 Pump c_3 Actuator c_{11}
		Deformation f_2	Actuator c_{11} Valve c_7
		Ageing/Hardening f_8	Accumulator c_{10}
		Aeration f_9 Contamination f_{10} Properties changes f_{11}	Oil c_{12}

Table 3. Functional failures (ff_3). System is able to perform intended function with minor malfunction.

Symptom	Failure Mode	Failure	Components
Noisy operation	Component malfunction fm_5	Wear f_6	Valves c_4, c_5, c_6, c_7 Pump c_3 Actuator c_{11}
		Deformation f_2	Pump c_3
		Corrosion f_7	Pump c_3
		Aeration f_9	Oil c_{12}
		Cavitation f_{12}	Pump c_3 Valves c_4, c_5, c_6, c_7
Overheating	Component	Wear f_6	Pump c_3
	malfunction fm_5	Cavitation f_{12}	Pump c_3 Valves c_4, c_5, c_6, c_7
		Ageing/Hardening f_8	Accumulator c_{10}
Leaks	Component	Wear f_6	Component seals
	malfunction fm_5	Ageing/Hardening f_8	Component seals

4. Results

Data from Table A1 along with failure values were allowed for calculating the criticality number C_r. The ranking lists were created for each functional failure and are presented on Table 4–6. Oil contamination or aeration appears six times among first five ranks for all functional failures. Pump and actuator failures were also recognized as components, which can lead to presented system failures.

Table 4. Functional failures ff_1. Criticality.

Rank	C_R	Failure	Component
1	1368	extreme oil cont. f_4	oil c_{12}
2	1310.1	deformation f_2	pump c_3
3	928.2	deformation f_2	actuator c_{11}
4	912.0	properties f_5	oil c_{12}
5	409.4	loosening f_3	pump c_3
6	309.4	fracture f_1	actuator c_{11}
7	83.7	fracture f_1	relief valve c_6
8	82.8	fracture f_1	directional control valve c_7
9	81.9	fracture f_1	pump c_3
10	81.0	fracture f_1	check valve c_4
15	71.6	fracture f_1	hose c_9
11	59.1	fracture f_1	pipe c_8
16	43.6	fracture f_1	accumulator c_{10}
14	33.8	fracture f_1	tank c_1
13	29.7	fracture f_1	relief valve c_5

Table 5. Functional failures ff_2. Criticality.

Rank	C_R	Failure	Component
1	2907.0	contamination f_{10}	oil c_{12}
2	2784.6	corrosion f_7	actuator c_{11}
3	2736.0	aeration f_9	oil c_{12}
4	2052.0	properties changes f_{11}	oil c_{12}
5	2784.6	wear f_6	actuator c_{11}
6	982.2	deformation f_2	actuator c_{11}
7	859.8	corrosion f_7	pump c_3
8	753.6	corrosion f_7	relief valve c_6
9	745.3	corrosion f_7	directional control valve c_7
10	728.7	corrosion f_7	check valve c_4
11	654.3	ageing/hardening f_8	accumulator c_{10}
12	628.0	wear f_6	relief valve c_6
13	621.1	wear f_6	flow control valve c_7
14	607.2	wear f_6	check valve c_4
15	267.3	corrosion f_7	relief valve c_5
16	248.5	deformation f_2	flow control valve c_7
17	297.0	wear f_6	relief valve c_5

Table 6. Functional failures ff_3. Criticality.

Rank	C_R	Failure	Component
1	2784.6	wear f_6	actuator c_{11}
2	2736.0	aeration f_9	oil c_{12}
3	1146.4	deformation f_2	pump c_3
4	1044.0	cavitation f_{12}	pump c_3
5	942.0	cavitation f_{12}	relief valve c_6
6	931.7	cavitation f_{12}	directional control valve c_7
7	910.8	cavitation f_{12}	check valve c_4
8	859.8	wear f_6	pump c_3
9	859.8	corrosion f_7	pump c_3
10	828.7	aeging/hardening f_8	accumulator c_{10}
11	628.0	wear f_6	relief valve c_6
12	621.1	wear f_6	directional control valve c_7

Table 6. *Cont.*

Rank	C_R	Failure	Component
13	607.2	wear f_6	check valve c_4
14	334.2	cavitation f_{12}	relief valve c_5
15	222.7	wear f_6	relief valve c_5

5. Discussion

Criticallity number for pair contamination–oil reached the highest value among all failure–component pairs. Almost all failures and related components for functional failure (ff_1) that are critical to the system are valued lower than for others functional failures (ff_2, ff_3). There are two reasons responsible for this situation. The first one is the detection number. The "fracture" failure for almost all components can be easily detected—for some, even without any instruments. The second reason is the components prioritization method that is realized by performed function, failure rate, and working regime. The tank, which is recognized as a highly reliable component, can be a source of critical failure for the system. Another aspect is that the components which play auxiliary functions and being in use occasionally (e.g., valve c_6) when failing make the system unable to operate. Failures that cause fluid losses are critical to the whole system and even if they occur in the component graded as secondary or minor. Treating such components with the highest importance can lead to overestimating other failures for these components. The nature of almost all failures for critical system failure ff_1 is random and unpredictable caused by sudden and extreme overload or hidden material/manufacturing and design flaws.

The first two criticality numbers for ff_3, which is less risky for the system than others, reached higher values than fourth rank in ff_2. Other pairs of failures and the corresponding components are higher for ff_3 than ff_2. This is caused by the intensity and exposure which determine the final effect, which can be marginal (at initial stages of wear, cavitation, and corrosion) or major after long exposure.

Presented results show that risk prioritization assigned to the system risk allows avoiding underestimating or overestimating potential failures for related components.

In all three functional failures, oil contamination plays the main role and should be recognized as a main problem of fluid power systems. It agrees with practical experience and also with the results of research presented in study [2] where failure analysis was conducted for a hydraulic system of a heavy-duty machine. The failure analysis in this work was conducted with more sophisticated methods and tools than the presented method: fault tree analysis, Dempster–Shafer theory, and rough set theory to fill were implemented to eliminate the incompleteness and the uncertainty delivered by experts.

The comparison of the presented method and conventional RPN approach was conducted for the severity factor, which in the proposed method is calculated according to Equation (2). To the comparison, we used failure: fracture that can occur in all of the system' components. The end effect of this failure for all of the components leads to critical system failure, which is unable to perform the intended function. As such, it should be ranked with maximal value according to the traditional RPN approach. The comparison of RPN value is presented in the Table 7.

Table 7. Severity number.

Component	Classical RPN (max 10)	Proposed Method (max 20)
Pump	10	19.9
Tank	10	16.9
Check valve	10	16.8
Directional control valve	10	16.7
Actuator	10	16.4
Filter	10	16.2
Hose	10	16.1
Pipe	10	16.0
Relief valve (c_6)	10	12.4
Relief valve (c_5)	10	12.2
Accumulator	10	8.1

The occurrence number may mainly depend on a subjective opinion of an expert (or experts), their knowledge and/or experience, and/or availability of relevant data. It means that the occurrence number may be scattered inside a wide range. The proposed method adopts quantitative data, including the essential information about components, which produce the occurrence number with less sensitivity to expert knowledge and/or experience.

The detection number in both methods are estimated in the same way.

Limitations of the method.

Although the structural design of fluid power components has remained unchanged for decades, the trend to implementing electronic control and diagnostic system can be observed recently. It brings new possibilities for system diagnostic and its management and makes the components are no longer purely mechanical/fluid but are more sophisticated. Additionally, new manufacturing methods and materials are implemented; thus, base failure rates from this study may not fit the latest components design. Furthermore, the values of base failure rates do not recognize differences in component structures or material and cannot evaluate the same component with various solutions separately. Another limitation of the presented method is its applicability only to components for which base failure rate is available. Those for which is unavailable would have to be estimated what can increase the level of uncertainty.

The proposed method can calculate the same criticality numbers for a few different components and corresponding failures. It can be overcome by detailed failures definition, which is sometimes problematic. Fluid power components encounter mechanical and fluid flow failures, which are too complex for easy identification.

6. Conclusions

FMEA analysis and its modification play an essential role in increasing reliability and safety despite the drawbacks, which, in classical FMEA analysis, is undoubtedly risk evaluation and uncertainties. In this study, a proposal of risk assessment for fluid power systems has been presented; its main aim was implementing a prioritization method of failures based on quantitative data. A classical risk priority number has been extended with modification factors for severity, while occurrence was replaced by a failure predictor, which uses failure rate value and corrective factors. The detection remained unchanged with classical risk prioritization. The severity number in the proposed method is calculated as a product of component importance, their influence on other components, and failure effects. It allows for prioritizing components that can be nondistinguishable in the classical RPN method. The proposed method's main application is a design stage or situation where details of the system components are unavailable. Therefore, the occurrence number is replaced by a failure predictor, which defines the likelihood of failure based on failure rate value and modification factors. These were determined based on specifications of typical components systems for mobile fluid power systems. If relevant data about components are available, the failure rate can be more precisely described. The proposed method was employed in a typical fluid power system which consists of common components and can be extended to any fluid power system. Modification factors presented in this study are universal and applicable for other systems of fluid power. Failure modes of individual components were classified into system functional failure (effects of component failure modes) to avoid underestimating failures whose consequences are catastrophic to the system. Obtained results allowed identify the most common failure for a considered hydraulic circuit, which agreed with research conducted by more sophisticated tools and methods and proved the usefulness presented method.

Author Contributions: Conceptualization, J.F.-D. and M.D.; methodology, J.F.-D.; software, H.M.; validation, M.D., J.F.-D. and H.M.; formal analysis, J.F.-D.; investigation, J.F.-D.; resources, J.F.-D.; data curation, M.D.; writing—original draft preparation, M.D.; writing—review and editing, H.M.; visualization, H.M.; supervision, M.D.; project administration, J.F.-D.; funding acquisition, H.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI	hlMultidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
MIL-STD	US Defense Standard
FMEA	Failure Modes and Effects Analysis
FMEDA	Failure Modes, Effects, and Diagnostic Analysis
FMCA	Failure Modes, Effects, and Criticality Analysis
NASA	National Aeronautics and Space Administration
RPN	Risk Priority Number
ISO	International Organization for Standardization
MCDM	Multicriteria Decision-Making

Appendix A

Table A1. Data chart.

						c_i	4.0	4.0	4.0	4.0	3.0	3.0	4.0	4.0	4.0	2.0	4.0	4.0	
t_f	λ_b	t_e	w_e	p	s		c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_e
2	1.00	1.00	1.00	1.00	1.00	c_1	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.06
2	1.36	1.02	1.00	1.00	1.00	c_2	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.01
2	1.15	1.12	1.02	1.25	1.25	c_3	0.0	0.0	1.0	0.7	0.7	0.7	0.7	0.3	0.1	0.5	0.7	0.9	1.25
2	1.56	1.08	1.02	1.25	1.13	c_4	0.0	0.0	0.0	1.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.5	1.05
1	1.56	1.09	1.02	1.25	1.13	c_5	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.01
2	2.12	1.11	1.02	1.25	1.13	c_6	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.3	0.5	1.04
2	1.54	1.12	1.02	1.25	1.13	c_7	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.5	0.5	1.05
2	1.08	1.03	1.05	1.25	1.25	c_8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.00
2	1.28	1.03	1.06	1.25	1.25	c_9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.1	1.00
2	1.55	1.03	1.06	1.25	1.25	c_{10}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.3	0.0	1.01
2	5.00	1.12	1.14	1.25	1.25	c_{11}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	1.02
2	5.00	1.00	1.11	1.00	1.00	c_{12}	0.0	0.3	0.9	0.7	0.1	0.7	0.7	0.5	0.5	0.3	0.7	1.0	1.25

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