SENSITIVITY ANALYSIS OF FMEA AS POSSIBLE RANKING METHOD IN RISK PRIORITIZATION

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The Failure Mode and Effect Analysis (FMEA) has spread in wide range of engineering. This means, today it is present in manufacturing and development of engineering systems such as vehicles, health care or food industry, etc. Although, the earliest focus was on the mechanical components, today electronic elements and software components must be included, due to the increase of system complexity. This change underlines the fact that complexity and size of these systems results in a reduced transparency and meaning of similar Risk Priority Numbers (RPN). Therefore an obvious and simple overview should support analysts in finding critical points of an entire system. This kind of method should not require additional and long term work packages, but should rely on raw values of FMEA. As a result, this method will support the identification of sensitive parts within an entire system, pointing out the meaning of critical content behind.

Keywords: FMEA, risk analysis, sensitivity analysis, risk prioritization.

1. Introduction

The Since the U.S. Military Forces standard document (MIL-P-1629) described the procedures for performing a Failure Mode, Effects and Criticality Analysis (FMECA) in 1949 [1]. The FMEA has been developed from this standard, which is a qualitative analyzing tool with highly structured, systematic technique in system modeling, facilitating reliability and risk evaluation [2]. This analysis can be done on separated worksheets and component levels, performing disciplinary risk modeling evaluation. However, the modeling and evaluation set up in a large, multidisciplinary team which is led by one moderator – can have unique scheduling (even in one project) and be individual because of human factors. Incompatibility and interconnection problems between worksheets can occur usually, due to the fact of different requirements, scheduling and understanding of disciplines in modeling. For this reason, interfaces should be declared between levels and disciplines. But how will the whole system look like in hardware, software and mechanical designs is another point. For an easier understanding, Carlson suggests the use of boundary diagram or block diagram

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[3] [4]. As a matter of fact usually these diagrams help starting discussions within the core team, but structuring and interconnecting hardware and software functions formulate a common analysis together. This still might not be an easy task, due to the fact that interdisciplinary knowledge, hard questions in software field – such as what should be presented for function and how can be a malfunctioning effect on the whole system. These are all leading to time consuming discussions and endless speculations with a demotivating atmosphere together with a high probability of missed failures or even a function itself. It can be reduced, if preconditions of disciplines are prepared, concerning a common understanding of structuring and meaning of function [5].

Sensitivity analysis can be performed to examine different reactions of the model by black box technique. The inputs must be known or determined, but output will be calculated according to the definition of input attributes [6]. This analysis can be performed to find sensitive or critical factors and elements of the system. These are identified easier in the system and can be very objective. It is also used in economy as well as in engineering. Well known events and effect of known failures can be simulated, also examined of unknown stochastic events [7].

Two modelling approaches are possible [8]: Deterministic and prognostic, while equations of the model are very accurate and enough to describe it. It means no extra declaration of physical or chemical, etc. law or rule is needed. Data driven or law driven, while the behavior of the model must be extended with additional law or data set to describe it.

Rest of the examination simulated and evaluated by Monte Carlo simulation. Pokorádi published a matrix-algebraic method for sensitivity analysis [9]. This easy algorithmic calculation is used to investigate software failure and shown by Pareto analysis [10]. There are two matrices, where one stands for independent variables (matrix $\mathbf{A} \in \Re^{m \times m}$) another for system state depending variables (matrix $\mathbf{B} \in \Re^{m \times n}$). The final outcome is a graph, which is generated by a calculation of these two matrices determination and inversion as line vector. These elements are transformed to a Pareto analysis, where probability of failures are ranked one-by-one.

This article will briefly introduce a hierarchically modelled system, then a risk assessment of multiple levels of FMEA focusing on seriousness. The other aim of this paper is to develop a new sensitivity analysis of an entire system FMEA.

The outline of this paper is the following: Paragraph 2 introduces multiple-level evaluation of FMEA worksheets. Paragraph 3 presents the proposed sensitivity analysis method of FMEA. Finally, the Authors summarize their work in Chapter 4.

2. Structuring FMEAs hierarchically

Building up FMEA worksheets in a hierarchical structure is not a new idea, but the implementation is solved individually. The main meaning of hierarchy is coming from the different levels of analysis - such as system, design or process (as built on one to another) [11]. The 'data connection' builds up through the logical connections of effect, function or cause content in the background presented in Severity (*S*), Occurrence (*O*) and Detection (*D*) values. For better understanding, example of a Wheel Speed Sensor (WSS) will be shown by Figure 1. This sensor is a part of the Anti-Block System (ABS) in the vehicles. The WSS detects the status of the given tire. It is build up by two main components. The magnetic sensor provides periodical signal according to the rotation speed of the cog-wheel-plate, which is fixed on each tire of the vehicle.

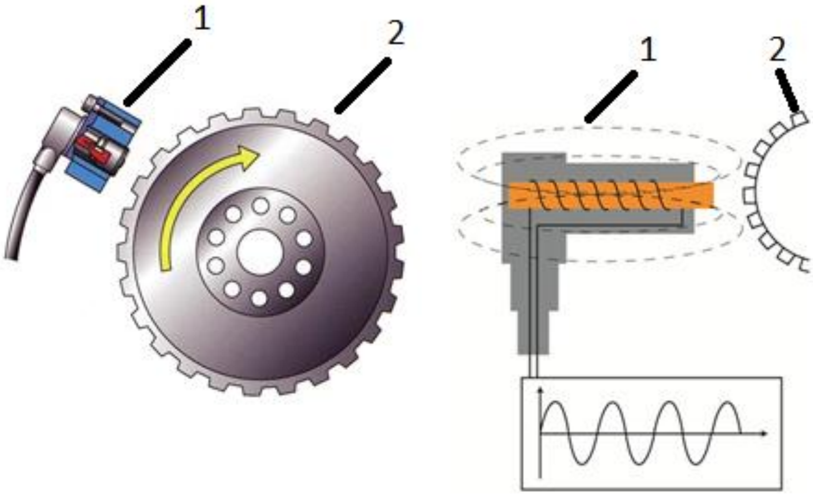


Fig. 1. Wheel speed sensor concept and measurement overview (source: [12])
1 – Magnetic sensor; 2 – Cogwheel plate

According to this example, two hierarchical levels are defined in the product FMEA to analyze system and design. The first sheet is dedicated to the effects, where failures are defined for the entire system. Each of these failures has derived value S, which are fixed for the entire system. It means that lower levels will use these failures and severity numbers together as a root cause of failure belonging to the given function. The first level is the Effect Level (EL) analysis of which is shown in Table 1.

This level does not contain fully evaluated risks, but a list of potential failures in the whole systems is grouped here. Column of function and potential failure are supporting a kind of grouping of potential effects with severity numbers, but column of cause are linked from potential failures one level below, called System Level (SL).

Table 1

Effect Level

No	Function	Pot.failure	Pot. effect	S	Cause	O	Prev. / Det. Action	D
EL1	Determine the wheel speed	Signal has not been provided	Velocity cannot be determined	10	No signal provided			
EL2			Wrong value of velocity	7	Periodic signal differs from wheelspeed			
EL3	Detecting if wheel has been blocked	Blocking wheel not detected	Vehicle became instable	9	Status of wheel has been detected as rolling instead of blocked			
EL4		Blocking wheel detected instead of rolling wheel	Wrong value of blocking status	8	Wheel blocking has not been detected			
EL5				8	Status of wheel has been detected as blocking instead of rolling			

For the better understanding, let us have a look at the next level, which starts analyzing functions on the system level. Therefore, it is called system FMEA, shown in Table 2.

Concerning hierarchical connection of failure effects, the SL is used as a source of failures in the entire analysis. All of these declared values guaranteed to be fixed and presented with similar meaning on lower level of worksheets as well.

As it is shown by Figure 2, the highlighted 'velocity cannot be determined' in the potential effect column can be found in both Table 1 and Table 2. This effect has severity ranking of 10, which has been inherited all of the lower levels from EL, via SL, DL down to CL.

It guarantees that each of these agreed failures have the same meaning of risk ranking in the entire system. Concerning the system evaluation, it should be read as follows: the function, which 'provide periodic signal according to wheel speed' carries a chance of potential failure as 'no signal provided' which affects that 'velocity cannot be determined' on the system.

Table 2

System Level

No	Function	Pot. failure	Pot. effect	*S*	Cause	*O*	Prev./ Det. Action	*D*
SL1	Provide periodic signal according to wheel speed	Periodic signal differs from wheelspeed	Wrong value of velocity	7	Sensor detects metals continuously	4	D: Check the cable binding P: Use water resist technology	2
SL2			Wrong value of velocity	7	Space between cogs is not equal	2	D crosscheck from other sensor P: declare periodical check of cogwheel	3
SL3		No signal provided	Velocity cannot be determined	10	Sensor does not detect metals	3	D: check plausible values P: Ensure fixture of sensor is sufficient	3
SL4		Wheel blocking has not been detected	Wrong value of blocking status	8	Space between cogs is not equal	2	D:Audit production P: Ensure by EoL measurement	2
SL5	Provide frequency of periodic signal according to wheel status	Status of wheel has been detected as blocking instead of rolling	wrong value of blocking status	8	Sensor does not detect metals	2	D: Check engine status, too P: Use cross-check from other wheel	3
SL6					Sensor detects metals continuously	2	D: Aperiodic signal presenting P: Ensure sensor fixture	3
SL7		Status of wheel has been detected as rolling instead of blocked	Vehicle became instable	9	Sensor detects metals continuously	1	D: Compare status to other wheel P: Ensure sensor fixture	2

Effect Level

No	Function	Pot.failure	Pot. effect	S	Cause	O	Prev. / Det. Action	D
EL1	Determine the wheel speed	Signal has not been provided	Velocity cannot be determined	10	No signal provided			

System Level

No	Function	Pot. failure	Pot. effect	*S*	Cause	*O*	Prev./ Det. Action	*D*
SL3		No signal provided	Velocity cannot be determined	10	Sensor does not detect metals	3	D: check plausible values P: Ensure	3

Design level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
DL3	Inductive sensor	Sensor does not detect metals	Velocity cannot be determined	10	cable cut	2	P: Assembly instruction D: Cable	2

Cause level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
CL3	Failures of	cable cut	Velocity cannot be determined	10				

Fig. 2. Top to bottom effect linking

This effect has a seriousness of severity 10 (highest) and the cause of this failure is determined from the design analysis originated from design level (DL) as 'sensor does not detect metals' (shown by Figure 3). Occurrence and detection are evaluated according to the catalogue of the used standard (i.e. VDA or SAEJ1739, etc.). The detective and preventive actions are defined; these actions have influence on value of occurrence and detection as well.

On the other hand, using domain specific failure catalogue is represented on Figure 3. This means that failure cause on EL linked directly to SL level showing possible failure cause of the given failure in the sub-systems below. Other benefit comes from the design, because DL has to face with similar causes usually, thus these similar meaning of causes collected one level below and linked up from DL to SL with a similar meaning behind. The benefit of this approach is a common catalogue of typical design failures supporting failure cause evaluation. The next level is the design evaluation, this is in Table 3.

Bill of Materials (BOM) has been analyzed on design level (Table 3). The evaluation method is similar to system level, but function column contains BOM elements [13].

Table 3

Design level

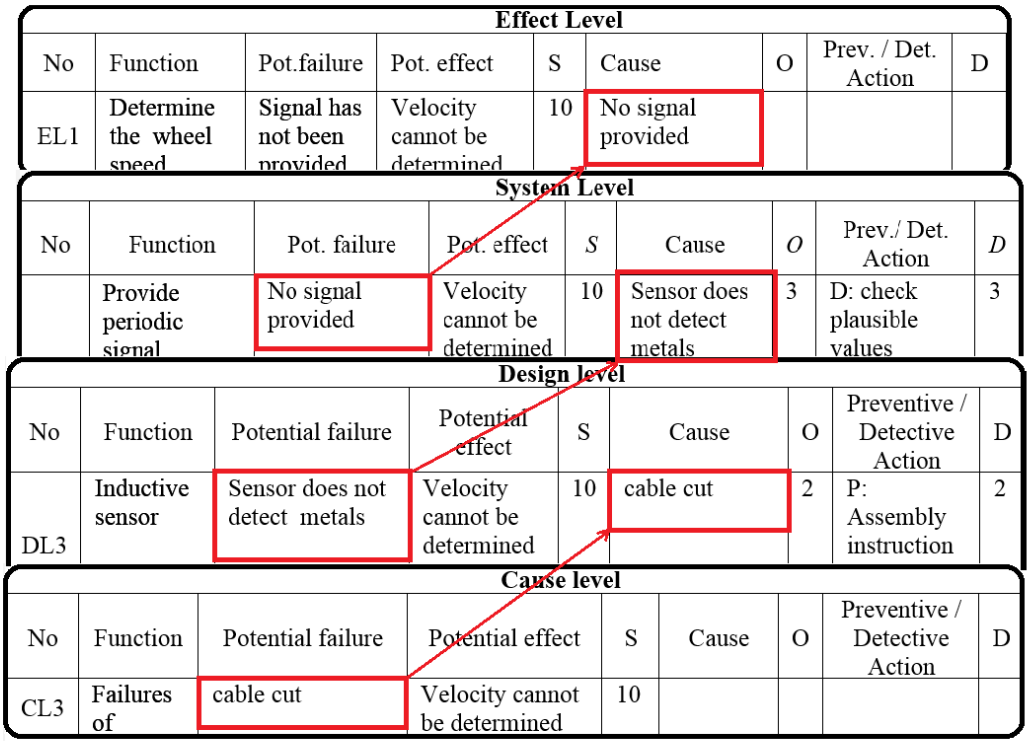
No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
DL1	Cogwheel	Space between cogs is not equal	Wrong value of blocking status	8	Dust on surface of cog	2	P: Add notice Assembly instruction D: Check other wheels	3
DL2		Space between cogs are not sufficient	Wrong value of blocking status	8	Too wide space between cogs	1	P: Production instruction D: Product measure	2
DL3	Inductive sensor	Sensor does not detect metals	Velocity cannot be determined	10	cable cut	2	P: Assembly instruction D: Cable protection	2
DL4		Sensor detects metals continuously	Velocity cannot be determined	10	cable shorting	2	P: Assembly instruction D: Cable protection	2

Table 4

Cause level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
CL1	Failures of cog wheel	Dust on surface of cog	Wrong value of blocking status	8				
CL2		Too wide space between cogs	Wrong value of blocking status	8				
CL3	Failures of inductive sensor	cable cut	Velocity cannot be determined	10				
CL4		cable shorting	Velocity cannot be determined	10				

Components can be evaluated in separated sheets in parallel, this will make easier to follow changes and introduction of new materials. This level is usually used for electronic hardware, mechanic components and base software (driver interface to HW) elements and functions. Software functions with calculations, actuations and high level functions are usually evaluated on system level, because these software elements are connecting to an interface to actuate.



Effect Level

No	Function	Pot.failure	Pot. effect	S	Cause	O	Prev. / Det. Action	D
EL1	Determine the wheel speed	Signal has not been provided	Velocity cannot be determined	10	No signal provided			

System Level

No	Function	Pot. failure	Pot. effect	S	Cause	O	Prev./ Det. Action	D
	Provide periodic signal	No signal provided	Velocity cannot be determined	10	Sensor does not detect metals	3	D: check plausible values	3

Design level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
DL3	Inductive sensor	Sensor does not detect metals	Velocity cannot be determined	10	cable cut	2	P: Assembly instruction	2

Cause level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
CL3	Failures of	cable cut	Velocity cannot be determined	10				

Fig. 3. Bottom to up cause linking

Finally, the lowest level defined as cause (shown in Table 4). This is the lowest part of the FMEA, advantageous to design it for a kind of catalogue of different disciplines. The failures and effects are linked from higher level as well. Table 4 shows possible failures of mechanical design, but also can be made for hardware or software. In case of software errors, development process, development toolchain and systematic failures of designers might be considered besides testing issues.

3. Sensitivity analysis of FMEA

Different reasons, such as time pressure or lack of field experiences generate the need of an objective overview of real risks in the background of the system. Generally used as first line risk estimation to order all of *RPN* numbers in the entire FMEA to a corresponding function. This might show where the highest values are indicating risks. Though, *S=10 x O=10 x D=10 = RPN=1000* indicates highly critical risks in the system, but similar *RPN*s with different *S*, *O*, *D* values for exapmle *10x4x2* or *8x10x1* both result *RPN* of 80 will not be distinguished that easy. Therefore, real meaning of similar *RPN*s should be derived and indicated in a common overview. Authors set up a sensitivity model and two representation modes, which compare the individual *S*, *O*, *D* and *RPN* values to the entire system. Results summarized on diagrams to have a better overview.

Collecting all evaluated values from the entire FMEA worksheets is the first step. This study has a 'No.' column to identify each fully evaluated line.

The first calculated value is the Ki which is calculated as the following:

$$K_i = \frac{RPN_i}{\sum_{i=1}^{n} RPN_i} \tag{1}$$

The second step is calculating sensitivity relations of S, O and D in the system:

$$K_{xi} = x_i K_i, \quad \text{where } x \in \{S, O, D\} \tag{2}$$

The calculated values, K_i, K_{Si}, K_{Oi} and K_{Di} are also presented by Table 5.

Table 5

Collection of evaluated RPNs and severity values

i	S_i	O_i	Di	RPN_i	K_i	K_{Si}	K_{Oi}	K_{Di}
SL1	7	4	2	56	0.1172	0.8201	0.4686	0.2343
SL2	7	2	3	42	0.0879	0.6151	0.1757	0.2636
SL3	10	3	3	90	0.1883	1.8828	0.5649	0.5649
SL4	8	2	2	32	0.0669	0.5356	0.1339	0.1339
SL5	8	2	3	48	0.1004	0.8033	0.2008	0.3013
SL6	8	2	3	48	0.1004	0.8033	0.2008	0.3013
SL7	9	1	2	18	0.0377	0.3389	0.0377	0.0753
DL1	8	2	3	48	0.1004	0.8033	0.2008	0.3013
DL2	8	1	2	16	0.0335	0.2678	0.0335	0.0669
DL3	10	2	2	40	0.0837	0.8368	0.1674	0.1674
DL4	10	2	2	40	0.0837	0.8368	0.1674	0.1674

The calculations are ready, so results can be plotted in two different ways of understanding. The first graph shown on Figure 4, this will support test managers finding critical points in the entire system. This graph shows severity, because it cannot be modified without any agreement of the project team and the customer. If the risk testing were applied in this analysis the distribution of additional weight would be shown graphically. There is a line shown on the graph as well, using threshold for a better understanding of the level of criticality.

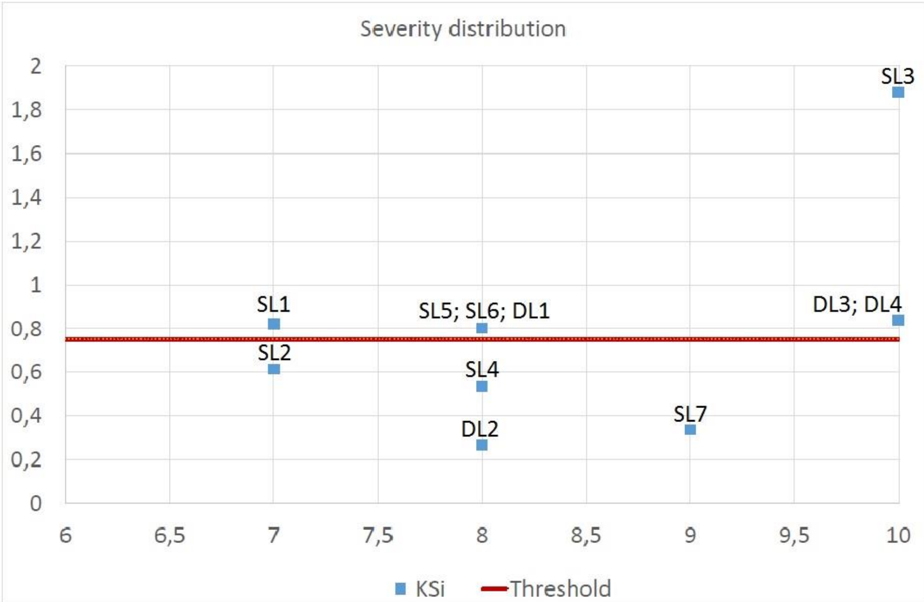


Fig. 4. Severity distribution (S_i and K_{Si})

Experiments have shown that certain threshold should be defined to highlight critical points in the entire system. Authors experienced that threshold of *0,75* for this purpose is the most reasonable choice to be used.

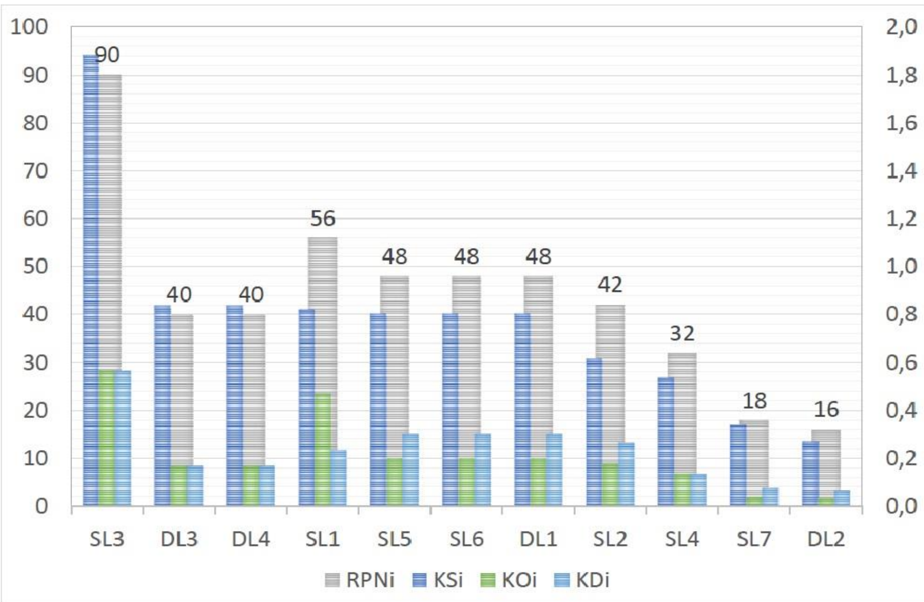


Fig. 5. Distribution of RPN and K_{xi} sensitivity parameters, ordered to K_{si}

On the other hand, the ranking of risks compared to former *RPN*s and the new K_x weighting factor. Experiences show that *RPN*s and weight of individual parameters have different meaning in the background. If only *RPN*s were used for risk priority decision, the order of critical object would be SL3, SL1, SL5, SL6, DL1, SL2, DL3, DL4, SL4, SL7, DL2.

But if order changed to K_{Si} the order is changed to the following: SL3, DL3, DL4, SL1, SL5, SL6, DL1, SL2, SL4, SL7 and DL2. It means that SL3 is not changed, but DL3, DL4 became more in focus besides SL3.

4. Discussion

This means that SL3 express that velocity cannot be determined. It might have higher risk than blocking wheel. This result highlights the leading cause of death on road facilities: improperly chosen speed. Due to the fact that even if the Vehicle Stability Program (ESP) has to calculate with inaccurate value of false tire speed – it will cause more problems for the vehicle stability. Just think about the ground reason of rolling over of trailer or even the truck.

Concerning the used methodology it will support system analysts and test managers in activity planning. This means, critical functions will be found easier and performance of system will become more comparable by these graphs.

5. Conclusion

In this paper we have proposed a new sensitivity investigation mode of FMEA. This method considers that severities have been defined by the customer. This method has been shown by case study of risk analysis of WSS. The authors have proposed scientific research including study of quality management method in the automotive industry. The sensitivity analysis together with FMEA analytical purposes enables engineers to create risk analysis even on software systems in finding security risks or other risks of information flow not only with surveys but with a thematically modeling of entire system together with multidisciplinary fields [14]. If a development team extended this method applying risk based testing, the regression tests could be identified. This method can be extended also with an additional weighting factor besides the *RPN*, which will provide a list of ‘must be tested’ functions similarly to risk based testing.

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