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An approach for using the FMEA and Network-Theory for the development of a novel rotation piston engine

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Abstract

The early stages of product development are characterized by incomplete and insufficient data. This lack of information will usually be resolved during the process. When dealing with a new product development, the situation intensifies. This is linked to the search for solutions to physical problems – especially in case of a revolutionary or evolutionary development. In case of the development of a completely new product, insufficient data on possible product malfunctions can impede early estimations. Therefore, it is necessary to develop a novel method to analyse the different possible solutions – dealing with the physical problems.
The focus of this paper lies on the development of a rotation piston engine. The pistons are going to be rotating around a common center. Consequently, the concept differs from the usual terms of the known engines. This paper explains, how the instruction of the FMEA (failure mode and effects analysis) have to be changed in order to support the developer estimating the risk of different concepts. For this purpose, the dependencies of components and functions are modeled into a network. The weighting of the connections (edges) between the nodes usually requires a lot of tests. As an alternative, the subjective rating of the developer is used to create classification numbers and, thus, to weight the network.
Thereby, variations are measured and compared to each other in order to make a decision which possibility is going to be the least risky one. Moreover, this analyzation helps to identify the most critical elements of the development process supporting the developer to plan tasks.

Keywords: FMEA, Rotation piston engine, Network- and Graph-Theory, Risk-Estimation

1 Introduction

Nowadays, a high level of functionality is expected from technical systems. This results in a higher complexity and an increasing amount of components. Interdependencies of a systems components are very difficult to understand. The complexity of technical systems is also caused by the innovative potential of current solutions. The early stages of product

development are characterized by the clarification and completion of information, that was formerly insufficient at the beginning of the process (Paetzold, 2006).
In case of a new product development, the situation becomes more complicated. This calls for revolutionary as well as evolutionary inventions. The latter are already including interacting physical elements. From a developer point of view, the interactions and their dependencies are unclear and should be specified at the beginning. As a result of this, the development process can take a longer time and requires many iteration loops, which increases the development risk. This is why technical aspects are rarely considered in the product design.
The development of new products poses a special challenge to the developer. A transfer of new ideas to a product with high functionality and quality requires additional aids. It is necessary to describe the influence of physical effects and functionalities on the technical system and the final design. Interactions and new information should be clarified and simple to understand in order to improve the development process (Krehmer, 2012).
The development of new products is linked to higher risks. This paper presents the development of a new and revolutionary invention of a rotation-piston-engine (RPE). From a company point of view, the risk of failing has to be minimized. FMEA is a typical method to explain and to understand the risks of a product for environment and human being. That is why every project is checked by a FMEA in order to analyse the system behaviour and identify possible malfunctions and their reasons (DIN EN 60812, 2016). The principle idea is, that FMEA can be also useful to analyse the risk of the development process.
Usually, the developer considers the number of expected malfunctions and then calculates the project risk. As RPE is a completely new product, there is no data given on potential malfunctions of a component or of the entire system. Consequently, an estimation of the expectable risk requires a method to perform a FMEA.

2 State of the art

2.1 Functionality of a Rotation-Piston-Engine

Before analysing the development risk of the RPE, it is important to understand its operation mode and innovation.
The principle of the RPE has been invented in 2011 by Peter Hruschka (Hruschka, 2011) and it is using the concept of a combustion engine. In general, the RPE can be designed as shown in Figure 1. In comparison to a reciprocating engine, the pistons of the RPE rotates on a circuit and do not move up and down. The advantage of such a rotation lies in the better dynamical effect. An increase in efficiency is to be expexted, since the RPE does not rely on the convertion of translatory motion into a rotation. This physical operating principle needs less space and components.
As can be seen in Figure 1, both pairs of pistons (1^{st} and 2^{nd} Piston pair) are rotating around a common centre. Each piston pair is built up of one part, the piston at the one side is rigidly connected to the one on the other side. The two piston pairs are surrounded by a case.

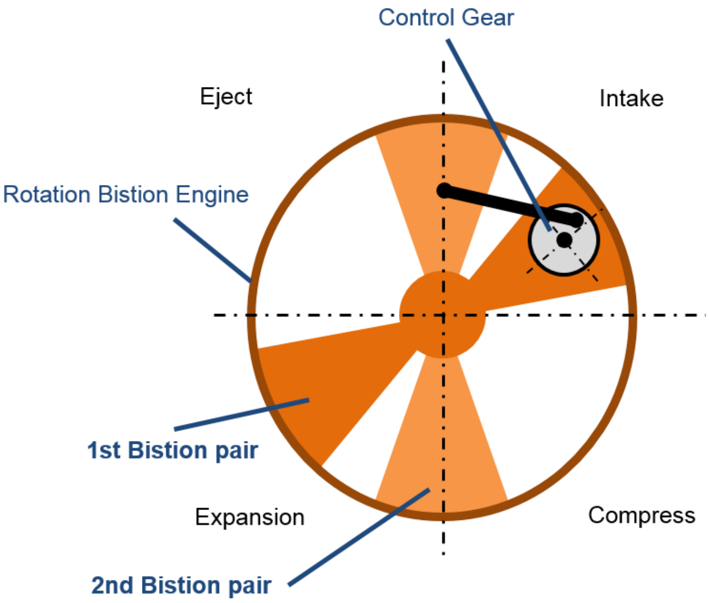

Figure 1: Sketch of Rotation Piston Engine

A certain relative movement of both piston pairs to each other allows an enlargement or minimization of the space between them. This can be achieved by holding one pair and moving the other one away (or closer respectively). It is also possible to rotate the 1st pair slower or faster than the 2nd one. Compared to that, the reciprocating engine can maximize and minimizes the space by moving the piston up and down.

2.2 Failure mode and effects analysis

The early stage of a PDP (product development process) is – according to Pahl/Beitz, VDI 2221, etc. – supposed to clarify the requirements (Mamorot et al., 2015). After defining the functions and setting up several potential solutions, the developers have to measure the different operating principles and settle on one of the solutions. One of the most used methods is the FMEA.
It should be done in the early stages of the PDP in order to identify and solve as many failures in the product as possible and to reduce development risks and costs. Moreover, a successful FMEA helps to identify potential malfunctions based on experiences with similar products and processes. Once the required functions are known, the analysis can be run on different system levels. According to DIN EN 60812 the advantageous of the FMEA are manifold:

- Detection of weak spots inside the first design
- Prevention of expansive subsequent modifications
- Identification of a single breakdown or those caused by a certain combinations

Basically, the FMEA is separated into five stages. The first one describes the functions of the critical parts by defining, which system, subsystem or device they are linked to. The second part examines the failure of the mentioned parts, investigating the reasons for the malfunctions and the magnitude of the damage dealt to a subsystem or the whole product. In general, the automobile industry usually uses a 10-step-scale to describe the severity of the failure. The next step of the FMEA outlines the reasons for such an incident, followed by the fourth section trying to find solutions or explantions in order to prevent failure. All in all, the last step covers the multiplication of every single classification number of step one to step four into a so called Risk Priority Number (RPN), cf. Figure 2.

FMEA Ref.	Item	Potential failure mode	Potential cause(s) / mechanism	Mission Phase	Local effects of failure	Next higher level effect	System Level End Effect	(P) Probability (estimate)	(S) Severity	(D) Detection (Indications to Operator, Maintainer)	Detection Dormancy Period	Risk Level RPN	Actions for further Investigation / evidence	Mitigation / Requirements
	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Figure 2: Example of a FMEA showing the steps and the RPN-Number (DIN EN 60812, 2006).

A high value of the RPN points to a risky solution or a critical component or subsystem. A sufficient set of data is necessary and inalienable to execute such an analysis and, thus, to estimate possible malfunctions and subsequent damage. In case of the RPE‘s development, there is insufficient data to precisely describe failures due to the innovative concept and the lack of a prototype. Therefore, it is nessesary to adapt the method of FMEA and define a manageable approach to calculate the risk of revolutionary inventions (VDI 4003, 2007).

3 Suggested approach using network theory

The following approach describes a way to utilize network and graph theory in order to identify critical functions of a product or situations and tasks in the development process. It can replace FMEA, if only limited data is available during early stages of a PDP. Usually, the FMEA starts with listing all desired parts. In this approach, it is, however, important to define the product functions first, since they determine the usage of certain components. Combinations of different components will be summarized into a concept.
After clarifying required functions, different concepts are analysed separately. For that, each concept will be translated to a network of its interacting components (Parraguez, 2015b). Another network pictures all functions defined earlier. Each component of a concept is linked to its corresponding node in the function network. This way, it is possible to see the interactions of all parts and functions of a product. This is similar to the second step of FMEA.
In addition, all NWs (networks) are weighted and directed – allowing a more detailed calculations. Different concepts can then be compared by their so-called K-value, which replaces the RPN number of the FMEA.

3.1 Modelling the weighted and directed network of functions

According to the established method of product development, the developer starts his job clarifying required functions. He then continues the development until he achieves a product meeting those requirements (Andreassen, 2005). Metrics are commonly calculated in order to evaluate the different concepts and to choose the most suitable one.
In the case presented above, there are two very different concepts meeting the requirements of the RPE. Precise estimation is, however, impossible due to a lack of data.
Network-Theory (NWT) allows to close that gap. For this purpose, a NW needs to contain required functions, examined product and their conjunctions. There will be one NW for each concept in order to compare them to each other. Subsequently, the NWs are analyzed and evaluated. The evaluation should support the developer in his decision.

The functions of the RPE describe its various strokes and all the necessary characteristics to ensure combustion. As described in chapter 2.1, the following functions are known in the very early stage of development:

- Intake: a mix of air and fuel enters the chamber
- Compress: the volume is reduced while increasing the pressure
- Fire: ignition by lighting of the sparking plug
- Expansion: work of the engine, pushing the pistons at high pressure
- Ejection: the gas is pushed out of the engine
- Control: control-gear for regulating the required movement of the pistons
- Density: closeness of combustion chamber
- Cooling: reducing the engines temperature
- Moving backwords: avoid movement reverse to the second piston pair
- Acceleration: speed up the first piston pair
- Slow down: decelerate the piston pair after an acceleration
- Linear movement: moving the second piston pair slowly behind the accelerated one

At this point, the developer can evaluate the interaction of functions and measure the dependence between them. This can be assessed on a 10-step scale, which is often used at the automobile industry to give a subjective evaluation (DIN EN 60812, 2006), cf. Figure 3:

1	2	3	4	5	6	7	8	9	10
less influence	.	.	.	middle influence		.	.	.	high influence

Figure 3: 10-step-scale

This allows a more detailed description of the dependencies among the functions. The NW's nodes depict certain functions of the product. Edges between nodes specify interactions of these functions. The weight of an edge represents the influence of one function on another, cf. Figure 4:

Figure 4. Node A has an influence of 7 of 10 on Node B

The result is a weighted and directed NW of the product's required functions, cf. Figure 5:

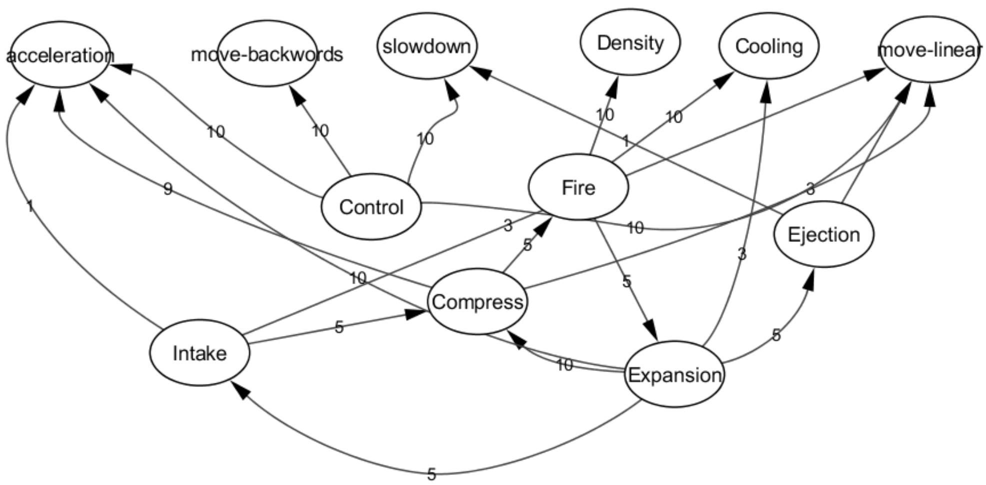

Figure 5. Weighted and directed function-network modelled with Cytoscape

3.2 Modelling the component's networks – concept A and B

The early stages of the PDP are supposed to result in several concepts, each of them meet the requirements in another way. A concept contains various possible components. Similar to the approach above, a NW will be created for the concepts.
Components are linked based on interactions regarding geometry, energy, solid- or information-exchange. However, if insufficient data is available, it is also possible to create edges based on subjective evaluations of the developer.
By using such subjective evaluations, the RPE components' connections are defined by the developer as follows: Part "a" affects part "b" with a certain intensity, cf. Figure 6. The aforementioned 10-step-scale can be used to weight the dependencies. The result is a set of weighted and directed NWs, each representing their respective concept, cf. Figure 6:

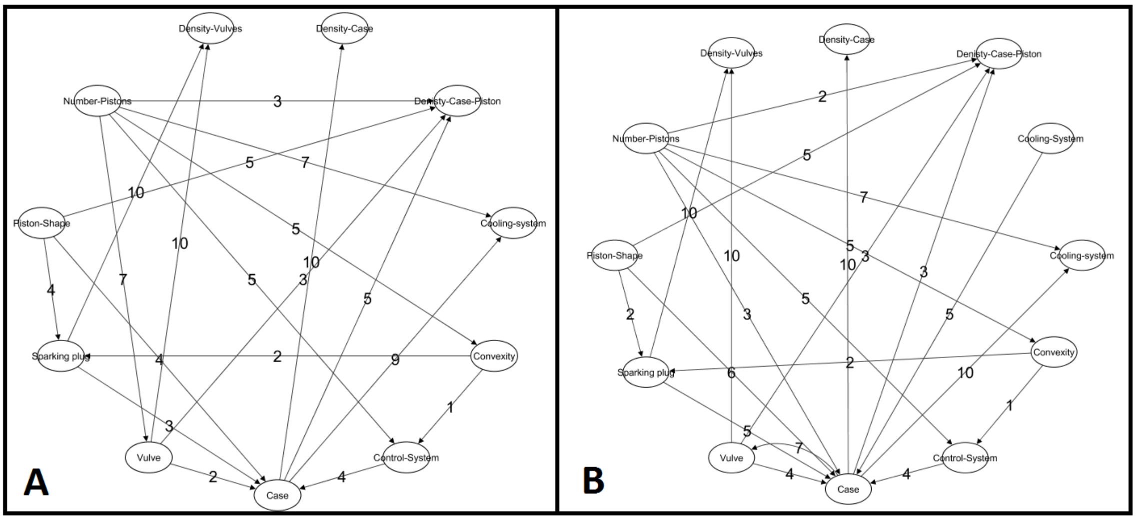

Figure 6. Weighted and directed part-networks of concept A and B, modelled with Cytoscape

All concepts have to fulfill the same requirements. Hence, the function NW remains unchanged, even if the concepts' NWs differ.
Consequently, the function NW is linked to the NWs of the concepts, cf. Figure 7. Each node of a concept, i.e. each component, can be linked to one or more functions. It is not necessary to assign a direction to these edges, because all edges will be evaluated with no distinction between inbound and outbound.

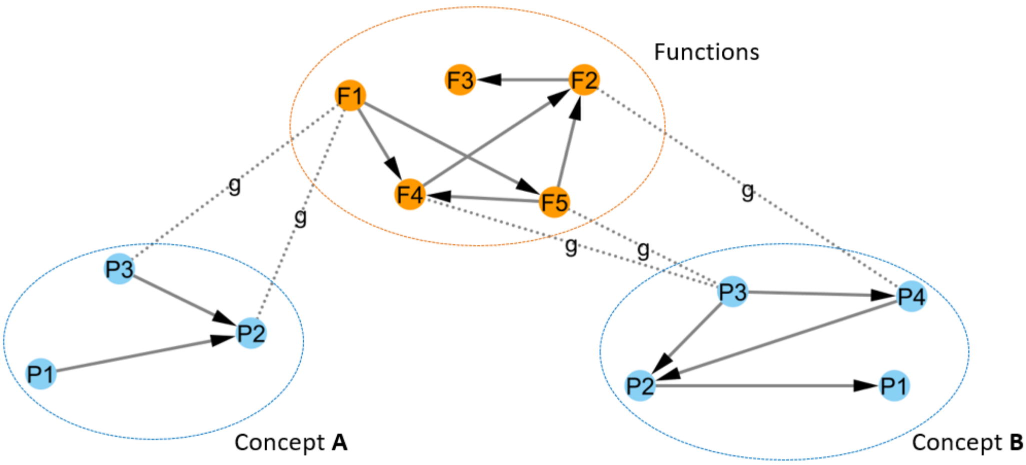

Figure 7. Overall network showing concept A and B connected to the functions

On the other hand, it is easy to define a weight of the edges regarding their importance for a certain function. A 10-step-scale will be used here, too.

3.3 Analysis of the networks using methods of network theory

The previously established NWs allow calculations that are similar to those typically performed in the graph and network theory. Those calculations will be used for an initial risk assessment (Parraguez, 2015a).
The identification of each node degree primarily serves as an indication for the critical components or functions. However, since this approach is dealing with directed graphs, it is possible to determine a more specific node degree exclusively considering the outgoing edges (Krischke, 2015).
In order to obtain a relation and to keep the values comparable, the node degree has to be normalized by the maximum emerging node degree:

$$F(d_j) = \frac{\sum_i d_{i_j}}{\sum_i d_{i_m}} \ , \ i \triangleq outgoing\ edges,\ j - node,\ m \triangleq node\ with\ highest\ d_i \quad (3.1)$$

The same calculation is made for each node of the concept NWs:

$$P(d_j) = \frac{\sum_i d_{i_j}}{\sum_i d_{i_j}} \ , \ i \triangleq outgoing\ edges,\ j - node, m \triangleq node\ with\ highest\ d_i \quad (3.2)$$

P and F-values are per definition between 0 and 1. If a function severely influences another function, F would approach the value 1. If it is an insignificant interaction, the value will be close to 0. The same applies to the components. An important component's P-value would approach 1. If it is an insignificant part, P will be approximately 0. This analysis allows the developer to detect the most influential nodes.
The sum K is formed as a final statement about the degree of risk. It describes the connection of the function and the component network of concept A and B:

$$K(d) = F_j \cdot \sum_i P_i \cdot g_i \ , \ j - node,\ i - connected\ Parts\ to - with\ weight\ g_i \quad (3.3)$$

The value K is assigned to each node of the function network. It evaluates their impact on the overall function. A high value of K points to a high risk, cf. Figure 8:

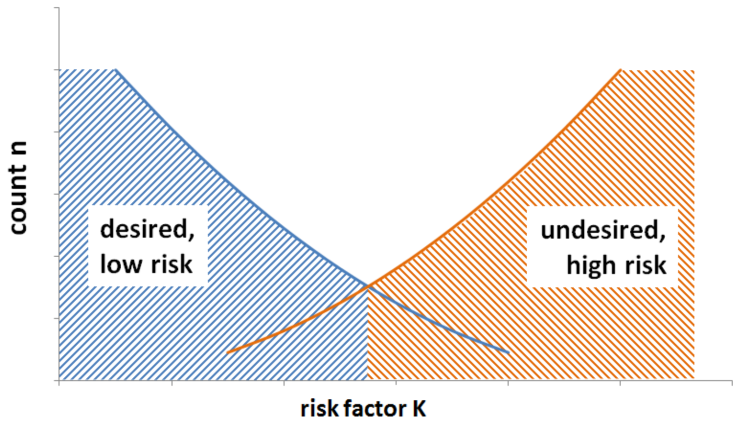

Figure 8. Expected and desired distribution of risk value K

This happens whenever one of the essential functions is run by few critical components. This shows that an important function could fail and have a big impact on the performance of the RPE. The distribution of K-values describes the overall risk of a concept.

A non-critical variant should make it possible to avoid high K-values, and instead reach an optimum of n-times 0. Consequently, it is important to spread the risk of a malfunction on several components rather than rely on one critical part. Analyzing the K-values of the RPE-concepts A and B, the following K-distribution is desired (see Figure 8).

It is now possible for the developer to analyze the two concepts and to evaluate the expectable risk by applying and using the methods of the NW theory. It is also possible to identify critical nodes and to make a final decision on the risk involved in a concept.

4 Conclusion and discussion

This article shows a way to use network and graph theory in order to support the development of new products. The approach describes a risk analysis based on intitally insufficient data during early stages of a product development process. The lack of information on potential malfunctions and failure of components is corrected by the clarification of dependencies between functions and parts of a concept. This method is used for modelling a function network, which is linked to multiple concept netwoks. It is compareble to the FMEA approach. All three netwoks are weighted and directed.

The mathematical analysis of a single network opens up the possibility to define a risk value K. This paper explains, which K-values are desired and undesired respectively. The K-value replaces the RPN-number of the FMEA and represents the impact of a single part on the overall system. Using NWT, the columns of the FMEA are summarized into one NW.

The developer now has the possiblity to analyse concepts in a very early stage of the product development process and make decisions between different concepts based on explicit numbers. This is important when the available amount of data is insufficient for a FMEA. Moreover, this appraoch allows the developer to identify critical nodes, that cause high K-values and increased the expectable risk. The given example of an application of network theory shows that there is a large potential to support developers during the PDP (Chahin, 2015). There are ways to evaluate early concepts even with very little data. Therefore, it is possible to estimate risks of a development in earlier stages of the process. In contrast to the proposed approach, commonly used methods rely on a large amount of information about the product and, thus, can only be executed during later stages. The approach represents a FMEA alternative that supports the decision making process in terms of involved risks by providing in-depth insights to the dependencies between required functions and possible parts.

As the model represents the real situation, it is as faultless as modelled by the developer. However, it highlights the possibility of understanding the relation of data on each other and supports the developer to defend his decision.

5 Outlook

Several options exist to use the NWT except of calculating need degrees. Larger and more detailed NWs allow for additional methods (Parraguez, 2015a). Another possibility is the introduction of centrality values as an indicator of a node’s position within the NW. This enables the search for functions or components of special interest and meaning, which could have a distinctive impact on the overall system or subsystem. In addition, it might be possible to use community detection algorithms to evaluate a NW and restructure it regarding selected parameters. The NWT adds a possibility to determine the complexity of a concept during early stages of the product development process. Further information could be gained by

examing the second or third node degree. In this way, indirect relations between unconnected components and functions might be identified.
Alternatively, it might also be useful to extend the NW by adding subnetworks to nodes. This, in turn, would lead to a higher level of detail and would lead to advanced mathematical options.

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