# Product-Process MBSE and Dysfunctional Analysis Approach Applied to a Production Line

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Mourad Chibane, Faïda Mhenni and Jean-Yves Choley
Quartz Laboratory, Supmeca
Saint-Ouen, France

***Abstract*— The integration of new technologies and the increasing customer requirements in manufactured products requires more complex and automated production lines. Manufacturing processes are usually designed for a specific range of products. Thus, it is important to consider the dysfunctions of the product ans process conjointly. The aim of this paper is to propose a Model-Based Systems Engineering product-process approach for the dysfunctional analysis. This methodology consists in two phases: a functional analysis using SysML language for the system behavior and structure modeling, and a dysfunctional analysis using a combination of FMECA and FTA considering external intervention of the humans. This approach highlights the relations between the process and product failures and the importance of MBSE in the product-process dysfunctional analysis.**

***Index Terms*— Dysfunctional analysis, MBSE, FTA, FMECA, Product, Process.**

## I. INTRODUCTION

The manufacturing industry benefited from the technological advances in automation over the last twenty years to strongly enhance its performance and competitiveness. Today, the scientific and technological progress brings several possibilities of collecting information to enhance the piloting and controlling of the industrial production lines thanks to the presence of numerous sensors and control components integrated into the machines. However, this improvement is not well used because of a delay in the development of the production monitoring and piloting tools with regard to the development of the machines.

The fourth industrial revolution, that was first introduced by the German government through a strategical project, promotes the computerization of manufacturing and thus benefit from available technologies to the full extent. This initiative was later supported by other countries and regions [1]. Solutions proposed by the concepts of the Industry 4.0 allow to optimize data collection and analysis to convert it into real-time exploitable information for a better monitoring of the production processes.

The present work is done within the "EUGENE" project which aims at the modernization of the production lines in perfume industry in order to improve existing systems and make them compliant with Industry 4.0. These improvements shall enable an optimal exploitation of the production line and assure a better product quality. A multi-view modeling of the industrial scenario and a reliability analysis are the starting point to the expected improvements and play essential role in the realization of this project.

The reliability analysis aims at ensuring the good functioning of the production line during the exploitation by identifying and reducing the effects of potential failures. There are several methods for the reliability and safety analysis. The most used in the manufacturing industry and other critical sectors are the Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA).

FMEA is a systematic inductive method for reliability analysis. It aims at estimating the possible effects and causes of the potential failure modes. FMEA provides a classification of the failures using Risk Priority Number (RPN). FTA is a structured deductive method for the analysis and the identification of the internal and external causes of a failure. FTA provides both qualitative and quantitative analysis. Unlike FMEA which considers single component or function failures, FTA analyzes the combination of basic event failures that lead to a given system-level failure or faulty state (usually called top/ undesirable event).

The use of these methods for safety analysis requires a thorough knowledge of the studied system [2],[3]. Thus, a system model is necessary to assure a good application of FMEA and FTA analyzes.

To model system under study, there are several methods, tools and approaches. Model Based Systems Engineering (MBSE) approaches using SysML language [4] is widely used to provide a descriptive architectural model of systems. SysML allows building structured system models with different views and traceability links enabling to efficiently conduct modifications on the systems and to compare various configurations or possible solutions.

However, most of MBSE approaches focus on the product modeling independently from its productions system. Due to the mutual interdependence between both the system (or product) and its production system, the latter should also be considered since early phases of the product design to enable the optimization of the product-process simultaneously. Such conjoint design highlights the inter-dependencies and thus helps in making better design choices as shown in [5].

This paper presents a methodology for improving an existing production line within the EUGENE project. The proposed methodology is based on a conjoint modeling and dysfunctional analysis of the product (perfume) and its production system in order to identify the critical points that

need to be improved in the whole process while taking into account the product-process dependencies.

The approach starts with building a system model for both the product and the process and then uses these models to perform FMEA and FTA analyses for both the manufacturing process and the product in order to identify the ways in which defaults in the product influence the production line and failures in the production line lead to a quality default in the product. The critical points needing to be improved are identified at the end of the approach.

The remainder of this paper is organized as follows. Section II presents some related work on MBSE approaches and the integration of the safety and reliability analysis. Section III explains the proposed methodology for the product-process dysfunctional analysis starting with the functional analysis using SysML and the dysfunctional analysis with the FTA and FMECA methods. A case study is presented in section V to illustrate the steps of realization of the methodology. Finally, the paper is concluded in section **??**.

## II. Related work

This section discusses related work about the integration of MBSE with safety and reliability analyses based on FMECA and FTA. Concerning MBSE approaches, SysML is one of the most used languages in both academic and industrial fields. Developed by the Object Management Group (OMG), SysML is a graphical systems modeling language with the objective of providing an easier and less ambiguous way for the description of complex systems. Indeed, it allows modeling of different complementary aspects of a system in a single model by offering several diagrams to represent the requirements, the structure and the behavior. It is used for MBSE in several works such as [6] that presented a SysML-based methodology to design mechatronic systems starting from the initial requirements until the synthesis of a system architecture that respects them. SysML is also complemented with other techniques such as artificial intelligence in [7] where an approach called SysDICE is presented for the conceptual design and evaluation of mechatronic systems. Mhenni et al.

Other works also attempted to integrate safety analysis within SysML-based MBSE approaches. For instance, Mhenni et al. [8] complemented the methodology presented in [6] with the integration of safety and reliability analysis and proposed an approach called SafeSysE. This approach uses SysML language for the critical system modeling then performs the safety analysis by automatically generating safety artifacts such as (partially filled) FMEA and FTA from the system models. Safety analysis is performed based on the generated artifacts and the resulting safety requirements imply changes in the system design to take into account the results of the safety analysis.

Evans et al. presented a methodology in [9] to perform safety analysis for a NASA system designed for a long duration mission. Based on an MBSE approach, they represented the system with SysML under various views. Then, based on the information provided by the system model, they implemented an automatic extraction of the FMECA. In addition, FTA is performed on top level events selected from the system effects list in the previously generated FMECA.

Several similar works can be found in literature such as [10], [11] to cite a few. However, although the proposed methodologies help in bridging the gap between safety analysis and MBSE, none of them considered the human factors as a cause of the failure while human errors play a significant role in causing system failures.

A number of studies have postulated a convergence between FMEA or FMECA and FTA. Indeed, there are two main approaches in the application. In one side, the recursive manner, starting with the FTA to identify the failure modes and after that the application of the FMEA proposed by Peeters et al. [12]. On the other side starting with the FMEA and develop the resulted effects using FTA the most used one [9]. However, the FMEA Risk Priority Number (RPN) present weakness in the real appreciation and signification in the case of an equal Number. Other approaches are proposed to calculate the RPN like Fuzzy FMEA to Separate the priority of intervention, but it remains an ambiguous task for the application [13].

## III. Methodology

In order to perform a complete safety analysis for a given system, the international standards such as [2] recommend relying on a thorough knowledge of its architecture and functioning. These aspects can be described in the system models using languages such as SysML, that provides designers and experts with graphical multi-level views of the system. Consequently, the first step of the proposed approach is to build a system model with SysML.

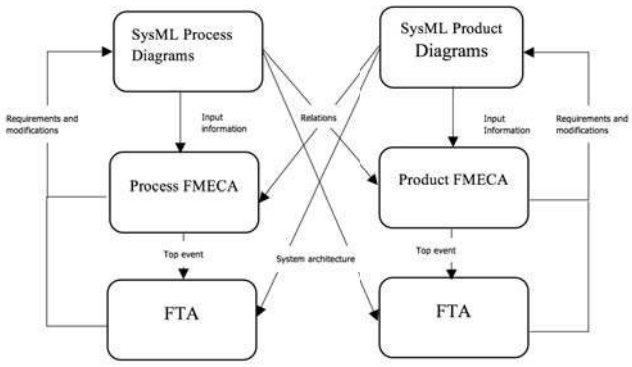


Fig. 1. Steps of the Proposed Approach

When it comes to dependability, FMEA and FTA analyses [14] are among the most widely used techniques for reliability and safety.

They focus respectively on the failure effects and propagation in the studied system. However, they are usually performed without a close collaboration with system designers.

In this paper, we propose a methodology that:

- strongly connects design to safety analysis since the latter is based on MBSE models.

- takes into account the inter-dependencies between the product and its production system.

The proposed integrated approach combines the MBSE approach and safety and reliability analysis of both the product and its manufacturing line. First, the MBSE approach provides the necessary information about the system/product and its production line. Then, dependability analysis is performed through FMEA and FTA techniques based on the information provided by MBSE models. The steps of the proposed approach and their relationships are presented in Fig.1.

As, for this work, we aim at improving an existing system, we start our MBSE modeling from the functional view given by the SysML activity diagram. After that, the Block Definition Diagram and Internal Block Definition Diagram is used to model the structure of respectively the product and its production line.

### A. MBSE System Model

In this first step, the nominal model of the system in built using an MBSE approach with SysML language. The functional architecture, system structure and components interactions are respectively modeled for both the system and its production line.

*1) Functional architecture:* SysML activity diagram is used to model the activities or functions performed by the system under study be it the product itself or the production line.

The SysML activity diagram provides a general view about the functional breakdown of the system and the different flow transformations among the functions and sub-functions represented by activities or actions in SysML. The breakdown may be performed into several levels until it is obvious to identify the components to be allocated to the functions.

*2) System Structure:* After the different functions are identified in the activity diagram, a Block Definition diagram provides the composition of the system considered as the main block and the hierarchy of the components that constitute it, be they software or hardware. As a Structure Diagrams, the BDD adduces information about the structure of the system by specifying their role and their quantity. Each component can be the object of a more detailed description by specifying its components.

*3) Components Interactions:* The final step in the MBSE part of the process is to model the interactions among the components. This is achieved through an IBD diagram in accordance with the previous steps, i.e. the flows exchange in the functional architecture and the components allocation. Indeed, all the system components declared in the BDD are automatically included as parts in the IBD. In other words, the IBD is an internal view of blocks and it provides information about connections between the components. The logical organization and the functional distribution of components are clearly shown. Based on the in, out or bidirectional flow ports, the IBD highlights the physical and/or signal flows circulation in the represented system by the directed links between the parts.

### B. Safety Analysis

Once the system model is built, a dysfunctional analysis is performed to identify the critical points that need to be improved. This analysis begins with an FMECA in order to identify the potential causes and effects for the failure modes and their criticality. Then, an FTA is performed to represent the possible combination of basic events which engenders the undesired event.

*1) Failure Mode Effects and Criticality Analysis (FMECA):* FMECA is a systematic widely used method for the analysis of dependability in several domains to determine the causes and effects of the defined failures modes in a technical system. It is a deductive and bottom-up method [3]. The analysis starts from the functional or components level, determines the failures modes of each element (function or compnent) to identify the consequences of each failure mode at the system level. The FMECA is performed by a safety experts. The inputs of an FMECA are the functions and/or components and should be provided by the designers or MBSE team.

TABLE I
EFFECTS APPRECIATION FOR A FAILURE ON THE PRODUCT AND PROCESS.

| Effect Appreciation | Effects on the Product (for process FMECA) | Effects on the Process (for product FMECA) |
|---|---|---|
| **None** | No effect | No effect |
| **Minor** | Problem in the use of the product | Loss of production time |
| **Low** | Quality problems | Production stop for < 2 h |
| **Major** | Non-commercial product | Production stop for > 2 h |

FMECA includes a criticality evaluation to classify the failure modes based on a Risk Priority Number (RP. The RPN is the product of three indicators: an occurrence indicator (O), a severity indicator (S) and a detection indicator (D) [2]. The weakness of the traditional FMECA is that in the case of an equal RPN for two different failure modes the determination of the most important one is not done. In this paper, we propose a modified FMECA to solve this problem by the addition of criteria based on the effects on the product in the case of a process FMECA and the effects on the process in the case of the product FMECA. The classification of the effects is given in the TableI and range from "No effect" to "Major effect". The rates for the parameters O, S, D are also determined by the industrialist for both the product and the process and range from 1 to 4.

*2) Fault Tree Analysis (FTA):* FTA is a deductive reliability analysis method based on a deductive process from an undesired event to a potential combination of failures that causes it, called basic events for the FTA. It is a top-down method based on the directed cyclic graph (Tree) composed

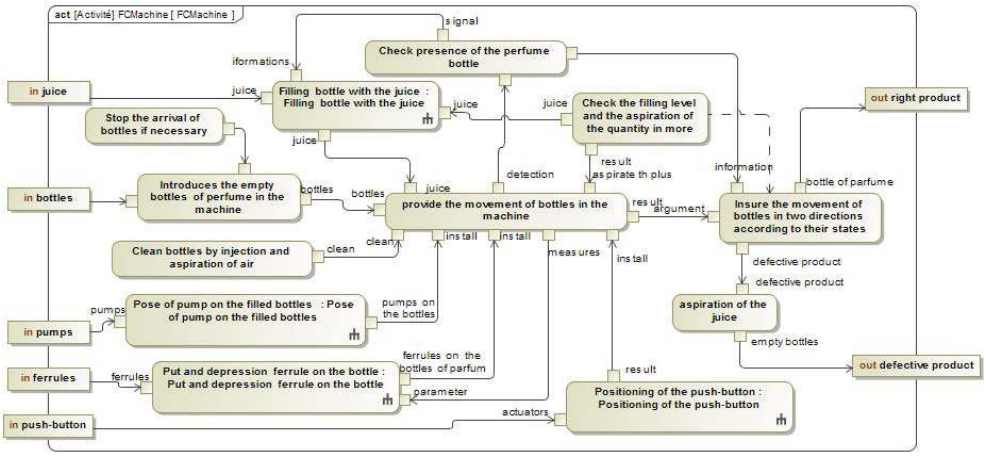


Fig. 2. FCMachine Activity Diagram

of two types of nodes "events and gates[15]. The inputs of a complete FTA analysis for the liability is the knowledge of the studied system and the detailed information about the functioning and the relations between the components of the system. Information provided by the functional analysis done using MBSE. In addition, the definition of the top event to start the FTA is an important step of the analysis. Indeed, the top event is provided by the FMECA analysis performed on the same system. The FTA can be performed on a process as well as a product.

## IV. Case Study: The Perfume Pump Installation

In this section, the proposed methodology (Fig.1) is applied on a case study. To give a simple overview of a part of the studied system to better understand the process of achieving the methodology. First, the functional analysis of the two systems is given in the section IV-A. Second section IV-B, the application of failure analysis and discussion of the results. Because of the lack of space constraints and clarity, we only show a part of the system.

### A. MBSE System Model

For the case study the functional architectures of the product and its production line are both modeled using activity diagrams. For the production line, two different activity diagrams are built, one for the whole production line describing the different steps for the production of the perfume (the filling and the assembly of the different components of the perfume bottle) given in Fig.2 and another focusing on the pump pose given in Fig.3.

The functional architecture of the product (perfume bottle) also modeled is not presented in this paper.

Once the functions are identified, the composition of the product and the production system are both modeled by allocating the components to the appropriate functions and then building a Block Definition Diagram to describe the structure (composition). Fig.4 shows the composition of the production line. The product components will be shown directly in the next step. The multiplicity (number at the bottom of the arrows) indicates the number of components that are part of the system.

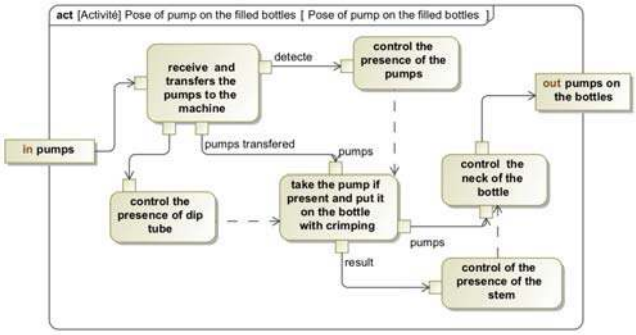


Fig. 3. Pumps installation Activity Diagram

At this level, we are able to model the interactions among the identified components to show the different flow exchanges among them. For the production line, a first level IBD is shown in Fig.5. This diagram shows that composed of four main subsystems: the "Juice Circuit", the "Bottle Circuit", the "air Compressor" and the "Electric Power Supply". In the following, we will be interested in the dysfunctional behavior of the "Pump Placing System" that is part of the "Perfume Bottle Circuit". The IBD of this sub-system is thus given in Fig.6.

The product models are realized following the same steps as for the processes and due to their simplicity, we only provide the IBD showing the flow exchange for the perfume bottle in Fig.7.

### B. Safety Analysis

*a) FMECA:* The failure modes that we choose for the application of FMECA on the subsystem are: "fail to perform" and "performs incorrectly". Based on the functional analysis we extract manually the components list and their functions in the system to constitute the first FMECA worksheet. After that, the safety team experts directly add the information about the Occurrence, Severity, Detectability,

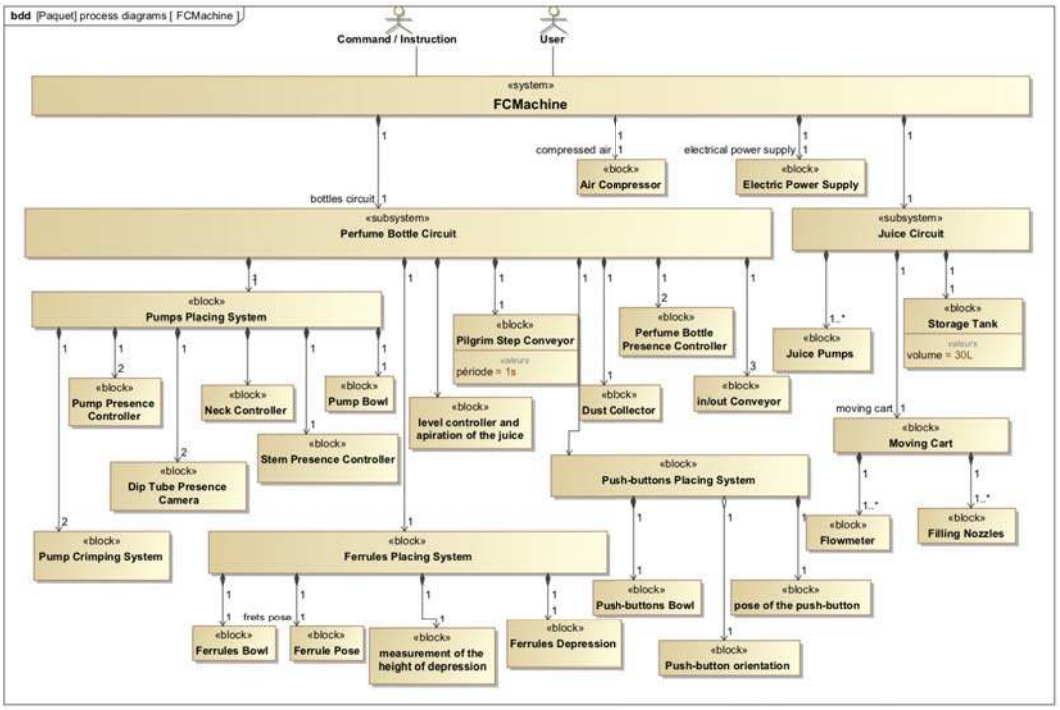


Fig. 4. FCMachine Structure Diagram (BDD)

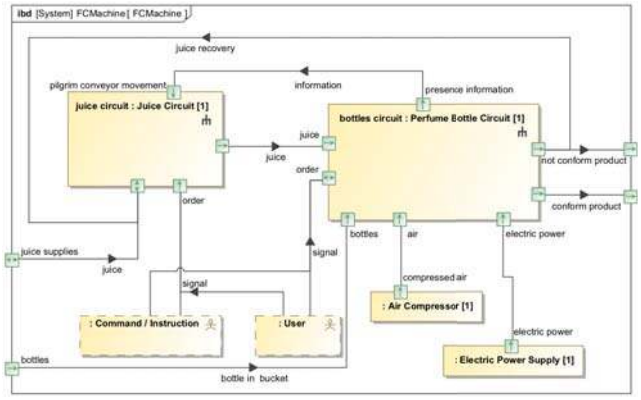


Fig. 5. FCMachine Internal Block Diagram

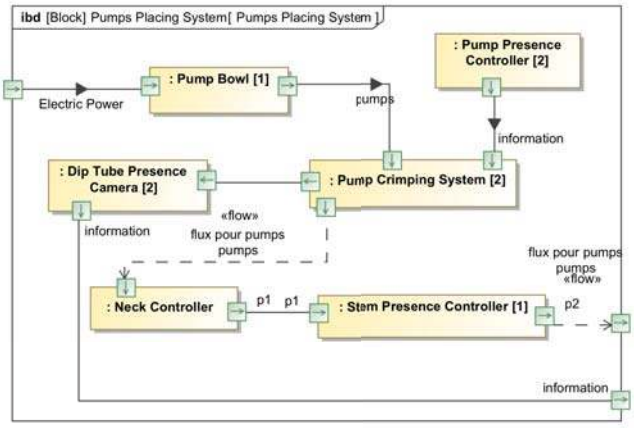


Fig. 6. Pumps Installation Internal Block Diagram

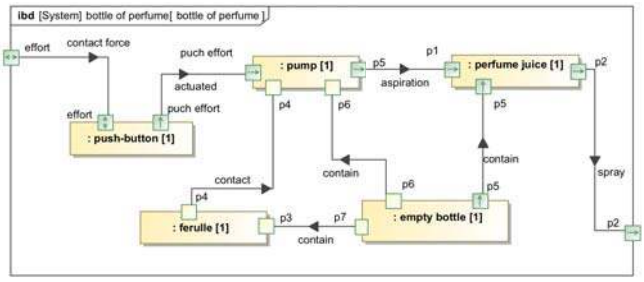


Fig. 7. Product Internal Block Diagram

and effect on the product or effect on the process based on the available rating tables.

For the process FMECA, we considered that the composition of the studied system is a set of the functional chain of an automated system. So, each component is a separate chain made up of an effector and an actuator. Indeed, the generic causes of the failures are parts of the functional chain. In addition to that, we take into account the human, product, and interaction of the product and process causes. For the product FMECA we propose a generic list of causes chaired by all the system components. The MBSE models provide the expert team with a multi-view and multi-level model of the system. Information about the occurrence, severity and detectability are extracted from the data collected during the operation of the production line. However, the values provided here are only approximate. The complete FMECA for the function "Aspiration of the juice to spray it in the air" is given in Fig.8. The last column gives the effect of each failure of the product on the process itself and this effect is also considered

| Product | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pump | | | | | | | | |
| Aspiration of the juice to spray it in the air | | | | | | | | |
| **Failure modes** | Cause | O | Direct effects | System (Product) effects | S | D | RPN | Process Effects |
| **Fail to perform** | Manufacturing defect | 2 | Non-functioning | defective product | 3 | 2 | 12 | Loss of production time |
| | Damaged by packaging | 2 | Non-functioning | defective product | 2 | 4 | 16 | Production stop for > 2 h |
| | Operator Error | 1 | Non-functioning | defective product | 4 | 2 | 8 | Loss of production time |
| | Process / Product Interference | 2 | Non-functioning | defective product | 2 | 2 | 8 | Production stop for < 2 h |
| | Juice pollution | 1 | Non-functioning | defective product | 4 | 4 | 16 | No effect |
| | Assembly (components of a product) | 2 | Non-functioning | defective product | 3 | 3 | 18 | No effect |
| **Performs incorrectly** | Manufacturing defect | 2 | Functioning problems | Uneven perfume spray | 3 | 2 | 12 | Loss of production time |
| | Damaged by packaging | 3 | Functioning problems | Uneven perfume spray | 2 | 4 | 24 | Production stop for > 2 h |
| | Operator Error | 1 | Functioning problems | Uneven perfume spray | 4 | 2 | 8 | Loss of production time |
| | Process / Product Interference | 3 | Functioning problems | Uneven perfume spray | 2 | 3 | 12 | Production stop for < 2 h |
| | Juice pollution | 2 | Functioning problems | Uneven perfume spray | 4 | 4 | 16 | No effect |
| | Assembly (components of a product) | 2 | Functioning problems | Uneven perfume spray | 4 | 3 | 24 | No effect |

Fig. 8. Product FMECA Extract

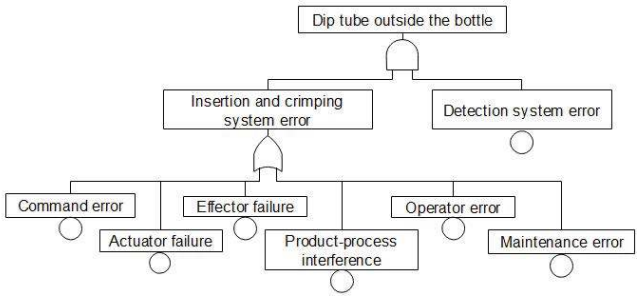


Fig. 9. Fault Tree

in addition to RPN to classify the different failure modes and identify those who require a bigger effort to deal with. In the same way, we augmented the process FMEA by the effects on the product and this was part of the decision making about the enhancements to bring to the production line.

*b) FTA:* Fault trees are then built for each critical system effect identified in the FMECA. Taking the considered system effect we want to mitigate as a top event of the fault tree, the combinations of causes leading to that event are identified through the construction of the corresponding FT. Solutions such as redundancy or higher reliability should then be considered in enhancing the system by eliminating single failure points. The fault tree for the "Dip tube outside the bottle" is given in Fig.9

### C. Discussion

The modeling of the product and the process using SysML allowed us firstly to have a global view on the functioning of the system and its structure by providing the multi-view and multi-level models, and secondly to establish a consistent basis for the dysfunctional analysis with the use of FMECA and FTA method, and to take into account the relations between the production system and the product. The case study provides a clear and practical example of the proposed approach. The SysML modeling allows us to perform a reliability analysis in an easier and consistent manner, with less time needed. The deployment of the method provides reliability information on both the manufacturing system and its product, taking into account all components and the relation between the production system failures and the product defects.

The FMECA highlights potential causes and effects of a failure mode of each component separately. The FTA provides a mapping of the combination of failures which may generate the undesired top event, taking into account the relationship between the components of the system. These analyses generate change recommendations on the production system and the product in order to avoid potential failures.

However, implementing this method comes at a cost since a dual product-process system modeling has to be performed. This may be a heavy task for a highly complex manufacturing system, but this kind of modeling can be reused and adapted if it is applied to a family of systems. A real added value may come with a partially automated generation of FMEA and FTA artifacts, thus reducing the whole modeling and analysis task.

## V. Conclusion and Future Works

In this paper, we have proposed a Model-Based System Engineering approach for the reliability analysis on a perfume manufacturing line and its product. They are both modeled using SysML modeling language with Activity Diagram, Block Definition Diagram, and Internal Block Definition, providing a multi-level and multi-view modeling of the structure and the functioning of the whole product-process system, thus allowing experts to perform a consistent reliability analysis using FMECA and FTA to determine the potential process failures and their effects on the product and the potential failures of the product and their effects on the process functioning.

We also suggest a modification in the priority classification of the Risk Priority Number depending on the effects of the process on the product in one hand, the effects of the product failures on the process in the other hand, in the case of an equal RPN.

Our next research studies will extend the use of these SysML modeling, FMECA and FTA to support diagnostic during the production.

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