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Environmental Audit improvements in industrial systems through FRAM

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Abstract: Environmental risk management requires specific methodologies to focus audit activities on the most critical elements of production systems. Limited resources require a clear motivation to put attention on specific technological, human, organizational components, and often should address the monitor of interactions among these elements. Recent research in environmental risk looks at methods to deal with complexity as interesting tools to reduce real impacts on pollution and consumption. In this paper, we provide evidence of the advantage in using the Functional Resonance Analysis Method (FRAM), not only to identify the criticalities of a complex production system but to provide a methodology to continuously improve the audit activities in parallel with the introduction of technique to reduce environmental risk. The case study presents the evolution of environmental audit in a sinter plant, proving the need for a review of the criticality list and the successful application of FRAM to refocus the control activities.

Keywords: Risk-based audit; risk-management; environmental audit; functional resonance; Best Available Technologies.

1. INTRODUCTION

Recently, environmental assessment has increasingly shifted to the field of risk management (Boiral and Gendron, 2011; Knechel, 2007; Power, 2003) and resilience engineering (Patriarca et al., 2018), with greater demand for tools to identify risk levels and control critical issues (Oliveira et al., 2011). In this, the Environmental Audit (EA) increases its orientation to a risk-based approach, overcoming the limitation of a strict assessment of the compliance with regulations, with an always more common risk-based audit (RBA) (Noble and Nwanekezie, 2016). EA is a recurrent activity defined as a "management tool comprising systematic, documented, periodic and objective evaluation of how ell environmental organization, management, and equipment are performing with the aim of helping to safeguard the environment" (ICC, 1991). Starting from this, an Environmental RBA should focus on the environmental risks, considering the integration of human, technical and organizational aspects (He et al., 2015). The analysis of mutual causal factors is indispensable in the definition of the risk-based audit when its scope considers composite real case scenarios or complex system (Cardenas and Halman, 2016). Since modern plants are commonly considered complex systems, innovative systemic methods, i.e. FRAM (Hollnagel, 2012) or STAMP (Leveson, 2004), are plausible candidates to improve EA. Moreover, recent explorative researchers introduced a semi-quantitative evolution of FRAM to identify criticalities in the domain of safety (Patriarca et al., 2017c) and of environment (Patriarca et al., 2017d). Finding motivation from these topical applications, the paper investigates the potential of the FRAM method in the field of EA, specifically in combination with technological improvement choices. Thus, considering production as a complex systems, a methodological shift moves from a *causality credo* (an accident or incident happen because something goes wrong, with the possibility to find and treat its causes) to a *systemic approach*, that means even environmental risks occur because of tight couplings among human, technical, procedural and organization agents (Hollnagel, 2014; Patriarca et al., 2017b). This paper shows FRAM is a valid method to build a better knowledge about the criticalities of an industrial plant and to improve EA, specifically when technical solutions are added to process to reduce environmental impact and unforeseen criticalities may arise.

2. FUNCTIONAL RESONANCE ANALYSIS METHOD (FRAM)

2.1 The method

FRAM is a recent methodology to model complex systems and develop risk assessment (Herrera et al., 2010; Sawaragi et al., 2006) and accident analysis (De Carvalho, 2011; Nouvel et al., 2007). Literature presents applications especially focused on safety in several sectors, (e.g.) railway (Steen and Aven, 2011) maritime (Patriarca and Bergström, 2017), nuclear power (Lundblad and Speziali, 2008), oil production (Cabrera Aguilera et al., 2016; Shirali et al., 2013). FRAM is continuously improving with contributions of other approaches, to verify several paths of variability (Zheng et al., 2016), to cut subjectivity (Rosa et

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al., 2015), to reduce the complexity of its representation (Patriarca et al., 2017b).

2.2 The FRAM principles

The four principles of FRAM are (Hollnagel, 2012):

- Equivalence of failures and successes. Failures and successes come from the same origin, i.e. everyday work variability. Both should be considered in the analysis of the processes.
- Principle of approximate adjustments. The human factor adjusts everyday activities and performances to match the unexpected situations and conditions in complex systems.
- Principle of emergence. It is not possible to identify the deterministic causes of any specific event because some of these are emergent rather than resultant from a specific combination of fixed conditions. Some events emerge due to a combination of time and space conditions, which could be transient, not leaving any traces.
- Functional resonance. The variabilities in the processing of activities sometimes interact causing resonance in the final performances and risks. These interactions could be recognized and analyzed.

2.3 The FRAM building steps

Firstly, a FRAM analysis requires the clarification of the scope of the analysis, i.e. risk assessment or accident analysis. For the purpose of this paper, it is relevant only to discuss the risk assessment, because the goal is to integrate a risk-based approach in the EA. Then, this process requires 4 steps, as described below.

Step 1: Identification and description of system's functions. A FRAM function represents the activities required to produce a certain outcome. Every function should consider and possibly indicates input (I), output (O), Precondition (P), Resource (R), Control (C), Time (T). These six aspects are generally represented as corners of a hexagon and links represent the relationships among functions. Functions aim to describe daily system work as really done and not as imagined. The recent evolution of FRAM introduced hierarchical decompositions of processes (Patriarca et al., 2017a).

Step 2: Identification of performance variability. The functions' variability must be defined precisely. The technological functions consider the machinery and the probability of failures, usually because of specific conditions, (e.g.) sensors subjected to unexpected temperature conditions, machinery with inadequate maintenance. Human functions are tasks made by an individual or a small group of individuals, and their performances change rapidly and with high frequency. We should consider physiological, psychological and working conditions. Lastly, organizational functions consider the system rules, regulations or policies, which foresee big differences in the change (and thus a high amplitude).

Hollnagel (2012) classifies the different causes of performance variability in simple case, considering only the variability in timing and precision, or multiple case where more issues should be analyzed (e.g. speed, distance, sequence, object, force, duration, direction). In this paper, the so-called simple solution is sufficient to identify criticality and suggestions for EA. The timing variability can be too early, on time, too late or not at all (useless for its purposes or even not produced at all). Precision variability can be precise, acceptable, imprecise or wrong. If the output is precise, it satisfies entirely the needs of its downstream function. If it is acceptable, it requires some adjustment in the downstream function, even bigger in case it is imprecise.

A simple numerical score permits to apply a semi-quantitative score instead of a qualitative judgment (Patriarca et al., 2017c) like in Table 1, where the higher the score, the more critical the output variability.

Table 1. Variability scores

	VARIABILITY	SCORE
TIMING	Too early	2
	On time	1
	Too late	3
	Not at all	4
PRECISION	Precise	1
	Acceptable	2
	Imprecise	4

The variability of the upstream output j, OV_j is the product of these two scores, as in (1):

$$OV_j = V_j^T \cdot V_j^P \qquad (1)$$

where:

V_j^T represents the score of the upstream output j score in terms of timing;

V_j^P represents the score of the upstream output j score in terms of precision.

Step 3: Aggregation of variability. Because of the functional resonance principle, a specific step measures the potential variability of each function that can become resonant and lead to unexpected results. The aggregation of variability is a combination of the function variability and the variability deriving from the outputs of the upstream functions, considering the linked aspects' type. The effects of a coupling variability CV_{ij} of the upstream output j and the downstream function i is expressed as (2):

$$CV_{ij} = OV_j \cdot a_{ij}^T \cdot a_{ij}^P \qquad 1$$

where:

a_{ij}^T represents the amplifying factor for the upstream output j and the downstream function i, in terms of timing;

a_{ij}^P represents the amplifying factor for the upstream output j and the downstream function i, in terms of precision.

Step 4: Managing the variability. Step 3 provide evidence about the critical couplings, that FRAM links to explicit functions and variabilities to be changed or prevented. The critical couplings can be filtered by a threshold CV^* and a confidence level P^*, and then defining critical only the couplings whose cumulative distribution over the threshold is lower than (1- P^*). This classification defines priorities for the mitigating actions. Moreover, the analysis highlights critical paths in case other critical couplings, backward or afterward, link the same functions, in multiple upstream-downstream relationship functions of the process.

3. APPLICATION SCOPE

The paper focuses on the assessment of technical improvement in terms of environmental impact, through the implementation of FRAM as a tool for RBA. The application field is a real case of sinter plant, where iron minerals dust agglomerates with other fine materials using high temperature, to produce a porous mass that can be used in blast furnaces. The typical application of sinter process is the conversion of iron into steel (Van Wortswinkel and Nijs, 2010). Specific attention is given to blast furnace/basic oxygen furnace (BF/BOF) where the input materials i.e. sinter, iron pellets, limestone, and cokes, enter to be converted into molten pig iron (Fig. 1).

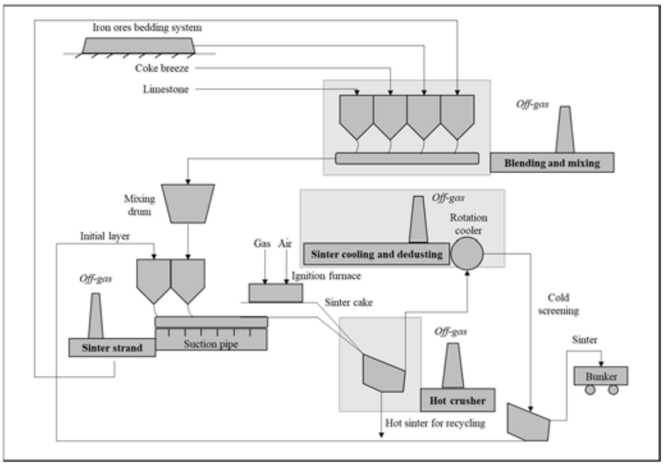


Fig. 1. Sintering process with BF/BOF.

3.1 *The phases of the process*

The sinter plant under analysis processes the downdraft sintering on continuous traveling grates, as detailed by EU BREF for Iron and Steel Production (Remus et al., 2013). The main phases of the production are the following:

- *Raw materials preparation*. Iron ore fines, fuel, fluxes, return fines of the sinter plant and in-plant metallurgical waste materials. Coke breeze, i.e. coke with a diameter less than 5 mm, is an output of external activities.
- *Mixing*. A rotating drum mixes the raw materials, the coke breeze and water forming agglomerated micro-pellets.
- *Sinter strand*. The sintering machine levels the micro-pellets into a 30-50 mm hearth layer. This is ignited by gas (or oil) burners.
- *Hot crushing*. The sintered cake is discharged into the roll crusher to a maximum particle size.
- *Hot screening*. Pellets whose size is less than 5 mm are dismissed to a recycle process.
- *Cooling*. The sinter is discharged onto a circular sinter cooler, whose diameter is 25m. The sinter layer's height is approximately 1 m and it is cooled by air.
- *Cold Screening*. The cold screening filter separates product by size, the product sinter (5-50 mm), bedding (10-20 mm) and return fines (0-5 mm).

The analysis of this specific process can be explained in terms of main equipment, operators, control points, and emission (Patriarca et al., 2017d). In the paper presents a 56 functions model of sinter plant under RBA, with the identification and aggregation of variabilities, a Monte Carlo analysis to calculate the criticality of couplings, and the identification of critical couplings paths. With this approach, the available indications from BATC (EU Commission, 2012) are enhanced by adding specific activities to be focused in EA (e.g. purchase material and monitor availability, transfer coke to the crusher, crush coke, transfer coke to BF, collect and gas purification from coke crushing and coke transfer).

Since the critical paths point to specific environmental risks and prevention opportunities, Best Available Technique (BAT) are available to act on these paths. The process designer can thereby consider available technologies to improve environmental performances, control, stabilization of activities involved in the critical paths, previously discovered. To understand the impact of improvements in techniques while using FRAM model, the real case considers improving the critical path "collect and gas purification from coke crushing and coke transfer" by adding a Bag Filter solution, as suggested in BATC.

4. BAT BAG FILTER IMPROVEMENT

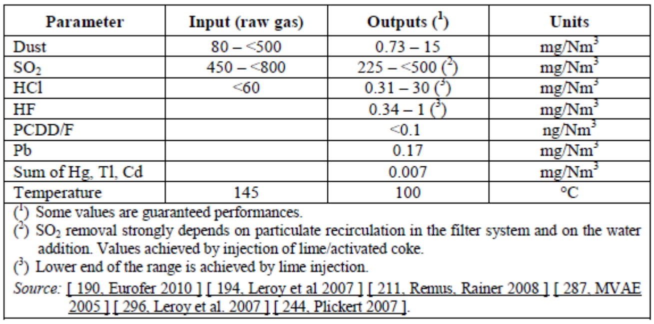
The Bag Filter MEROS (Maximized Emission Reduction Of Sintering) technique is a highly efficient dry gas filtration process for the treatment of gases coming out of agglomeration plants. The process works by applying, downstream of the ESP, a high performance sleeve filter. The MEROS process operates on dust and polluting components still present in the off-gases after treatment in electrostatic filters, reducing to the emission levels of dust to <10 mg/Nm^3 (Siemens VAI Metals Technologies, 2008).

4.1 Environmental improvements of the filter bag

The installation of a bag filter is highly effective in reducing dust and heavy metal emissions. Moreover, filter bag with additive injection allows a significant reduction of *PCDD/F* (of which sintering plants are the main source within an integrated steelwork) and acid gases such as *HF*, *HCl,* and *SO_2*. A reduction of *VOC* and *PAH* is also reported.

Table 2 shows the emission concentration values achieved for emissions from three sintering grids with bag filter systems.

Table 2. Emissions off sintering grids with bag filters



Parameter	Input (raw gas)	Outputs (1)	Units
Dust	80 – <500	0.73 – 15	mg/Nm^3
SO_2	450 – <800	225 – <500 (2)	mg/Nm^3
HCl	<60	0.31 – 30 (3)	mg/Nm^3
HF		0.34 – 1 (3)	mg/Nm^3
PCDD/F		<0.1	ng/Nm^3
Pb		0.17	mg/Nm^3
Sum of Hg, Tl, Cd		0.007	mg/Nm^3
Temperature	145	100	°C

(1) Some values are guaranteed performances.

(2) SO_2 removal strongly depends on particulate recirculation in the filter system and on the water addition. Values achieved by injection of lime/activated coke.

(3) Lower end of the range is achieved by lime injection.

Source: [190, Eurofer 2010] [194, Leroy et al 2007] [211, Remus, Rainer 2008] [287, MVAE 2005] [296, Leroy et al. 2007] [244, Plickert 2007].

4.2 Costs of the bag filter

The investment is in the range 16-35 $euro\ /Nm^3/h$ (for new and existing plants). The operating cost is about 0.3-0.6 *euro /t sinter* and depends mainly on the costs of supplying active carbon, limestone and extra energy. Table 3 shows examples of the cost of sleeve filters installed in some sintering plants.

4.3 FRAM model of sinter process with Bag Filter

The improvement through the insertion of bag filter requires new functions inside the FRAM model, thus 8 new functions are added (Fig. 2), analyzing the operative process of bag filters.

1) *Additive dosing*. The absorbent and desulphurizing agents (calcium hydroxide and lignite) are dosed and injected into the flow of gases exiting from the ESP.

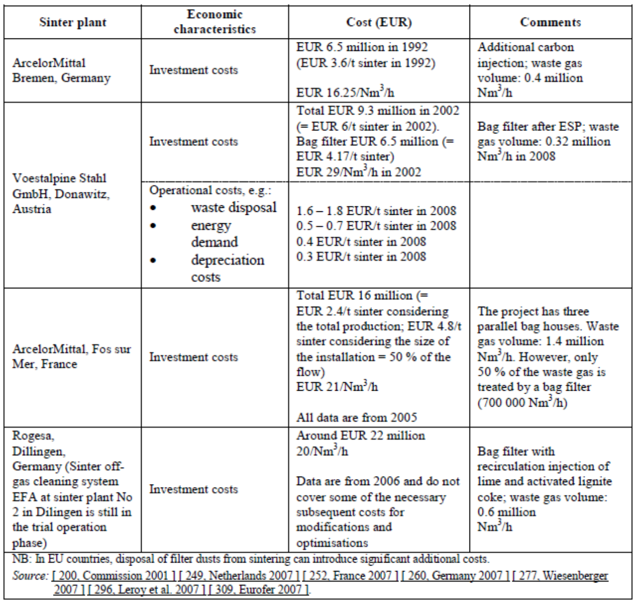
2) *Additive injection*. The prepared additives are injected into the flow of gases exiting from the ESP in the opposite direction to fix heavy metals and organic components.

3) *Conditioning reactor*. The gas flow passes to a conditioning reactor where it is humidified and cooled to a temperature of about 100 °C by injection from two water and air nozzles.

4) *Remove dust by a high-performance bag filter*. The flow of gas exiting the conditioning reactor passes through the high-performance bag filter in which dust with pollutants are removed.

5) *Recirculate dosing*. In order to increase the efficiency of the cleaning gas and reduce the additive costs, a portion of the dust is recirculated and injected into the flow of gas coming out of the conditioning reactor.

Table 3. Costs of bag filters from real applications



Sinter plant	Economic characteristics	Cost (EUR)	Comments
ArcelorMittal Bremen, Germany	Investment costs	EUR 6.5 million in 1992 (EUR 3.6/t sinter in 1992) EUR 16.25/Nm^3/h	Additional carbon injection; waste gas volume: 0.4 million Nm^3/h
Voestalpine Stahl GmbH, Donawitz, Austria	Investment costs	Total EUR 9.3 million in 2002 (= EUR 6/t sinter in 2002). Bag filter EUR 6.5 million (= EUR 4.17/t sinter) EUR 29/Nm^3/h in 2002	Bag filter after ESP; waste gas volume: 0.32 million Nm^3/h in 2008
	Operational costs, e.g.: • waste disposal • energy demand • depreciation costs	1.6 – 1.8 EUR/t sinter in 2008 0.5 – 0.7 EUR/t sinter in 2008 0.4 EUR/t sinter in 2008 0.3 EUR/t sinter in 2008	
ArcelorMittal, Fos sur Mer, France	Investment costs	Total EUR 16 million (= EUR 2.4/t sinter considering the total production; EUR 4.8/t sinter considering the size of the installation = 50 % of the flow) EUR 21/Nm^3/h All data are from 2005	The project has three parallel bag houses. Waste gas volume: 1.4 million Nm^3/h. However, only 50 % of the waste gas is treated by a bag filter (700 000 Nm^3/h)
Rogesa, Dillingen, Germany (Sinter off-gas cleaning system EFA at sinter plant No 2 in Dilingen is still in the trial operation phase)	Investment costs	Around EUR 22 million 20/Nm^3/h Data are from 2006 and do not cover some of the necessary subsequent costs for modifications and optimisations	Bag filter with recirculation injection of lime and activated lignite coke; waste gas volume: 0.6 million Nm^3/h

NB: In EU countries, disposal of filter dusts from sintering can introduce significant additional costs.

Source: [200, Commission 2001] [249, Netherlands 2007] [252, France 2007] [260, Germany 2007] [277, Wiesenberger 2007] [296, Leroy et al. 2007] [309, Eurofer 2007].

6) *Convey removed dust*. Dust removed from the system is conveyed to storage silos for later use in other applications.

7) *Conditioning reactor maintenance*. The conditioning reactor, as well as other plant equipment, must be kept in good condition and eventually replaced when no longer functioning or obsolete.

8) *Bag Filter maintenance*. The bag filter, as well as other equipment of the system, must be kept in good condition and replaced if necessary when no longer working or obsolete.

To better understand how FRAM is applied to this part of the system I-O-P-R-C-T elements and their relations from a function to the others is explicated in table 4.

Table 4. I-O-P-R-C-T elements (excerpt)

Downstream function		**Upstream function**
Name of function	*Aspect*	*Name of function*
Blend ore beds	Input	Purchase materials and monitor availability
	Control	Calculate stacking for ore bed blending
Calculate stacking for ore bed blending	Input	Purchase materials and monitor availability
	Resource	Provide SIMETAL software package
Calculate geometry of ore beds	Input	Provide materials information
	Resource	Provide SIMETAL software package
Calculate raw mix composition	Input	Plan sinter target quality
	Resource	Provide SIMETAL software package
Plan sinter target quality	Resource	Manage HR
Transfer ore blend to storage bins	Time	Blend ore beds
Transfer coke to crusher	Input	Purchase materials and monitor availability
Crush coke	Resource	Roll crusher maintenance
	Time	Transfer coke to crusher
Collect and purificate gas from coke crushing and coke transfer	Input	Crush coke
Transfer coke breeze to storage bins	Time	Crush coke
Transfer coke to BF	Time	Crush coke
Transfer limestone fines to storage bins	Input	Purchase materials and monitor availability
Transfer return fines to storage bins	Input	Screen hot sinter
Transfer additives to storage bins	Input	Purchase materials and monitor availability
Transfer waste materials to storage bins	Input	Blast furnace and Coke oven operations
Transfer raw materials to mixing drum	Input	Transfer ore blend to storage bins
	Precondition	Raw materials charging management and supervision
	Control	Control raw materials feed rate
Control raw materials feed rate	Input	Control hopper level
	Resource	Provide SIMETAL software package
Mix materials	Resource	Mixing drum maintenance
	Control	Manage water supply
	Time	Transfer raw materials to mixing drum
Manage water supply	Input	Plan sinter target quality
	Resource	Provide SIMETAL software package
Ignite coke breeze in the mixture	Resource	Cool sinter
	Control	Control ignition furnace temperature, pressure and hood
	Time	Place material to sinter on the heart layer
Control ignition furnace temperature, pressure and hood	Resource	Provide SIMETAL software package
BTP Control	Resource	Provide SIMETAL software package
Fine particles sintering	Input	Ignite coke breeze in the mixture
	Resource	Sintering machine maintenance
	Control	BTP Control
Dedust gas from sinter strand	Input	Fine particles sintering
	Resource	ESP maintenance
Monitor emissions from sinter strand	Time	Remove dust by high-performance bag filter
Collect solid emissions	Input	Dedust gas from sinter strand
Discharge sinter cake	Input	Fine particles sintering
Crush the sinter cake	Precondition	Shredding management and supervision
	Resource	Roll crusher maintenance
	Time	Discharge sinter cake
Collect and purificate gas from hot sinter crusher and sinter transfer	Input	Crush the sinter cake
Screen hot sinter	Input	Crush the sinter cake
	Resource	Screen maintenance
Cool sinter	Resource	Rotating cooler maintenance
	Control	Control cooler speed
	Time	Screen hot sinter
Control cooler speed	Resource	Provide SIMETAL software package
Screen cold sinter	Resource	Screen maintenance
	Time	Cool sinter
Move sinter to BF	Input	Screen cold sinter
Collect and threat water	Input	Dedust gas from sinter strand
Collect and purificate gas from cooling	Input	Cool sinter
Raw materials charging management and supervision	Resource	Manage HR
Sinter strand operations management and supervision	Resource	Manage HR

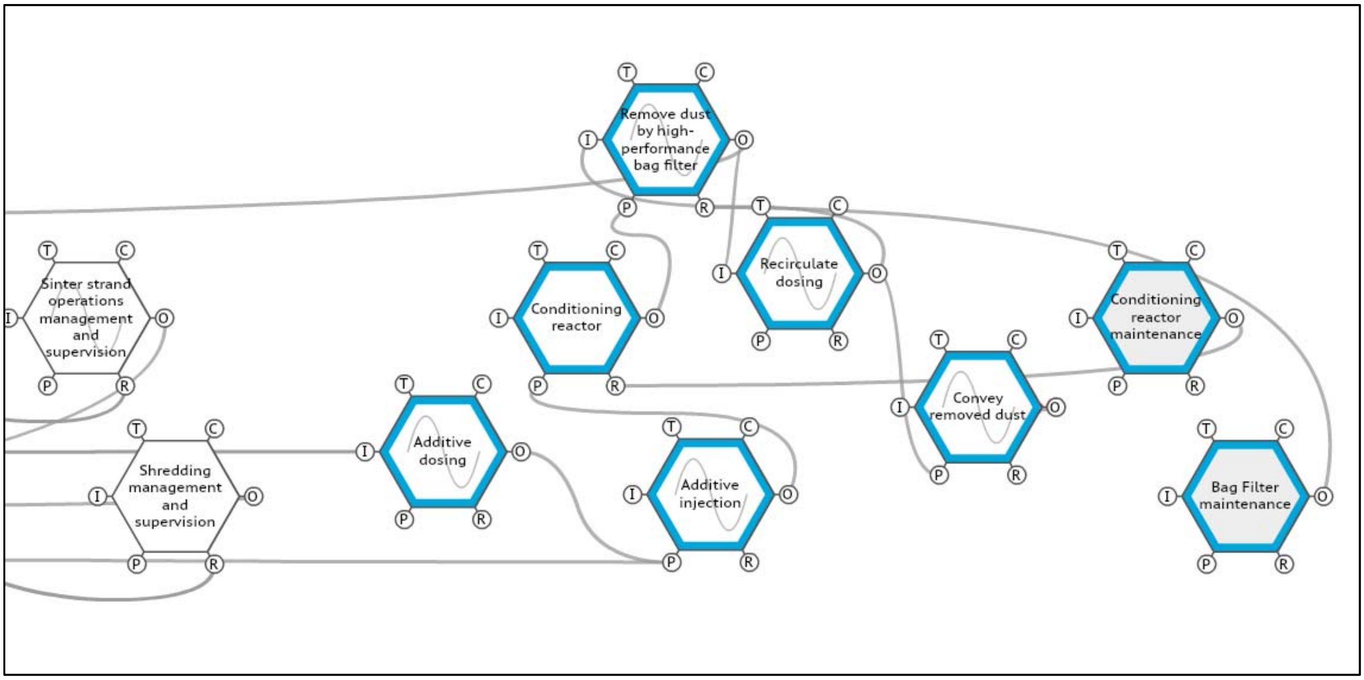


Fig. 2. FRAM modelling of Bag Filter MEROS (full model extraction)

Also for the newly defined functions, the two most representative parameters of each have been chosen and the probability values in probabilistic terms. The variability aggregation is then calculated considering an increased number of couplings (from 109 to 119) and a new criticality path is identified. In fact, in this second scenario, that risk manager could consider environmentally better than before, the FRAM model suggests a new criticality arises in the control of variabilities of functions *Purchase material and monitor availability, Additive dosing, Additive injection.*

5. CONCLUSIONS

The FRAM modeling of a sinter plant permitted to identify the critical path to be monitored in Environmental Audit, considering risk-oriented perspective. The BAT regulations suggest adding specific technical solution (e.g. filter bag) to reduce environmental risks, acting on the critical path. Nevertheless, the paper proved that FRAM used for risk assessment as part of the auditing process, introduces new critical paths, that is an important insight to manage auditing activities, monitor and investment. It is not trivial or self-evident to verify that the introduction of an improved technical solution could generate new critical issues. The main result of the paper is to prove how an environmental improvement should be accompanied by a modified environmental audit. Moreover, the FRAM modeling is a valuable method to keep on updating the list of criticalities to reduce environmental risks.

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