

Functional resonance in industrial operations: A case study in a manufacturing plant

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Abstract: The increasing complexity of large-scale industrial processes demands for innovative approaches to manage risk and safety. Considering the tendency to automate activities, the role of humans changed over years, generating different types of tight, even symbiotic, inter-relationships. In these coupled interacting scenarios, industrial processes have to be studied focusing jointly on technical and human elements of work, following thus a socio-technical perspective. This paper deals with an application of the Functional Resonance Analysis Method (FRAM) to analyze socio-technical safety-related issues in manufacturing. A detailed case study related to forging operations clarifies the outcomes of the proposed method, supporting the identification of mitigating actions to reduce risks and increase system's resilience.

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1. INTRODUCTION

In the last decades, industrial plants becomes increasingly complex in terms of interactions, number of components, levels of automations and process structure. Nevertheless, especially for complex processes, it is still necessary to include the contribution of human operators, mainly for tasks where adaptation is a crucial factor to guarantee the productivity of the plant. However, traditionally, human beings are seen as responsible for negative events, due to their inherently flawed nature, i.e. their unreliability. Human reliability becomes thus a primary area of concern, as proved by a number of studies in the field (Alvarenga et al., 2014). However, as shown by the analysis of industrial practices, often incidents happen under normal conditions, i.e. systems' states characterized by no component failure (Hollnagel, 2014; Rosa et al., 2015). In these cases, the attempt to address a single root cause could be biased by a constructive reasoning - see WYLFY logic (Lundberg et al., 2009) - rather than on the understanding of the reasons contributing to the incidents' happening, and the potential for its replication. The dynamic complex nature of work activities could generate transient connections, which become hardly detectable in an a posteriori reliability-oriented reductionist analysis. This observation is particularly relevant for systems including a large number of elements - both technical, human and organizational - which are tightly interacting, having thus the potential for generating non-linear behaviours. Based on these observations, nowadays, industrial risk and safety management have to focus on real operational processes,

maintaining a complexity-oriented (rather than reductionism-oriented) perspective (Soliman and Saurin, 2017). As a consequence, in terms of safety management, in the last decade the paradigm of Resilience Engineering started acquiring an interest in a number of domains, defining resilience as the ability of a system to adjust its functioning prior to, during or following changes and disturbances, in order to sustain required operations under both expected and unexpected conditions (Hollnagel, 2011). Resilience Engineering demands for a complexity-oriented analysis of real processes (the so-called work-as-done, rather than work-as-imagined) with no preconceptions for the characterization of human beings as flawed components of the system, rather considering them to have the potential for dealing with process complexity. In a socio-technical resilience-oriented perspective, the human component has to be studied in relation to technical elements, rather than in isolation. A socio-technical analysis becomes thus necessary to gather and integrate information at a system level, and deal with the events arising under normal work conditions (Patriarca et al., 2018). The remainder of the paper is organized as follows. Section 2 briefly refers to the Functional Resonance Analysis Method (FRAM). Section 3 offers a description of the scenario in the considered manufacturing plant and the focus of the study, related to forging operations. Section 4 presents the case study. Lastly, the conclusions summarize the outcomes of the study and the potential for further research.

2. THE FRAM

The FRAM is a method for modelling complex socio-technical systems, aiming at gathering data from real work practices, for modelling non-trivial adaptive behaviours, in line with Resilience Engineering (Hollnagel, 2012). The FRAM has been used widely for the purpose of risk and safety management in a number of different socio-technical domains (aviation, maritime operations, railway, healthcare, etc.). With particular focus on industrial practices, the FRAM provided a foundation for several systemic analyses, (e.g.) an accident investigation about the Fukushima disaster (Hollnagel and Fujita, 2013), or for the risk assessment in a process unit of an oil refinery (Shirali et al., 2014), even considering oil spill emergency response systems (Cabrera Aguilera et al., 2016), for manufacturing risk management (Albery et al., 2016) and operation guidelines refinement in engine blade forging (Zheng et al., 2016). The FRAM relies on four principles, i.e. equivalence of success and failure, emergence, approximate adjustments, and functional resonance, aligned with a complexity-oriented approach based on Resilience Engineering. This paper details the application of the method, developed starting from the traditional FRAM, combined with a semi-quantitative approach, in line with the approach recently introduced for environmental process risk management (Patriarca et al., 2017c). In addition, for structuring the functional space, the method used in this research has been enhanced through the Abstraction/Agency (Patriarca et al., 2017a).

3. DESCRIPTION OF THE SCENARIO

The study has been conducted in a metalworking company that produces power-tools accessories. The bills of material are characterized by a low number of raw materials and an extended number of products. Products are sorted in three families that mainly differ for the dimension of the raw materials. Turning and/or milling phases are necessary for the creation of standard shank from a metal cylinder plank. Subsequently, forging is used to shape the plank, tempering and sandblasting to provide metallurgical characteristics to the chisel. Finally, packaging is requested for shipping the products to the customers. Each product is processed through the same working phases, but phases are slightly different depending on the size of the product (diameter range: approximately 10-30 mm).

This paper focuses on the forging operations, which are perceived - at managerial level - as having a critical role for the plant being analysed. More specifically, the analysis developed for the first family of products (Forging 1, see Figure 1), whose process has been previously affected by a number of safety-related events. About forging operation, at the beginning of every work-shift, the operator starts performing a structured step-by-step check following the so-called 6S approach (Safety-I oriented), which aim to allow for a clear, well-organized safety work area (Hafey, 2010). Afterwards, the operator carries out simple routine maintenance checks (e.g. Control oil level, control cooling water refiner, control collective and

individual barriers). In case the machine is configured properly for manufacturing the required code, and no specific problem has been encountered during the routine checks, the worker starts the production, loading the machine. In particular, note that the observed forging machine is automatic: the worker loads raw material and discharge the products, after performing quality control checks, as scheduled in the company quality control plan.

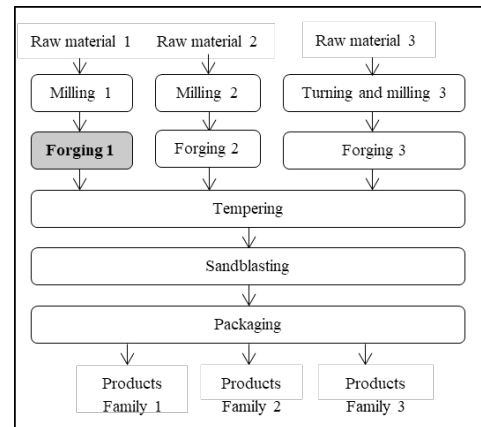


Fig. 1. Plant outline for the three families of products.

The machine operates to generate a chisel through steel plastic deformation: firstly, the input material is heated, and then shaped by applying a standard load. According to the manufacturing plan, once the scheduled set of pieces have been manufactured, the worker has to replace the molds, in agreement with a dedicated set-up procedure necessary to prepare the machine for manufacturing a different code. In case of a technical problem encountered in the set-up procedure, workers must contact the maintenance technicians by a phone call. Figure 2 sketches the flowchart of the process.

4. CASE STUDY

This section presents the application of the method in the scenario presented in §3, detailing the methodological steps of the analysis.

4.1 Data collection

Three different methods of data collection have been used. Firstly, document studies have been developed to understand the work processes, at least in line with procedural prescriptions. Then, two focus groups (including a researcher with experience in the area of risk and safety management, three operators, and the designer of the machine) has been conducted to understand the actual operations in everyday work, and develop a detailed flowchart of activities. Each of the two meetings lasted about 90 minutes. Afterwards, four semi-structured interviews have been conducted to gather knowledge that is more specific on the process, starting from the inconsistencies between procedures and developed flowcharts. Note that one interview has been conducted with the plant safety manager, and the remaining three

were conducted with three different operators, directly working with the forging machine. Each interview lasted about 60 minutes (data from the interviews have been used for defining the scores of the variability, see §4.5).

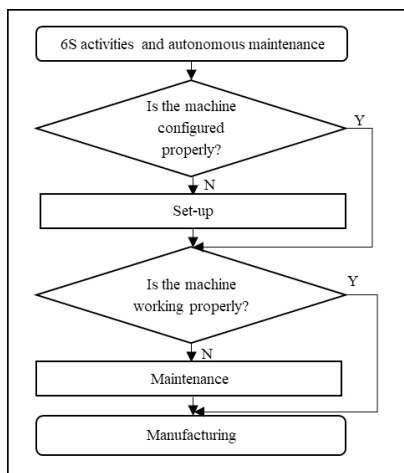


Fig. 2. Forging machine summary flowchart.

As prescribed by Resilience Engineering, further attention has been paid to real operations, gathering further information through naturalistic observations. These latter have been performed analysing the work process during ten different work-shifts to discover dismissed details and understand the potential for variation in the activities carried out by different workers. The observation has been accompanied by an informal conversational interview with the observed worker, just soon after the task has been completed. The overall time for data collection has been about 800 minutes (data used for defining the variability, see §4.5).

4.2 Modelling the work-as-imagined

Following the data gathering process, work-as-imagined (WAI) is the idealized concept of work activities (Hollnagel, 2012). In operational practices, it could be wrong (presenting inconsistencies with actual operative needs), or under-specified, both threats emerging due to the difference between work-as-imagined at the blunt end and work-as-done at the sharp end. The construction of the WAI model took origin from the documental studies and continue to open-ended interviews: standard procedural modules have been used as a basis both for the discussion with machine designer and working standards executive during focused group, and for the design of the observational study. The WAI includes four macro-activities (i.e. four FRAM Generalized Functions, GF: execute forging post activities; manage safety issues; execute auxiliary actions and design), each one is made up of multiple more detailed sub-functions (Physical Functions, PF), following the Abstraction/Agency framework. The complete WAI model consists thus of 52 Physical Functions (PF): 44 foreground and 8 background functions.

With respect to the agents, 8 professional figures have been identified for having a relevant role in the process being analyzed.

- Post worker (blue): the responsible for the manufacturing of products
- Milk-runner (light blue): the responsible for material handling in the plant
- Maintenance technician (brown): the responsible for correct operation of the machine
- Safety manager (green): the responsible for safety in the plant
- Personal protective equipment (external) personnel (red): the responsible for managing vending machine
- Machine designer (yellow): the responsible for machine equipment and possible machine modification
- Auditor (purple): the responsible for evaluating safety management system
- Auxiliary activities personnel (white): the responsible for instrument calibration and availability.

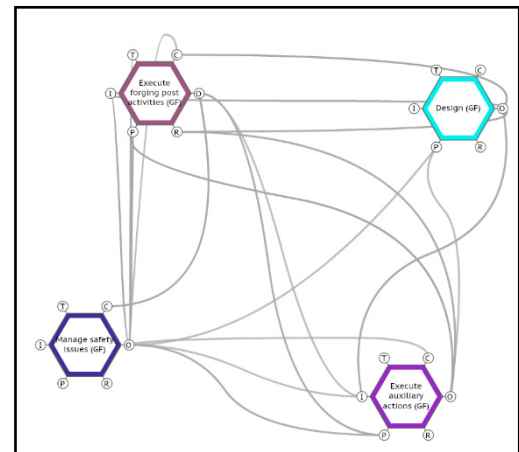


Fig. 3. WAI model at Generalized Function (GF) Level.

4.3 Modelling the work-as-done

The work-as-done (WAD) is the representation of work activities, in order to capture the real nature of work (i.e. limiting the potential bias of work-as-observed, work-as-disclosed). Following a Resilience Engineering perspective, the WAD envisages for process variation, aiming to represent human adaptability as a means to adapt to disturbances and increase system resilience (Hollnagel, 2012). Although most of the time the outcomes of the actions are acceptable (i.e. normal work), understanding the key aspects of work improvisation has the potential to define systemic safety actions to prevent negative events, managing performance variability in relation to lack of time, lack of knowledge, lack of competence or resources (Amorim and Pereira, 2015). The FRAM WAD model has been also analysed in terms of variability, expressing it through three different phenotypes: timing, precision (both used in standard FRAM representation) and ergonomics (originally included here only for those functions whose degree of physical adaptation to a task has relevance for

the analysis). Each function is characterized by a value of criticality for each phenotype (see e.g. an example of a

FRAM function in Table 1). Fig. 4 represents an instantiation of a possible scenario, focus of the analysis.

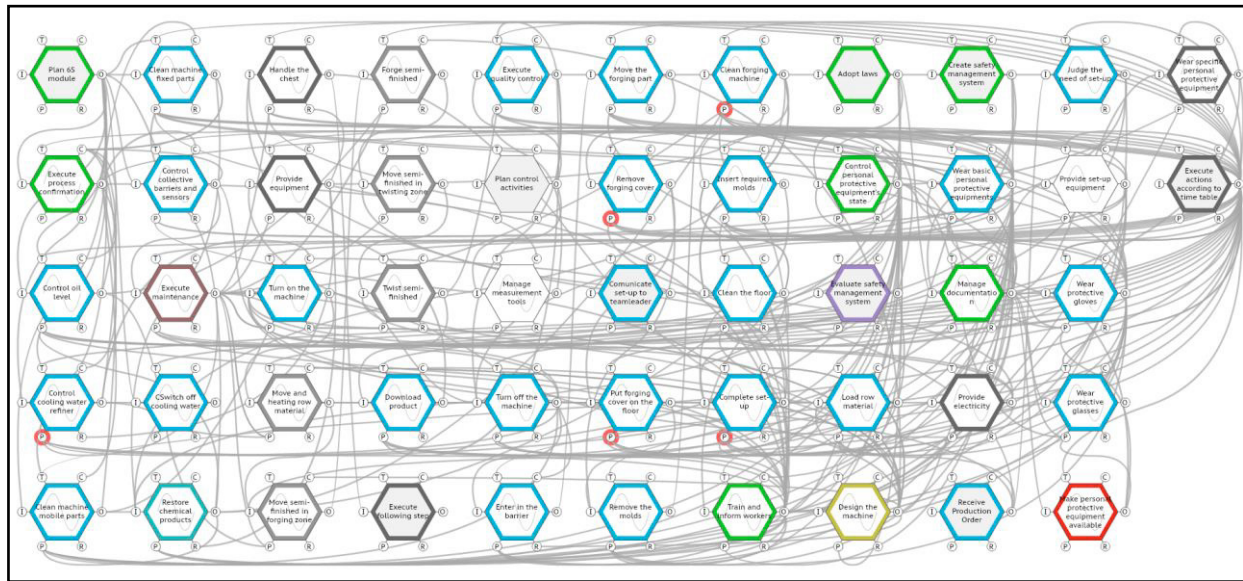


Fig. 4. FRAM model for WAD related to forging operations. Note that each colour refers to a different agent performing the task. In particular, in addition to colours detailed in section 4.2, grey hexagons refer to forging machine (intended as background function) and dark grey hexagons refer to the team responsible for subsequent work phases (tempering, sandblasting, packaging). Note that the presence of red rings around the aspects of the functions helps to indicate the deviation from WAI model.

Table 1. Example of a FRAM function with variability exploited

Name of function	Control collective barriers and sensors
Description	Worker controls the integrity of collective barriers and sensors operation
Function type	Human
Timing	Generally on time
variability	
Precision	Generally acceptable
variability	
Ergonomic	Generally negligible effort
variability	
Aspects	Description of aspects
Input	Check-list for 6S activities
Output	State of barriers and sensors Worker's signature in the blank row Request for maintenance
Precondition	Workers are informed and trained Personal protective equipment is worn State of personal protective equipment
Resource	-
Control	Process confirmation
Time	Activities frequency

4.4 Management of variability: differences between WAD and WAI

The comparison between the WAI and WAD models highlights some relevant differences listed in Table 2. Note that the function names in red indicate those functions included in the WAI model (i.e. proceduralized tasks), which are not included in the WAD (i.e. in operational practices that are not performed). The function names in yellow indicate revised functions (i.e. those function performed differently in

terms of FRAM aspects in WAI and WAD). The differences between the WAI and the WAD allow for a preliminary control and definition of mitigating actions.

Table 2. List of FRAM modified functions and relative descriptions

Name of function	Description
Control cooling water refiner	Worker controls and eventually clean cooling water refiner
Communicate set-up to teamleader	Worker communicates and waits teamleader's help
Remove forging cover	Worker removes machine forging cover
Put forging cover on the floor	Worker puts forging cover on the floor
Wear protective glasses	Worker wears protective glasses
Clean forging machine	Worker cleans internal part of forging machine
Complete set-up	Worker insert cover and move again the forging part

First of all, the omission of the function <Communicate set-up to team leader> has the potential for criticality, since not communicating the end of set-up processes, the operators could exceed Italian law limits (in terms of weightlifting), as prescribed for a male worker during the fulfillment of the functions <Remove forging cover>, <Put forging cover on the floor> and <Complete set-up>. This deviation, which is actually necessary to deal with time pressure and the potential lack of available personnel, justifies the proposal of a mitigating action suggesting a pulley on a tow truck to move the forging cover in a semi-automatic mode. This tow truck

would reduce muscular-skeletal risks due to manual moving of a heavy cover, contributing to damp the potential for functional resonance. Furthermore, the function <Wear protective glasses> which is not usually performed in everyday work (in the WAD model is missing) exposes the operators to risks related to compressed air, as emerging analyzing the link with the functions <Control cooling water refiner> and <Clean forging machine>. For this purpose, a specific training action is suggested to increase the awareness of this kind of events. Even in this case, the variability of in the process has to be damped considering a specific mitigating action.

4.5 Management of interactions variability

Each function's variability is obtained by multiplying the values of the three phenotypes and the amplifying factors, as for following formula to obtain the Coupling Variability (CV_{ij}) (Patriarca et al., 2017):

$$CV_{ij} = V_j^T \cdot V_j^P \cdot V_j^E \cdot a_{ij}^T \cdot a_{ij}^P \cdot a_{ij}^E \quad (1)$$

Where:

V_j^T (or V_j^P , or V_j^E) represents the score assigned to the variability of the coupling in terms of timing (precision, or ergonomics)

a_{ij}^T (or a_{ij}^P , or a_{ij}^E) represents the damping/amplification factor related to the interaction among the upstream function j-th and the downstream function i-th, in terms of timing (precision, or ergonomics)

The scores for V_j^T (V_j^P , V_j^E) have been assigned following Table 3. The scores assigned to a_{ij}^T (a_{ij}^P , a_{ij}^E) have been respectively {2; 0.5} if the upstream function had an amplifying or damping effect on the downstream coupling.

Table 3. Scores for the assessment of variability.

Phenotype	Variability	Score
Timing	Too early	2
	On time	1
	Too late	3
	Not at all	4
Precision	Precise	1
	Acceptable	2
	Imprecise	4
Ergonomics	Negligible effort	1
	Light effort	2
	Heavy effort	4

The score 1 has been assigned if no effect in terms of variability has been considered. In a preliminary phase, the analysis focused on couplings having the higher values of variability, i.e. those couplings demanding for high adaption. In a preliminary phase, the analysis focused on couplings having the higher values of variability, i.e. those couplings demanding for high adaption. The filtering process has been conducted applying a Pareto analysis (see orange histograms in Figure 5), for all the discussed scenarios.

The most critical couplings thus refer to:

- Ergonomic efforts to move forging cover alone
- Lack of training or communication for correct set-up
- Lack of compliance with quality control time table
- Absence of chemical's safety form
- Error in machine's safety form.

This analysis supports the identification of specific mitigating strategies. A tow truck to reduce the ergonomic efforts (as already discussed in §4.4), especially if combined with a training for correct use of tow truck, with the possibility to reduce rude set-up activities.

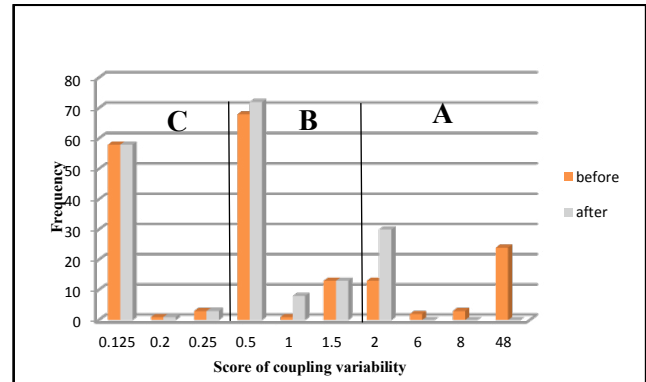


Fig. 5. Comparison frequency histogram before and after the proposed mitigating actions

In addition, after conducting a preliminary cost/benefit analyses, two actions have been formalized: **Action 1:** an electronic device connected to the machine can provide the typology and the timing for the functions <Execute quality control>, before executing the function <Download the products>. On one hand, it allows managing the potential worker's negligence (especially in rush overloaded scenarios) and low perception of time, having a potential impact also on the scrap rate (as explained by the connections with the quality data monitoring, and thus the functional resonance in this sense). On the other hand, it may reduce stress on machine during the manufacturing process, suggesting the proper moment to unload it, in particular affecting the functions <Forge semi-finished> or <Twist semi-finished>.

Action 2: it could be beneficial to add a formal safety manager's approval before buying chemicals in SAP, in order to allow minimizing the effect of variability in the function <Adopt law>, also allowing compliance with Italian regulations in terms of chemical safety card. **Action 3:** the formalization of heuristics, i.e. functional hot spots, rather than long proceduralized tasks, in order to support local rationality and local decision-making of operators working in the plant. Consequently, operators would be allowed to follow simpler rules of thumbs, especially for the machine loading and unloading, with benefits in terms of <Manage documentation>, i.e. ease to fulfill risk assessment forms. This action would require extended conceptual efforts, also involving experienced workers to add an operational perspective to the analysis.

Starting from the analysis of system functioning under normal circumstances, the FRAM allows for identifying a set of activities having the potential for resonating within the system and thus generating emerging events, rather than focusing on the presence of standard hazards, as for traditional risk assessment techniques. The aim of this paper is to present the positive outcomes related to a FRAM application in a manufacturing plant, highlighting the key role of analyzing punctually a work domain. The study confirms the benefits to include sharp-end operators in interviews and observations, taking advantage of what people know about what they do in everyday work. Manufacturing processes can be complex so that only if their complexity is understood and properly analyzed, one can estimate how changes will affect the overall system performance. On this path, the FRAM allows for risk assessment, limiting the bias of reductionist a posteriori analyses, as for example Root Cause Analysis (RCA), or FMEA/FMECA. These approaches become increasingly less usable in case of large human and organizational contributions in the system. The developed model for the WAD could be also used for incident analysis, allowing for systemic assessment of functional variability (Patriarca et al., 2018). It has to be observed that a Resilience Engineering approach, besides technical solutions require culture and management efforts to introduce a no-blame culture, involving systemic organizational learning to extend the significance of sharp-end local rationality. In terms of future applications, the analysis might adopt more detailed assessments, (e.g.) by means of fuzzy logic for the assessment of variability. In addition, a Monte Carlo simulation framework would guarantee the assessment of variability in larger domains, including variability of industrial practices (Patriarca et al., 2017b). A cognitive engineering approach would also be beneficial for understanding the distributed criticalities, in a multi-agent joint cognitive system perspective.

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