Transition from Work-As-Imagined to Work-As-Done Processes Through Semantics: An Application to Industrial Resilience Analysis

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Abstract Increasing industrial resilience is a big challenge for manufacturing enterprises that are continuously facing severe accidents causing injuries, casualties, and economic losses. Assessing industrial resilience requires the analysis of production processes in order to find possible safety flaws. Sociotechnical process management suffers often from misalignments of process descriptions according to formal organization documents or manager views (Work-As-Imagined) and actual work practices as performed by sharp-end operators (Work-As-Done). Furthermore, existing modelling approaches leveraging on techniques such as process mining from digital traces cannot be used to solve such misalignments as these traces are often hardly available. In this context, we propose a computational creativity approach for a semantics-driven transition from Work-As-Imagined to Work-As-Done process models based on the functional resonance analysis method (FRAM). In particular, through formalized semantics, it will be possible to use automatic reasoning for

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identification of criticalities and prioritization of normal work analyses. To this aim, we introduce some examples of rule patterns, inspired by typical data quality issues, which can be automatically applied to guide such a transition. An explorative case study on chemical cleaning for industrial process is presented to clarify the proposed approach.

Keywords Safety · Ontology · Rules · Functional resonance analysis method · Computational creativity

1 Introduction

According to Dinh et al. [1], resilience is the ability to recover quickly after an adverse event, and adequate safety management strategies can contribute to increase the resilience of industrial processes. In sociotechnical work systems, safety can be considered an emergent property due to the often non-predictable interactions among humans and technological components. Manufacturing enterprises aiming to increase industrial resilience have to deal with a variety of severe accidents causing injuries, casualties, and economic losses. Industrial resilience should be about anticipating such events or at least enhance response capacity.

One of the existing approaches to assess industrial resilience is to model and analyse production processes in order to find possible safety flaws, for instance, by means of simulation approaches [2]. For several manufacturing enterprises, processes are characterized by a high number of complex human activities and relations and by a low usage of process support technologies. Furthermore, process descriptions are usually derived from company documents (e.g. standard, procedures, notes) or from manager perspective (WAI: Work-As-Imagined). These views could be different from the actual work as performed, which are usually derived from exhausting interview sessions with sharp-end operators (WAD: Work-As-Done). Such misalignment hinders availability of reliable process models to be analysed. Furthermore, existing approaches as those in [3, 4] that reconstruct the WAD processes from digital traces through techniques such as process mining often cannot be used as these traces are either not available or they cover minimal parts of the overall process.

In such context, our aim is to define an approach to support the work of safety analysts in designing WAD processes starting from WAI descriptions. We propose a computational creativity approach for a semantics-driven transition from Work-As-Imagined to Work-As-Done process models. This approach does not intend to cut sharp-end operators out of this knowledge elicitation process. We rather provide a means to suggest possible process variations of the WAI models to safety analysts, through a facilitated interpretation of relevant WAD details. In particular, we propose to use the CREAtivity Machine [5], i.e. a software tool enacting automatic reasoning on a semantic representation of the WAI model and on an application ontology, to generate the above-mentioned possible variations. We introduce a list of examples of model transformation rule patterns, inspired by typical data quality issues, to be automatically applied to guide such a transition. We provide also a case study on chemical cleaning to clarify the main elements of the proposed approach.

The remainder of the paper is organized as follows. Section 2 presents the related work in the area. Section 3 briefly describes the functional resonance analysis method (FRAM) [6], a process representation method used as a core of the safety analysis. Section 4 describes a case study concerning manufacturing enterprises and related to chemical cleaning. Section 5 presents our approach for a semantics-driven transition from WAI to WAD models. Finally, Sect. 6 closes the paper with some considerations on this computational creativity approach to safety management and some future research directions.

2 Related Work

The work, as it is carried out in the situated reality of the sociotechnical systems (WAD), takes place according to patterns—that is, according to criteria of compromise efficiency accuracy [7]—with the aim of achieving a well-defined objective, in a particular context, producing consequences that can be unexpected and modify context and objective. The context of sociotechnical systems in general is such that [8]: the environment is different from the one imagined in the project; the objectives are multiple and changeable; needs are variable and unpredictable; resources have been degraded (e.g. staff; competence; equipment; procedures; time); and there is a system of constraints/penalties/incentives generally put in place. Any operator possesses an operating know-how of the work context, and WAD adaptations belong to such know-how, that usually becomes hardly detectable. In the event of an accident, operators can be usually blamed, when contrasting prescriptions. The same prescriptions are on the contrary ignored, if not even discouraged, if they can ensure productivity.

Its attainable version—the work as disclosed—is a partial representation, whose the analyst can make instrumental use, or simply it can be influenced by the presence of prying eyes (e.g. people may not feel comfortable, they may try to deceive the viewer), even unconsciously. Many distortions due to social pressure can distract the disclosed version of the work from its adherence to the work as a fact. Finally, a practitioner may know her/ his own work, but she/he does not know how much of it is being done by another practitioner. The WAI is similar to a unitary reductionist perspective; the WAD is made up of many complexity-oriented different views.

Both are partisan stories but, while in the WAI we are interested in knowing the interpretation given by the narrator, in the WAD, the ideal narrator should be objective and impartial. For such reason, the interview lends itself well to the WAI, while naturalistic observations in conjunction with complementary semi-structured interviews are a glimpse of the work to suit the WAD.

Naturalistic observations—besides being extremely expensive and time-consuming—do not protect the detection of the WAD from biases. In this sense, the use of IT applications can complement traditional investigation techniques. Due to the dependency of the WAD reliability on the observer/interviewer, developing an automatic or semi-automatic technique for data collection in collaboration with sharp-end operators may have the potential to generate relevant benefits in terms of WAD development.

Furthermore, most of the existing works related to business processes analysis [3, 4] face the issue of process models conformance checking, which can be considered similar to the problem of alignment between WAI models and WAD. However, they use process traces, which for social-technical systems are often hardly available. Hence, with respect to them, we propose an automatic support to suggest possible WAI process variations to safety analysts. At the best of our knowledge, such approach is unprecedented.

3 Basic Notions on the Functional Resonance Analysis Method

The functional resonance analysis method (FRAM) is a method of resilience engineering (i.e. the discipline that aims to engineer resilient sociotechnical systems) that, giving a functional description of the many activities involved, allows to effectively represent a work domain. The FRAM does not assume preemptively that there is a unique valid way to perform the work. Following the principles of resilience engineering [9], through its four principles (equivalence of failures and successes, approximate adjustments, emergence, functional resonance [6]), it acknowledges the variability of processes as an essential condition for adaptability, and therefore, for resilience as an emerging effect at the system level. The FRAM gives a functional description of the processes whose various agents perform many activities (i.e. functions in FRAM terminology). Such activities are usually tightly interrelated, implying interrelation among their variabilities as well. Each agent (both individual and collective) of the sociotechnical system usually regulates its own functions' variability in order to harmonize with other functions' variability. Sometimes the actions of individual agents—given their inevitable bounded rationality based on local (i.e. non-systemic) knowledge—may interact in an unintended manner, giving rise to emerging out-of-control variability phenomena, a condition also known as functional resonance.

The method itself is composed of four steps (excluding the so-called step 0, i.e. establishing the purpose of the analysis: risk assessment for proactive analysis or accident analysis for reactive analysis):

1. To identify the functions of interest; i.e. to delimit the scope of the model, to establish which functions are in focus—and therefore which must be detailed in the foreground—and to establish which must remain on the background. In FRAM, a function can interact with other functions by links (i.e. so-called couplings) in a process (i.e. instantiation) establishing which functions are being performed, how they are connected and under which specific conditions. In a

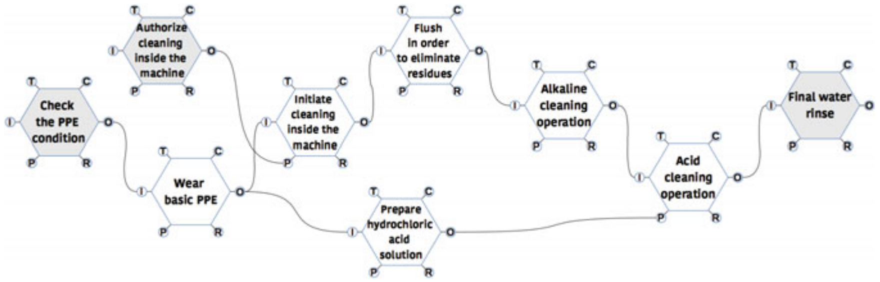

Fig. 1 FRAM model used for the analysis

single instantiation, the couplings link functions in sequential terms (i.e. an upstream function will precede a downstream function) and in modal terms; such mode is specified through the so-called six aspects; therefore, a FRAM function is traditionally depicted as a hexagon whose vertices are the aspects: Input (I), output (O), time (T), control (C), precondition (P), resource (R), see Fig. 1.

2. To identify the functions' variability. The variability of an activity is partly endogenous (intrinsic to the nature of the function itself), partly exogenous (specific to the context in which it is carried out), partly due to the specific upstream–downstream relationship that has taken place in the instantiation process. The entirety of these three components manifests itself at the output of each single function through the so-called phenotypes (i.e. the observable manifestations of variability at function level). The result of this step is the characterization of the potential variability as performed in the work context.
3. To aggregate the variabilities and, thus, to determine the actual variability. This step focuses on how the system affects, and it is in turn affected by, all the variability couplings, by the whole upstream–downstream interaction. Such intertwined functional aggregate determines the instance. Changing the scenario will produce another instance. By changing functions (in number, connected aspect, potential variability), another instance is obtained. Each possible variant begets a different FRAM instantiation. These instantiations can be used either for risk or accident analysis purposes. Moreover, FRAM allows comparing Work-As-Done and Work-As-Imagined simply by analysing the corresponding FRAM instantiations.
4. To manage variability. Since variability is necessary for the system to operate, it must be managed, not necessarily just damped, according to the scenario, by adequate work practices and possibly through suitable indicators.

4 Case Study: Chemical Cleaning Process

In this Section, we present a WAI description of a fragment of a chemical cleaning process, which is intended as a use case relevant for safety analyses of a typical manufacturing process. The work domain is described by means of the FRAM notation presented in Sect. 3.

The fragment depicted in Fig. 1 represents the following scenario. A sharp-end operator initiates cleaning operation inside the machine after he/she receives the authorization by the production manager. Such authorization is a precondition to start the cleaning operations. Meanwhile, the operator checks its personal protective equipment (PPE) and, wears it, if not ready yet. The output of the activity *wear basic PPE* is an input of the activities *initiate cleaning inside the machine* and *prepare hydrochloric acid solution*. Once the cleaning activity is started, the sharp-end operator flushes the machine in order to eliminate residues. Then he/she performs the alkaline cleaning operation and afterwards the acid cleaning operation. This operation needs as a precondition that a hydrochloric acid solution is prepared beforehand. Finally, the sharp-end operator rinses the machine with water.

5 Semantics-Driven Transition from WAI to WAD

We present an approach where semantics-based techniques are used to drive the modelling activity of a FRAM analyst in the transition from a WAI model to a WAD model. In particular, we define a method aiming at supporting the analyst in the exploration of potential modelling alternatives of the WAI to identify those variants that may lead to WAD models. The variants that seem most promising to the safety analyst, based on his/her experience, are then evaluated by eliciting specific information from the sharp-end operators.

This approach follows ideas and goals of computational creativity, a subfield of artificial intelligence aiming at defining computational systems that create artefacts and ideas [10]. Generally, computational creativity methods address the problem of thinking something new, e.g. a risk situation, by varying one or more aspects of what already exists, e.g. old experiences of incidents or normal situations.

The proposed approach essentially consists of a human-in-the-loop generative method of FRAM models, guided by automatic reasoning techniques that leverage on: the semantics of the model components expressed by an ontology structured according to the FRAM conceptual elements, and a set of predefined logical rule patterns, representing recurrent misalignments between WAI and WAD.

5.1 Evolution of FRAM-Based Manufacturing Ontology

The FRAM-based manufacturing ontology gathers both application and domain knowledge structured according to the FRAM Upper-level Model (FUM), an upper model derived from the FRAM method that was initially discussed in [11]. Such knowledge concerns WAI processes, existing standards and domain ontologies on manufacturing and expert knowledge. The FRAM upper-level model gathers the most relevant FRAM concepts and the ontological relationships linking them. FRAM_Element is the generic concept of the FUM upper-level concepts that is specialized in agent, aspect, function, and phenotype. Then coupling allows representing how two different functions link together and Coupling_effect models the corresponding effect, which could be amplifying, damping and No_effect. The FUM relationships are modelled in the ontology as object properties. The hasAspect object property relates two Aspects. It is specialized in the hasControl, hasInput, hasOutput, hasPrecondition, hasResource, and hasTime object properties. hasFunction is the inverse relationship of hasAspect. The hasPhenotype object property relates an output with its phenotype. The hasDownstreamAspect object property between coupling and input and hasUpstreamAspect object property between coupling and output allow to specify the role of the aspects in a coupling. Finally, the hasEffect object property relates the coupling concept with the corresponding CouplingEffect.

The FRAM-based manufacturing ontology is built by means of an incremental approach starting from an automatic export from the FRAM WAI process to the FUM application ontology, which organizes the FRAM WAI elements according to the FUM upper model ontological entities. Then, the FUM application ontology is enriched by considering existing standards and domain ontologies and by involving experts [12]. This final step is fundamental both to transform the tacit implicit knowledge of stakeholders and sharp-end operators in new concepts and relationships and to further validate existing knowledge. A sketchy representation of this process is depicted in Fig. 2, which conceptualizes the FRAM-based manufacturing ontology building process, through the FRAM WAI, standards, existing manufacturing domain

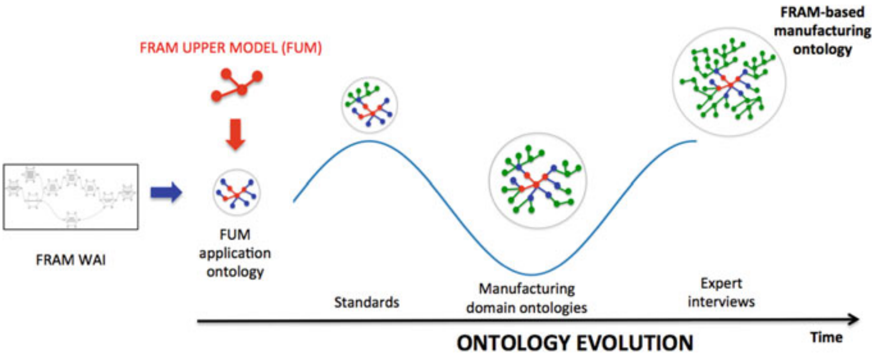

Fig. 2 FRAM-based manufacturing ontology evolution

ontologies as those addressed by the Industrial Ontologies Foundry group [13] and expert interviews.

5.2 Rule Patterns for WAI to WAD Transition

Given a WAI model, whose semantics is obtained by means of the FRAM-based manufacturing ontology, possible variations of model elements are generated by applying logical rules in queries to the ontology. These rules instantiate predefined model transformation rule patterns founded on some data quality dimensions proposed in [14]. The problem of misalignment of WAI models with the WAD may be faced as a problem of information quality occurring in the WAI models in their aim to effectively describing the WAD. With this meaning, the model transformation rules attempt information quality improvements of the WAI models.

We defined a patterns-based classification of model transformation rules, where a rule pattern may be founded on one or more data quality dimensions. As a preliminary outcome, we selected some data quality dimensions from the classification proposed by Pipino et al. in [14] and analysed them for the case study. In Table 1, we report the chosen quality dimensions and present some related transformation rule patterns. Each pattern is described by its purpose in the verification of the corresponding quality dimension over the model and by example rule types. One or more rules will be instantiated at run time with specific components of the model and enacted by means of queries to the FRAM-based ontology.

Table 1 Selected transformation rule patterns

Quality dimension	Description	Selection of transformation rule patterns
Completeness	The extent to which information is not missing and is of sufficient breadth and depth for the task at hand	*Purpose*: Verify conceptual representation coverage of model elements *Rule type*: **If** *model component* **is** a leaf concept **and** has a sibling, **replace** it with one of its siblings
Understandability	The extent to which information is beneficial and provides advantages from its use	*Purpose*: Verify appropriateness of model elements *Rule type*: **If** *model component* **is not** a leaf concept, **replace** it with one of its leaves
Relevancy	The extent to which information is applicable and helpful for the task at hand	*Purpose*: Verify organizational constraints of model elements *Rule type*: **If** *precondition* of function **is of type** *general organization rule,* **then remove** it from the model

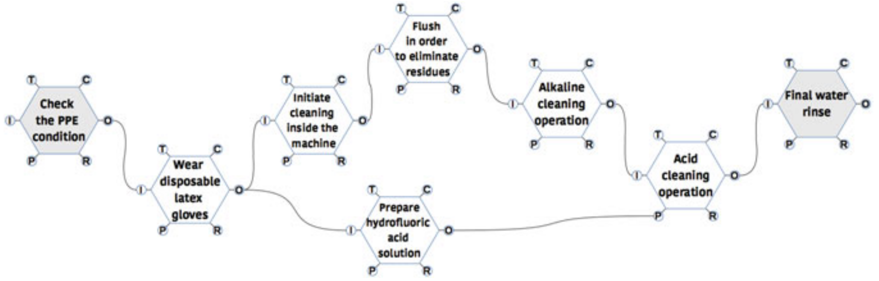

Fig. 3 FRAM WAD process

We show how the presented transformation rule patterns may be applied to the WAI model in Fig. 1 to suggest the model in Fig. 3, which better represents the WAD after evaluation of the information by the sharp-end operators (note a coupling is missing with respect to *initiate cleaning inside the machine*).

Transformation rule patterns related to *completeness* aim at verifying whether the WAI model contains all safety-relevant details of the real process. One method consists in checking whether a safety-relevant function, such as *prepare hydrocloric acid solution* in Fig. 1, correctly represents the practice. Indeed, the acid resource specified in the function description could not be available and sharp-end operators could use a similar type of acid instead. The attached rule type in Table 1, instantiated with the concept *prepare hydrochloric acid solution* as model component, would propose alternatives for that function, automatically retrieved from the ontology by means of concept similarity metrics. Thus, sharp-end operators could indicate the concept solution *prepare hydrofluoric acid* as the correct substitution for WAD model representation. It is worthy to note that, as such type of acid requires to be handled with special care, this could lead to safety flaws that deserve to be analysed.

Transformation rule patterns related to *understandability* aim at verifying whether the WAI model is correctly understood. One method consists in checking whether a safety-relevant function, such as *wear basic PPE* in Fig. 1, is not too generally described. Indeed, this level of abstraction of a function description would mean that sharp-end operators could choose any type of PPE, whereas some types of acid solutions may require specific PPE. The attached rule type in Table 1, instantiated with *wear basic PPE* as model component, would propose all the most specific variants for that function, retrieved from the ontology using concept subsumption relations. Thus, sharp-end operators would indicate the leaf concept solution *wear disposable latex gloves* as the correct substitution for WAD representation. However, as handling acid solutions could require wearing heavy chemical resistant gloves, this case deserves to be analysed in details.

Transformation rule patterns related to *relevancy* aim at verifying whether the WAI model is not over specified compared to WAD. One method consists in checking whether some preconditions are really required and do not block necessary functions, such as *initiate cleaning inside the machine* in Fig. 1, which requires *authorize cleaning inside the machine* to be performed first. However, in real work practices, some organizational procedures could be simplified, for example, to handle unexpected situations. Thus, sharp-end operators would confirm whether the concept solution *wear disposable latex gloves* is relevant for the WAD representation. Again, removing such function could lead to emergent issues that require to be explored by more detailed work domain analyses.

6 Conclusion

Industrial resilience of manufacturing enterprises requires anticipating accidents or improving the response capacity. A precondition to this is achieving a better understanding of industrial processes by means of an in-depth analysis. However, this is usually hindered by misalignments between WAI descriptions and WAD processes. In this context, we propose an automatic approach based on computational creativity and enhanced by semantics to support transition from WAI models to WAD models. To this purpose, possible WAI model variations are generated by applying some transformation rules according to patterns inspired by typical data quality issues and suggested to safety analysts. An exploratory case study on chemical cleaning shows an application of the method. To the best of our knowledge, application of computational creativity techniques to solve this misalignment problem is unprecedented. Future work will be devoted to further improve these techniques and to extend the list of transformation rule patterns.

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