Journal of Industrial Information Integration 35 (2023) 100489

Contents lists available at ScienceDirect

Journal of Industrial Information Integration

journal homepage: www.elsevier.com/locate/jii

Full length article

Development and measurement of a resilience indicator for cyber-socio-technical systems: The allostatic load

Antonio De Nicola [a,*], Maria Luisa Villani [a], Mark Sujan [b,c], John Watt [d], Francesco Costantino [e], Andrea Falegnami [e], Riccardo Patriarca [e]

[a] Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Casaccia Research Centre, Via Anguillarese 301, 00123, Rome, Italy
[b] Nuffield Department of Surgical Sciences, University of Oxford, OX3 9DU, United Kingdom
[c] Human Factors Everywhere, Woking, United Kingdom
[d] Middlesex University, School of Science and Technology, Centre for Decision Analysis and Risk Management, London, NW4 4BT, United Kingdom
[e] Sapienza University of Rome; Department of Mechanical and Aerospace Engineering, Via Eudossiana, 18, 00184, Rome, Italy

ARTICLE INFO

Keywords:
Resilience
Cyber-socio-technical system
Ontology
Semantic similarity
Business process
Leading indicator

ABSTRACT

Management of cyber-socio-technical processes often suffers from misalignments of process descriptions according to formal organization documents or manager views (Work-As-Imagined) with actual work practices as performed by sharp-end operators (Work-As-Done). Even if sometimes the accomplishment of a process requires workers to diverge from the Work-As-Imagined, the corresponding changes can potentially cause organizational tensions in the overall system and lead to safety incidents. This consideration led us to define a new resilience indicator, named *allostatic load*, to capture such misalignments, and the corresponding level of organizational tensions, a cyber-socio-technical system is exposed to. Then, we propose a method to measure it by leveraging semantic technologies, the Functional Resonance Analysis Method (FRAM) to model industrial processes, the WAx conceptual framework to keep track of the variety of the different process perspectives, and a crowd-based approach to elicit industrial knowledge. Finally, we discuss the feasibility of the approach in two real case studies related to a pharmaceutical manufacturing plant and an enterprise in the aluminium sector.

1. Introduction

Systems thinking is necessary to cope with the complexity and interconnections of today world [1]. For this reason, several system classifications, such as, Cyber-Physical Systems [2] and Socio-Technical Systems [3], exist to focus attention on their main constituent elements and their inter-relations. Among them, Cyber-Socio-Technical Systems (CSTS)s, also known as Cyber-Physical-Social Systems (CPSS)s [4], are socio-technical systems that include interconnected cyber technical artefacts [5], i.e., devices with both computational and physical capabilities. Hence, CSTSs are networks of inteconnected cyber artefacts, physical devices, and human agents aimed at serving a common purpose. Manufacturing industries are examples of CSTS where humans, robots, and machines interact with one another in order to carry out their assigned tasks and to achieve a productive goal. Indeed, leveraging the collaboration of the creativity of human experts and the efficiency and accuracy of machines is regarded as a key feature of the upcoming Industry 5.0 [6]. Usually, all the CSTS agents participate in processes that could be numerous, especially in case of large-sized enterprises, and complex even in small-sized enterprises. Furthermore, there could be misalignments between how two different agents perceive the same process. For instance, blunt-end operators such as managers could have a different idea of a process (WAI: Work-As-Imagined) with respect to the actual process (WAD: Work-As-Done) performed by sharp-end operators [7]. Sometimes, for instance when a WAI process is not fully specified, a misaligned WAD could be beneficial if it allows a process to complete. Alternatively, misalignments could lead to coordination problems [8] and unexpected system behaviours not foreseen by the process prescription, such as safety incidents. Indeed, in both cases, the system is subject to organizational tensions due to these different views and the consequent lack of internal agreement on its processes. Furthermore, existing modelling approaches leveraging techniques, such as process mining from digital traces [9,10], cannot be used to solve such misalignments as these traces are often hardly available, especially for processes involving human activities.

---

[*] Corresponding author.
E-mail address: antonio.denicola@enea.it (A. De Nicola).

https://doi.org/10.1016/j.jii.2023.100489
Received 15 December 2022; Received in revised form 6 May 2023; Accepted 29 June 2023

The main aim of the paper is to develop a method to cope with the plurality of the different process views, which are peculiar to CSTSs. To this regard, the research questions are: (RQ1) How to elicit, integrate, and manage the different process views? (RQ2) How to measure the level of organizational tensions caused to the system by misaligned process views?

We addressed RQ1 by defining a partially automated methodology to elicit, integrate, and manage process knowledge. According to this methodology, the WAI is modelled by an analyst by interviewing blunt-end operators and by following the Functional Resonance Analysis Method (FRAM) [11]. Then, WAD knowledge is elicited from sharp-end operators through an innovative approach based on semantic technologies. Worth bearing in mind that this will always be a snapshot, because WAD is continuously evolving in response to a changing context, demand profile, opportunities, etc. Finally, WAI and WAD are compared to the purpose of measuring their misalignments.

RQ2 was addressed by defining a new resilience indicator, named *allostatic load*, for CSTS. This permits assessment of the level of organizational tensions caused by the different views of the blunt-end and sharp-end operators on how work should be performed in the system. Put simply, this indicator compares the differences between WAI (the plan) and WAD (what actually happens). This difference, of course, could mean either that workers are in error or that the process plan could be improved. We describe an algorithm that rapidly identifies the greatest differences between the two models and, thus, facilitates efficient examination of those anomalies that are likely to contain most information for organizational learning. Allostatic load was originally defined in the context of physiological systems [12,13]. Here, we have adapted its definition to cyber-socio-technical ones. Then, we propose to measure allostatic load by a proxy indicator derived from the semantic distance between process models. To this purpose, we defined an algorithm that computes the semantic similarity between two FRAM process models. It is worth mentioning that techniques to compute semantic similarity are developed in the context of computer science [14]. Here, the purpose of our algorithm is to provide a new tool to analyse CSTS processes and, hence, increase industrial informatization. Semantic similarity $\mathcal{S}$ is defined in the [0, 1] range, where 0 represents the case where two models are completely different and 1 the case where they are identical. Accordingly, the semantic distance $\mathcal{D}$ is defined as $\mathcal{D} = 1 - \mathcal{S}$.

The proposed framework leverages an ontology named EPOWAx (Enterprise Production Ontology based on the WAx framework), which encompasses industrial knowledge organized according to an ontological version of the WAx (Work-As-x) framework [5] and the FRAM meta-model [15]. EPOWAx is used to automatically generate questionnaires to elicit industrial knowledge and to manage the variety of the different process perspectives.

Finally, we discuss the validity of the approach in real case studies related to a pharmaceutical manufacturing plant and an enterprise operating in the aluminium sector.

The rest of the paper is organized as it follows. Section 2 presents related work in the area. Section 3 recalls the background methods for the proposed approach, which is presented in Section 4. Experimentation of the approach is discussed in Section 5 and, finally, Section 6 provides concluding observations.

2. Related works

This Section addresses the three main topics at the basis of the work we did to define and measure a novel resilience indicator for cyber-socio-technical systems. First, we present some of the most relevant works on resilience management of cyber-socio-technical systems. Then, we discuss the problem of business process modelling and some available analysis tools. Finally, we present some of the existing ontologies for business process management.

Resilience management of cyber-socio-technical systems. Cyber-socio-technical systems (CSTSs) are complex systems built to pursue a useful goal for human beings, co-inhabited by organizations, technical devices, and autonomous agents; the latter might be: human, cyber, or collective agents, each endowed with peculiar characteristics (e.g., human, artificial, collective intelligence) [16].

CSTSs are usually approached by describing them in functional rather than structural terms: being complex systems, they typically have subsystems that are complex as well, therefore, structural descriptions are ultimately ineffective, since the resulting organization is fractal in nature. In between the different parts of the system are mutual interconnections – non-linear, multiple and continuously mutable – extending, in relation to the structural organization, both in depth and in width; similar relationships occur with objects belonging to the external environment. This results in an objective difficulty in recognizing the limits of the system under consideration. Practically, these are defined according to the purpose of the analysis. Often, analyses are conducted at the level of local interaction between a few units of agents, yet, even in these limited cases, they are easily affected by hundreds of relationships. CSTSs are impossible to know entirely both because of their size and because of the large number of dynamic relationships, but most importantly, because of the impracticality of Cartesian-Newtonian approaches, such as fault tree analysis and event tree analysis [17,18].

What is often referred to as the principle of emergence represents a salient feature of CSTSs, and captures a different dimension of complexity, whereby some phenomena occurring at the subsystem level, produce unexpected behaviour at the supersystem level. As an example, imagine a system in which the relationships between agents are not particularly complicated, such as a collective of cyber-agents (a drone fleet), where each might be endowed with some discretionary autonomy, but in addition they also are programmed with another simple rule: always keep a buffer distance from other cyber-agents. Just as happens to swarms of insects, schools of fish, or flocks of birds, collective behaviour (consistency in movement, ability to avoid obstacles and/or predators) is observed at the group level that is rather complex and unpredictable from the simplicity of agent programming (a single rule). Because CSTSs are complex systems, they exhibit emergent forms of behaviour. Other CSTSs' emergent phenomena relevant to their analysis and management are: collective intelligence, organizational myopia, and organizational cognitive dissonance [19], but especially with regard to safety management, so-called Organizational Resilience [20].

From a modern safety management perspective, human-made systems are CSTSs. This perspective is suggested since it is capable of characterizing several high-risk application domains such as healthcare, aviation, nuclear facilities, and process and manufacturing industries. Organizations operating in these fields, although often at the forefront of technology and safety, have residual levels of uncertainty and risk, that can be interpreted as a direct consequence of their inherent complexity [21]. On the other hand, some scholars believe that the same complexity (mostly embodied by the social and human side) is what gives the system the ability to strive for success. More precisely, resilient CSTSs adjust their performance as much in the face of threats as in the face of opportunities so that they break down with a relatively low frequency, especially if compared to human functions [22].

A new discipline has emerged, with the specific goal of designing, measuring, and managing CSTSs resiliently: Resilience Engineering (RE). RE recognizes the positive effects of variability in performance as intended to provide the means for security management, while including the substantive assumptions that CSTSs cannot be fully known, that descriptions may be complicated, and that system behavioural dynamics are in fact highly irregular and frequent. These assumptions can be summarized in the following:

1. Systems cannot be decomposed in a meaningful way in components to be studied individually.

2. System functioning is not bimodal (functioning vs. nonfunctioning) but everyday performance is flexible and variable.
3. Human performance variability leads to success as well as failure.
4. Even though some outcomes can be interpreted as a linear consequence of other events, some events are the result of coupled performance variability.

RE has developed its own set of methods and, progressively, is also enriching the phenomenological description by resorting to analog (e.g., mechanical stress–strain model, [23]) and foundational models (e.g., the Resilience Analysis Grid (RAG) [24]), as well as methods adhering to the principles mentioned earlier (e.g., the FRAM, [11]).

Business process modelling and analysis tools. Business process modelling is the activity of representing abstractions of business processes finalized to learning about the processes, making decisions and/or developing software towards business process automation, monitoring and improvement [25]. Thus, various modelling notations have been developed over the years based on one of the above mentioned specific objectives. Research in the field of business process automation and monitoring use the terms: *process instance*, to refer to an execution of a process; *process variant*, to refer to a set of executions of a business process that share some characteristic, for example, the same organization site in case of a multi-national company; *process trace* or *event log*, to refer to a sequence of events recorded by a software system during one process instance [26]. *Process mining* [27] comprises data science methods and software tools to gain insights on the business process from the analysis of process traces (i.e., representations of observed behaviour, perhaps machine generated). Formal and artificial intelligence techniques in this field have been developed to support: *process discovery*, such as building a process model from an event log without using any a-prior information; *conformance checking* to check the extent to which the process execution, as recorded in the log, conforms to the process model (i.e., the expected behaviour of the process) and vice versa; *process enhancement*, to improve an existing process model by using the information about the actual process executions recorded in the event log, or the misalignment identified via conformance checking. Despite the differences in the terminology used with FRAM-based modelling (i.e., process model vs instance), process mining techniques solve part of the problems in the WAD modelling, in the WAI-WAD models misalignment detection, and in the enhancement of WAI models based on WAD. Therefore, these techniques could be used to automate steps of our approach towards WAI and WAD FRAM representations in cases where event logs satisfying the requirements of the process mining tools are available in the cyber-socio-technical system at hand. However, from a methodological perspective, in our approach we differentiate among process-affecting behaviours of different operators and roles with respect to the same process function, as this is a significant indicator of resilience. Furthermore, the application of the approach to real industrial processes allowed us to identify and represent human activities as FRAM functions, components that could not be detected by the event logs alone.

Going into more detail about the business process analysis methods, similarity metrics are a valuable tool to quantify differences of business process models that undertake process analysis in a organization, but also to empower process model repositories with intelligent search mechanisms [28,29]. Becker and Laue [28] present a comprehensive account of similarity metrics and computation techniques defined on labelled graphs that formally represent activity flow diagrams. Furthermore, a comparison of the similarity metrics in relation with process modelling and search objectives is presented. These applications include: merging of processes; compliance checking of actual models with a reference model; management of changes; normative checking of process models, and design for business process automation and dynamic service search. In Schoknecht et al. [29], applications of these types are grouped into the following higher level goals: *conformance, standardization, search* and *reuse*. Process abstraction from different variants to identify a reference model, and supply process model recommendations, are additional cases where model similarity can be useful, combined with process mining methods [30].

In this paper, an extension of one of the well known similarity metrics, i.e., the Dice-based distance metric [31], is defined to measure FRAM models distances and its effectiveness is evaluated in the experimentation of the approach. However, other similarity metrics illustrated in the papers above could be adopted and experimented with. Moreover, our interpretation of process similarity measures as indicators of the resilience of an organization is a novel application for these metrics over a multi-perspective classification of the process models.

Ontologies for business process management. Adding semantics to business process representations aims at enhancing business process management systems with increased automated functionalities for specifying, implementing, executing, validating, and monitoring business processes [32]. Existing works focus on adding a semantic layer either to the behavioural model of a business process [33] or to the business process entities of the model with the purpose of increasing automation [32].

Among the works on semantic business process management, the BPAL (Business Process Abstract Language) ontological framework adds semantics to business processes entities, such as activities, decisions, and roles [34,35]. Along this line, Di Francescomarino [36] proposes the BPMN (Business Process Model & Notation) ontology to reason on semantically annotated processes.

de Medeiros et al. 2007 [37] present how semantics can be used in practice to support business process monitoring. In detail, they identify and describe 5 different phases of the business process monitoring lifecycle where semantics can have a role: observe, evaluate, detect, diagnose, and resolve. In Azzini et al. [38], the authors show how semantic lifting of business processes [39] can be used to improve process mining.

Our work can be thought of as complementary to the above works, as we propose to use semantics at a higher level where the semantically enriched entities are the whole processes rather than their constituents. As such, our method is independent from specific process modelling languages and/or log events used for process mining [40], and the ontology can also be used to link different representations (models or free text) of the same process. More generally, this approach aims at improving understanding of the processes and how knowledge on these is generated and transferred in a complex cyber-socio-technical system such as an industrial plant.

Our work builds on the work on the SECI model of Nonaka [41] devoted to organizational knowledge management and where the view of knowledge-as-a-flow is developed. We characterized processes as work varieties, we extended the knowledge dynamics and added a semantic layer to the model.

3. Background methods

3.1. The WAx framework

The WAx framework [5] is a conceptual framework specifically developed to provide a systematic structure for the variety of different industrial process perspectives. In the following, we recall only those concepts that are strictly necessary for understanding the proposed approach to measure allostatic load.

Cardinal to the WAx framework are the concepts of work varieties and knowledge. CSTS systems contain a massive amount of knowledge distributed within them, embodied in operators, embedded in technology and outlined in organizational structures. The WAx framework allows for tracing the processes of creation and loss, amplification transfer, and analysis of distributed knowledge in CSTSs. For example, the so-called knowledge entities are proper declinations of work (Work-As-x), which therefore give the framework its name. They are: Work-As-Imagined (WAI), Work-As-Prescribed (WAP), Work-As-Normative (WAN), Work-As-Done (WAD), Work-As-Disclosed (WADI), and Work-As-Observed (WAO).

WAI is the entity that represents the mental models concerning the activities related to human work; the work implied by WAI is the ideal work in terms of potentiality (i.e. how we imagine the present, past and future work to be performed) as well as ideal in terms of belief (i.e. how we imagine the various activities to be performed, but also how we believe we perform ours).

WAP encompasses all perspectives of work within the organization as it is formalized in terms of procedures, checklists, standards, task descriptions and descriptive training.

WAN encompasses all norms external to the organization in different degrees of formalization: laws, rules, international standards, safety procedures, technical standards.

WAD is the activity actually carried out in the working environment (i.e. within the CSTS world). The WAD is only partially accessible. As the working environment is characterized in reality by being dynamic, unstable and unpredictable, this variety of work is frequently different from what is imagined or prescribed.

WADI represents what the system's various agents consciously or unconsciously exhibit, show or explain about their work. What is disclosed is what is wanted to be conveyed as a specific message to a specific audience. In a more or less deliberate way the WADI is influenced by the interaction with the audience. In any case, a part of this communication eludes the will of the agent, transmitting additional side signals beyond the mere direct message. Therefore, the WADI always possesses a rich informational content.

Work-As-Observed (WAO) refers to the mental model related to an observation of work. Even when referring to the naturalistic observation of human work, it is expected that the WAO can be distorted as much by the mental model of the observer as by that of the observed.

For the sake of simplicity, in this paper, we reduced the different varieties of human labor to two: the WAI and the WAD. The former represents an idealized version of human work, the latter the work as it actually occurs in the ever changing and resource-constrained operating conditions. Both are de facto unattainable, but we can consider as their best proxy measures, respectively, the view of the process from the perspective of blunt-end operators and that from the perspective of sharp-end operators. In the case studies, they were both built by an analyst that used knowledge, respectively, collected by blunt-end operators, i.e. $\text{WADI}_{\text{Analyst}}$-of-WAI, and by sharp-end operators, i.e. $\text{WADI}_{\text{Analyst}}$-of-WAD. The knowledge flows from a knowledge entity to another one and, in doing so, it can become tacit or explicit (i.e., from the Sharp to the Blunt and vice versa), being reified or becoming the object of an analysis. Such transfers happen through so-called foundational conversion activities, whose details are fully discussed in earlier paper [5].

The WAx framework assumes a holistic and fractal perspective, such that systems are formed by organizations, formed in turn by teams, people and artifacts, each one possessing agency features from time to time (i.e., they are to all intents and purposes subsystems, also complex and autonomous). Moreover, the same individuals may take on different agency roles depending on the context.

Since the WAx framework was designed to be able to effectively describe knowledge in real systems, so-called influences play a prominent role in it. These represent effects of different nature due to prior knowledge and which can modify any new knowledge elicitation process. The WAx framework recognizes the amount of information loss and the deliberate search for trade-offs between efficiency and effectiveness, both of which are present in all real systems. These influences are considered as much in process realization activities as in communication activities, and as in meta-analytic (e.g., modelling) activities.

3.2. The functional resonance analysis method for safety critical industrial processes

The Functional Resonance Analysis Method (FRAM) is a method of resilience engineering (i.e. the discipline that aims to engineer resilient sociotechnical systems) that allows to effectively represent a work domain by giving a functional description of the many activities involved [20]. The FRAM does not assume preemptively that there is a unique valid way to perform the work. Following the principles of resilience engineering [20], through its four principles (equivalence of failures and successes, approximate adjustments, emergence, functional resonance [11]), 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, also implying interrelation among their variabilities. Each agent (both individual and collective) of the sociotechnical system usually regulates in its own functions 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 phenomena, caused by an operating condition also known as functional resonance. The method itself is composed of 4 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 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 6 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).
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), and 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 variability. This step focuses on how the system affects, and is in turn affected by all the variability couplings, by the whole upstream–downstream interaction. Such intertwined functional aggregation determines the instantiation. Changing the scenario will produce another instantiation. By changing functions (in number, connected aspect, potential variability), another instantiation 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 comparison of 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. A semantics-based framework to measure allostatic load

4.1. Allostatic load in cyber-socio-technical systems

In physiological systems, allostasis is defined as *the ability to achieve stability through change [12]*. The drawback of this adaptation to stress can be *allostatic load, which is defined as the wear and tear that results from chronic overactivity or under-activity of allostatic systems* [13]. According to McEwen [13], there are four typical situations associated with allostatic load. In the first situation, allostatic load causes frequent stress. In the second one, it causes lack of adaptation to repeated stressors of the same type. In the third situation, it causes the inability to shut off allostatic responses after the end of a stress. In the last situation, allostatic load originates inadequate responses to a stressful stimulus by some allostatic systems. This triggers responses in other systems to compensate the underactive systems.

Different situations can cause tensions to a system. Environmental stressors, such as those depending on contractual obligations (e.g., strict delivery times), large amount of work, or unexpected events, such as personnel unavailability due to COVID or misunderstandings between employees are among the factors that contribute to augment CSTS organizational tensions. This also depends on the individual differences among CSTS agents, such as those related to personality and experience. We define ETTO behaviours as all the behaviours motivated by the ETTO (Efficiency-Thoroughness Trade-Off) principle, i.e., *the idea that all human activity can be described as if it involved a trade-off between efficiency and thoroughness* [42]. Thus, organizational tensions cause ETTO behaviours of sharp-end operators that, in turn, are one of the reasons why several WAx entities exist for the same process. By following the ETTO principle, operators choose the most thorough alternative in scenarios characterized by the limitedness of resources. CSTS responses to perceived organizational tensions can be unpredictable and reflect different WAx entities due to the variety of work representations. As mentioned, ETTO behaviours and individual CSTS agent differences are among the contributing factors of the WAx entities variety. Even if such a variety can contribute to further increase the CSTS perceived organizational tensions, such as those due to stressed employees, it allows the CSTS to adapt by achieving stability through change. However, similarly to physiological systems, the side effect of adapting to CSTS organizational tensions can be allostatic load. Fig. 1 is inspired by a pictorial representation of allostatic load in physiological systems [13] but, here, it shows how allostatic load is developed in cyber-socio-technical ones. Again, the typical situations associated with allostatic load in CSTSs are similar to the four mentioned for physiological systems but, in this case, may threaten productivity and industrial safety. Here, we assess the allostatic load by measuring how semantically different the WAx entities that develop it are.

4.2. EPOWAx: An ontology for resilience assessment

EPOWAx (Enterprise Production Ontology based on the WAx framework) is the domain ontology that collects formalized knowledge about the variety of work representations and the main entities described in FRAM process models. It was constructed starting from the EPOWAx Upper Ontology Model that consists of a set of upper level concepts and relationships that can be extended to create an ontology for a specific application domain [43,44]. An upper-level ontology guarantees strong ontological foundations and a better precision of the concepts and their definitions. The EPOWAx upper ontology model consists of three different upper ontologies, which have been connected together: the WAx Framework Ontology [45], the FRAM Upper Model ontology [15, 46], and the Suggested Upper Merged Ontology (SUMO)[1] [47]. Indeed, EPOWAx extends the EPOWAx upper ontology model with application knowledge related to the CSTS processes under consideration (see Fig. 2). In the following subsections, these upper ontologies and how they have been connected are presented.

Table 1
Selection of WAx framework ontology concepts and their descriptions.

Concept name	Description
Agent	One that acts [Merriam-Webster].
Agent role	The role played by an agent in a process [5].
Knowledge entity	A knowledge entity represents a knowledge dimension, i.e., what knowledge is referred to [5].
Process	A series of actions or operations conducing to an end. [Merriam-Webster]

4.2.1. WAx framework ontology

The WAx Framework Ontology is an upper ontology derived by the WAx framework, which formally defines the relationships between different work representations (e.g. Work-As-Imagined, Work-As-Done, Work-As-Disclosed, Work-As-Observed) intended as knowledge entities generated by different agents, i.e. sharp-end operators, blunt-end operators, and analysts.

The goal of the WAx Framework ontology[2] is to provide the WAx framework with rigorous semantics. To this purpose, we built an upper ontology representing the main concepts of the framework that can be easily extended to include domain and application-specific concepts. According to it, a process (e.g., the packaging process of liquid inhalation products) belongs to a system (e.g., pharmaceutical manufacturing plant). It relates to subsystems, which can be physical objects (e.g., a bottle label) or agents (e.g., the labeller machine operator). A knowledge entity, generically addressed as a WAx entity, such as the WAI of a sharp-end operator (WAI_{SO}), refers to a process and pertains to an agent. The latter is characterized by an aggregation level, which, following the fractal nature of the WAx framework, could be, for instance, an individual or team, and an agent role, which could be a sharp-end or blunt-end operator or an analyst. The knowledge entity has a knowledge form, which could be tacit (in case, for instance, of a not disclosed mental model about the packaging process of an external analyst) or explicit (in case, for instance, of a written procedure about how to check that the equipment is still working properly). The level, the knowledge form, and the agent role are parts of the WAx framework knowledge structure. A knowledge entity can be subject to lack of information quality. This could motivate a knowledge conversion driver related to a foundational knowledge conversion activity, which has two different knowledge entities as target and source. An example is the ETTO communication driver, which could represent the situation related to someone that deliberately hides something related to a process to hold an individual know-how inside an organization. A foundational knowledge conversion activity can be influenced by a knowledge entity. This happens, for instance, when the Work-As-Observed of a blunt-end operator, which is a conceptualization of the Work-As-Done, is influenced by the Work-As-Imagined of the same operator.

Table 1 and Table 2, respectively, show the concepts and the object properties of this upper ontology, who are relevant for the purposes of the present work. In details, a `process` represents the actual series of actions or operation conducting to an end. A `knowledge entity` represents one of the possible knowledge dimensions referring to the `process` and pertains to an `agent`, which plays a role in the process (e.g., sharp-end operator or blunt-end operator).

---

[1] SUMO. Suggested Upper Merged Ontology (SUMO). Retrieved on June 5, 2021 from https://github.com/ontologyportal/sumo (2021)

[2] The WAx Framework ontology is available at [48].

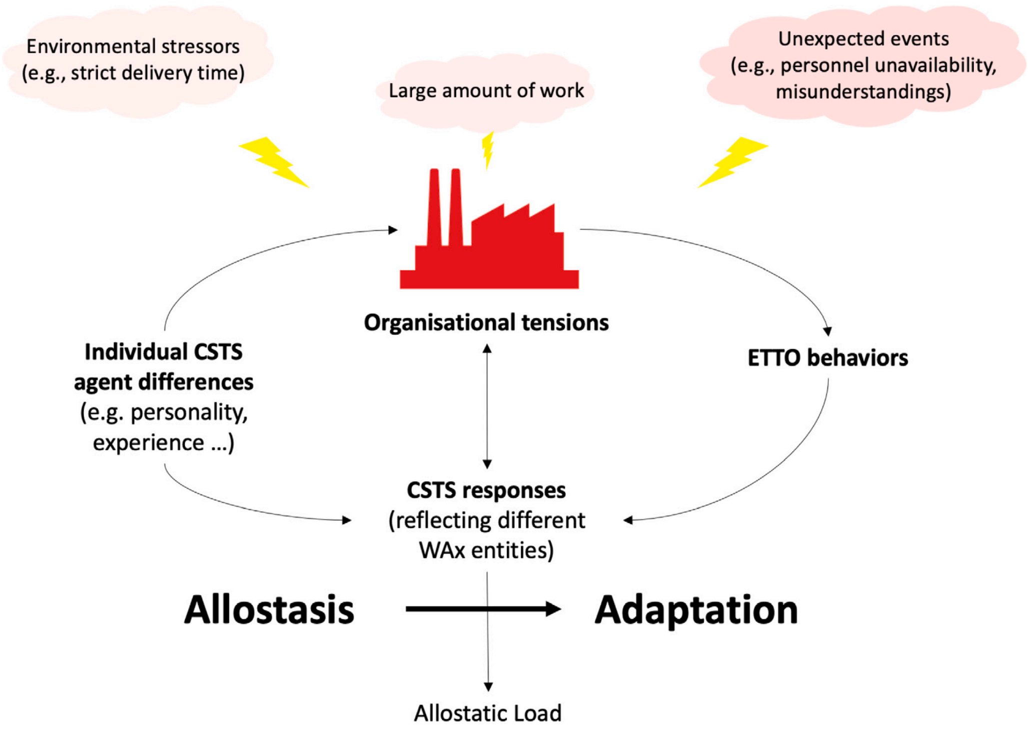


Fig. 1. Development of allostatic load in a cyber-socio-technical system (CSTS).

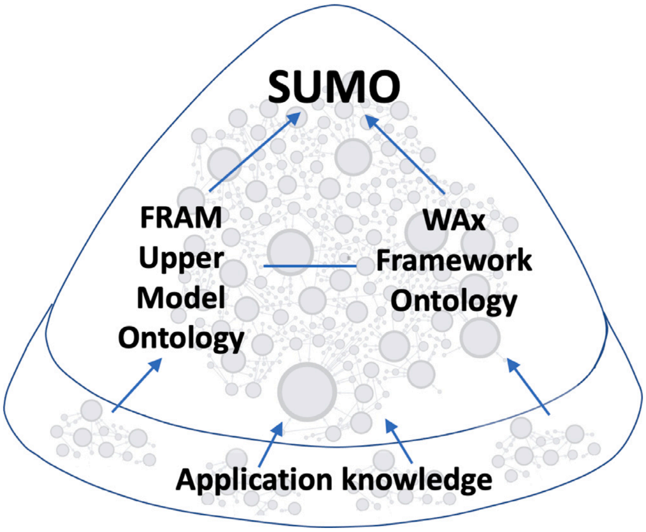


Fig. 2. A sketchy representation of EPOWAx.

Table 2
Selection of WAx framework object properties.

Domain	Object property	Range
Agent	hasRole	Agent role
Knowledge entity	pertainsTo	Agent
Knowledge entity	refersTo	Process

4.2.2. The FRAM upper model (FUM) ontology

The FRAM Upper Model (FUM) ontology is an upper ontology derived by the FRAM method presented in Section 3.2. Table 3 and Table 4, respectively, present the FUM concepts and the FUM object properties, which are relevant for this work.

Table 3
Selection of FRAM Upper Model (FUM) ontology concepts and their descriptions.

Concept name	Description
Aspect	That which characterizes a function [11].
Coupling	A link between functions [11].
FRAM element	Entity used in the Functional Resonance Analysis Method.
FRAM model	A description of functions [11].
Function	A function represents the means that are necessary to achieve a goal and, more generally, the acts or activities needed to produce a certain result. It typically describes what people, individually or collectively, have to do to perform a specific task and thus achieve a specific goal. It can also refers to something that an organization does or what a technical system does either by itself or together with one or more people [11].
Function type	The type of function, i.e., technological, human, or organizational [11].
Output	That which is the result of the function [11].

Table 4
Selection of FRAM Upper Model (FUM) object properties.

Domain	Object property	Range
Function	hasAspect	Aspect
Coupling	hasDownstreamAspect	Aspect
Coupling	hasDownstreamFunction	Function
Function	hasUpstreamAspect	Output
Coupling	hasUpstreamFunction	Function

According to the FUM ontology, a `FRAM model` consists of `couplings` and `functions`. The latter are `FRAM elements`, as well as `Aspects`. A `Function` is characterized by a `Function type`, to specify if it is either organizational or technological or human. A `function` has `aspects`, which could be `inputs`, `outputs`, `controls`, `preconditions`, `resources`, and `times`. `Couplings` allow specification of the process flow. They permit coupling of functions, by means of the object properties `hasDownstreamFunction` and `hasUpstreamFunction`, and function aspects, by means of the object properties `hasDownstreamAspect` and `hasUpstreamAspect`.

Table 5
Selection of SUMO ontology concepts and their descriptions.

Concept name	Description
Attribute	Qualities which we cannot or choose not to reify into subclasses of object [47].
Procedure	A sequence-dependent specification [47].
(SUMO) Process	The class of things that happen and have temporal parts or stages [47].
Process task	A function to be performed [47].
Proposition	Propositions are abstract entities that express a complete thought or a set of such thoughts [47].
Relational attribute	Any attribute that an entity has by virtue of a relationship that it bears to another entity or set of entities, e.g., social roles and positional attributes [47].
Quintary relation	Quintary relations relate five items [47].

Table 6
Selection of object properties aimed at integrating SUMO, WAx, and FUM upper ontologies.

Domain <ontology>	Object property	Range <ontology>
Coupling <FUM>	IS_A	Quintary relation <SUMO>
Function <FUM>	IS_A	Process task <SUMO>
Aspect <FUM>	IS_A	Proposition <SUMO>
FRAM model <FUM>	IS_A	Procedure <SUMO>
Function role <FUM>	IS_A	Relational attribute <SUMO>
Knowledge entity <WAx>	IS_A	Procedure <SUMO>
Process <WAx>	IS_A	Process <SUMO>
Agent role <WAx>	IS_A	Social role <SUMO>
Function type <FUM>	isRelatedToAgent	Agent <WAx>
FRAM model <FUM>	represents	Knowledge entity <WAx>

4.2.3. The suggested upper merged ontology

SUMO (the Suggested Upper Merged Ontology) is a foundational ontology, which guarantees strong ontological foundations and a better precision of the concepts and their definitions. Interoperability is a key requirement to reach operational excellence of productive processes [49] and to increase competitive capacity of industries [50]. Indeed, SUMO enables interoperability between domain ontologies when mapped to it. Table 5 includes a selection of SUMO concepts used to define those of WAx and FUM, while Table 6 presents a selection of object properties aimed at integrating SUMO, WAx, and FUM upper ontologies.

4.2.4. The FWS federated upper ontology model

EPOWAx was built by extending the FWS (FRAM-WAx-SUMO) Federated Upper Ontology Model[3] including the WAx framework ontology, the FUM ontology, and SUMO. Fig. 3 shows an excerpt of it in the form of an UML (Unified Modeling Language) class diagram where SUMO concepts are depicted in yellow, WAx framework ones in red, and FUM ones in light blue. In the figure, most of the WAx framework and FUM concepts are defined as specializations of SUMO ones. Then, the `represents` object property links the FUM concept named `FRAM model` with the WAx framework one named `knowledge entity` while the `isRelatedToAgent` object property links the FUM concept named `function type` with the WAx framework one named `agent`.

4.3. Guidelines for assessing allostatic load

We defined some guidelines to assess allostatic load. They consist of seven steps that span from knowledge elicitation of the Work-As-Imagined to the final allostatic load assessment. These are:

- WAI elicitation;
- Automatic population of the EPOWAx ontology from FRAM WAI;
- Supervised creation of the WAI survey;
- Sharp-end operators respond to the survey and workshop for “crowd-based validation”;
- Design of FRAM WAD and automatic population of EPOWAx;
- Computation of semantic distance between WAI and WAD;
- Allostatic load assessment.

The steps are presented in the following and in Fig. 4.

WAI elicitation. Preliminarily, the FRAM analyst performs data collection for the creation of the WAI instantiation. In consultation with management, a suitable process can be identified for analysis in terms of both business and safety criticality. Typically, a FRAM analysis pays particular attention to processes that are heavily, but not exclusively, anthropized. Relevant human activities can be identified from a range of different sources (e.g.) process documentation incident cases, risk assessments, or master records. It is important to maintain a broad yet reasonably deep perspective on the processes under investigation so that they possess the necessary relevance in both safety and business critical terms. When available, existing descriptions of the process, or even standard operating procedures (SOPs), should be considered to foster a preliminary understanding in favour of analysis. Such tasks often do not have formal procedures and, hence, how they are carried out in practice can vary significantly. In high-hazard industries the tasks may already have been analysed using some form of task analysis, and this could provide an excellent starting point. A commonly used approach is Hierarchical Task Analysis (HTA). More information are provided in [52].

The HTA determines a fixed structure and temporal sequence for the basic task steps, i.e. the HTA describes tasks in terms of a hierarchical decomposition (vertically) and in terms of their order of execution (horizontally). In FRAM, on the other hand, no such fixed order is assumed. FRAM uses the concept of aspects to describe explicitly the relationship between functions or activities. This is very useful in order to represent how functions interact and what the nature of their relationship is, e.g. whether it is an input–output relationship, a temporal relationship or whether the output of one function acts as the control for another function etc.

It is expected that the primary tool for data collection for WAI elicitation should be stakeholder interviews. Based on the review of existing documentation, the purpose of the interviews should be to understand how managers think the work is done by frontline workers. Typically, middle managers with shared supervisory responsibility are interviewed. Depending on the type of system being investigated a specific role may be shared across multiple agents. In any case, the WAx entity is designed to take these nuances into account.

The interviews can be conducted individually or within focus groups, moreover, they can be structured, semi-structured, or in-depth. However, semi-structured interviews are usually considered more suitable for the FRAM purposes. Questions should focus on functions to be executed, on their kind (e.g., technological, human, organizational), and on their variability. Please note that prospective FRAM analyses usually address daily work, not exceptional situations such as accidents or incidents.

A certain amount of conflicting evidence is expected and normal where different participants are interviewed. On the one hand, the FRAM method lends itself well to this dissimilarity of view, being able to interpret it as variability in performance. Further information about variability can be elicited from stakeholders during interviews or focus groups. FRAM includes default assumptions about variability relative to time scales normally associated with sociotechnical processes. Technological functions are assumed to have little output variability, while functions carried out by humans typically have high variability both with regards to frequency and amplitude, and organizational functions have lower frequency variability, but high amplitude. A second guiding

---

[3] The FWS Federated Upper Ontology is available at [51]

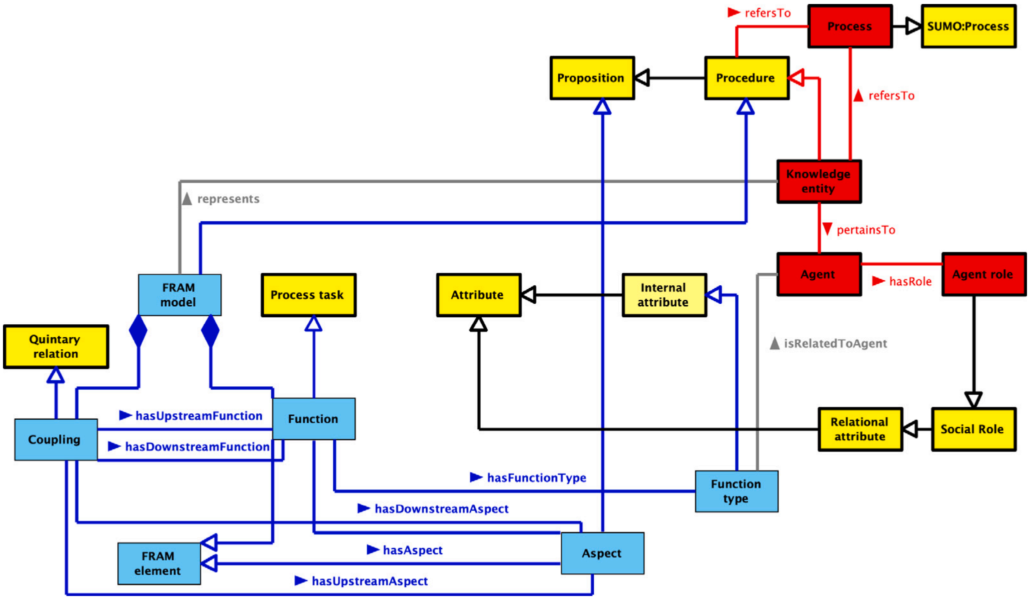


Fig. 3. An excerpt of the integrated concepts from the WAx (in red), FUM (in blue), and SUMO (in yellow) ontologies.

principle concerns the nature of performance variability. It is useful to distinguish between potential variability and actual variability. In the tabular representation of the FRAM model, we are concerned with the potential variability, i.e. the different ways in which the output of a function might vary. Once functions are looked at together in the form of scenario, we are starting to investigate the actual variability for that particular instantiation. Hollnagel [11] suggests that a reasonable simplification is to consider variability of outputs in terms of precision and timing phenotypes, i.e. the output of a function can be precise, acceptable or imprecise, and the output can be on time, too early or too late.

In our framework, the format (.xfmv) used to collect data (and consequently to convey the FRAM WAI instantiation) is the one used in the FRAM Model Visualizer[4]. The utility of the tool is it permits to visualize the instantiation. Then (or more probably at the same time), the FRAM analyst can import the WAI model into the myFRAM[5] addon for Excel, from which, through a parser developed ad hoc, it will be possible to feed the group of ontologies used in the next steps. The obtained FRAM model represents the so-called $\text{WADI}_{\text{Analyst}}$-of-WAI, that is the result of the externalization of the $\text{WAI}_{\text{Analyst}}$-of-WAI. However, for simplicity, in the continuation we will refer to this instantiation like FRAM WAI.

Automatic population of the EPOWAx ontology from FRAM WAI. This step is devoted to building the EPOWAx ontology by extending the EPOWAx Upper ontology model with Work-As-Imagined knowledge. This operation is automatically performed by a software application developed for the purpose named the Automatic WAx ontology builder. The input for this software is the FRAM WAI and the EPOWAx upper ontology, an ontological upper model gathering FRAM and WAx upper concepts. The Automatic WAx ontology builder consists of two modules: the former, the FRAM parser, devoted to parse the .xfmw file (originated by FMV, the FRAM model visualizer) specifying the FRAM WAI model and the latter, the ontology manager, devoted to create the EPOWAx ontology, which includes knowledge on the Work-As-Imagined.

Supervised creation of the WAI survey. Once Work-As-Imagined knowledge has been collected in the EPOWAx ontology, a gamified WAI survey is automatically generated by means of the Gamified WAI survey generator, which is a software application developed by ENEA. This takes the EPOWAx ontology as input and produces a questionnaire as outcome, by leveraging the guided questions for exploring the FRAM conditions presented by Clay–Williams et al. in [53], such as *"What starts the function?"* and *"What should be in place so that you can complete the function normally?"*, and patterns-based reasoning. Afterwards, the questions are revised by safety experts and included in a Google form. The aim of the questionnaire is to collect Work-As-Done knowledge from safety operators (as for the crowd-based indicators).

Sharp-end operators respond to the survey and workshop for "crowd-based validation". In this step, sharp-end operators complete the survey. Then, safety analysts and sharp-end operators validate the results of the questionnaire and discuss in person any doubts that occurred when responding to the questionnaire.

Design of FRAM WAD and automatic population of EPOWAx. In this step, the safety analyst designs the FRAM model of the Work-As-Done by using collected knowledge from the sharp-end operators and prior knowledge about the Work-As-Imagined. The evolution of EPOWAx from the EPOWAx upper ontology model to its enrichment with WAI knowledge first and WAD knowledge at the end is shown in Fig. 5.

Computation of semantic distance between WAI and WAD. As already mentioned, a preliminary step to assess allostatic load is to compute the semantic distance (i.e., the complement of 1 of semantic similarity) between two WAx models (e.g., WAI and WAD). Hence, we defined a composite algorithm consisting of three sub-algorithms (see Algorithm 1, Algorithm 2, and Algorithm 3 in the following). Algorithm 1 allows computation of the semantic similarity between two WAx entities. It uses Algorithm 2 to compute semantic similarity between two FRAM functions. Finally, Algorithm 3 is the most granular one. It is used by Algorithm 2 and allows computation of similarity between two vectors of FRAM aspects. Indeed, the composite nature of the algorithm permits modularization. There are several methods to compute semantic similarity between vectors [54] that can be selected, for instance, on the basis of the topological features of the available ontology. In the case studies, we decided to use the Dice algorithm [31] because the respective ontologies do not contain many hierarchical levels that would justify the use of a different algorithm such as $SemSim^p$ [14].

---

[4] FRAM Model Visualizer web site: https://functionalresonance.com/FMV/index.html (Last access on 14th September, 2022).

[5] myFRAM web site: https://functionalresonance.com/the%20fram%20model%20visualiser/myfram.html (Last access on 14th September, 2022).

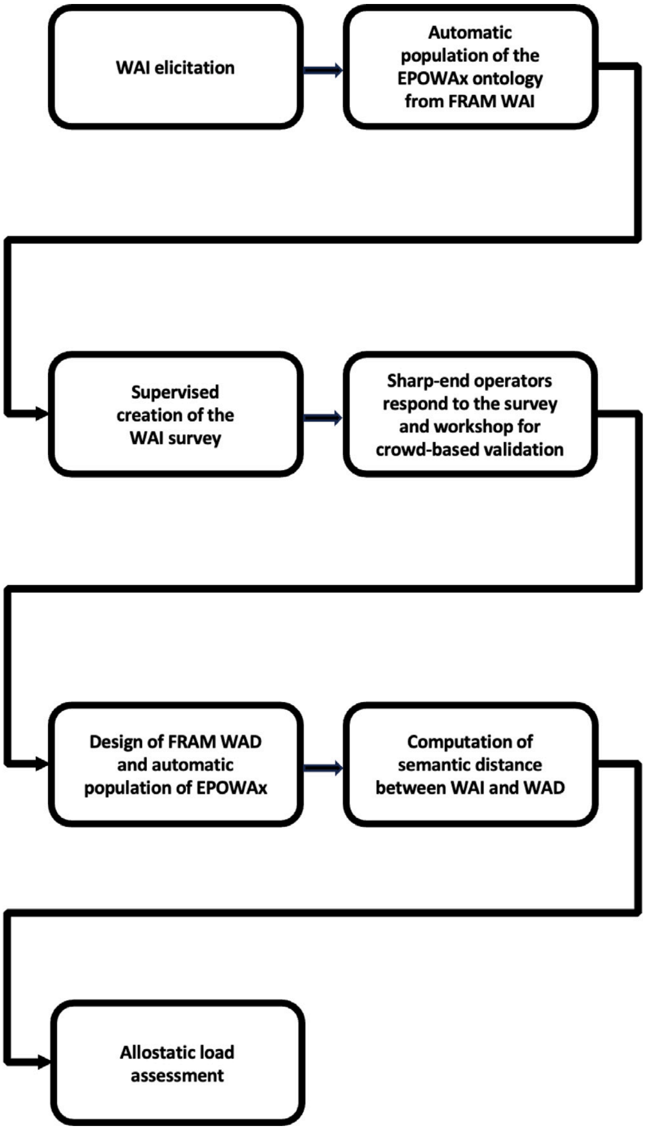


Fig. 4. Workflow for allostatic load assessment.

In the following, we describe the three sub-algorithms in details.

The sub-algorithm to compute WAx Semantic Similarity (WAxSS) (see Algorithm 1) requires as input two vectors of FRAM functions, respectively, belonging to two FRAM models pertaining the same process, and a pairing vector defining the correspondences between the functions belonging to the above-mentioned models (i.e., WAI and WAD). Indeed, three types of correspondences exist: (i) two functions have the same identifier and own the same aspects; (ii) two functions have different identifiers but own the same aspects; (iii) two functions have different identifiers and own different aspects.

As mentioned, Algorithm 1 uses Algorithm 2 that allows to compute semantic similarity between two FRAM functions. A function is treated as a set of predefined vectors of aspects, i.e., one vector for each type of aspect (i.e., input, output, precondition, control, time, and resource). Furthermore, a function owns a type, which could be either human or technological or organizational. Algorithm 2 recalls Algorithm 3 to compute semantic similarity between the vectors corresponding to the types of aspects and accumulates the results in the $fuSim$ variable. If both the functions have no aspects for a given aspect type, 1.0 is added to the $fuSim$ variable. Similarly, if the functions own the same type, 1.0 is added to the variable. Finally, $fuSim$ is normalized.

Algorithm 1 Algorithm to compute WAx Semantic Similarity (WAxSS).

```
function WAxSS(wai, wad, pairingVector)
    waxSim = 0.0
    pairings = 0
    for i in [0,wai.size()-1] do
        if (pairingVector $\neq$ null) then
            fun$_1$ = wai[i]
            fun$_2$_Index = pairingVector[i]
            fun$_2$ = wad[fun$_2$_Index]
            waxSim += computeFunctionSimilarity(fun$_1$, fun$_2$)
            pairings += 1
        end if
    end for
    waxSim = waxSim / (wai.size() + wad.size() - pairings)
    return waxSim
end function
```

Algorithm 2 Algorithm to compute function semantic similarity

```
function compute_Function_Similarity(function_1, function_2)
    fuSim = 0.0
    aspects = [input, output, precondition, control, time, resource]
    for all aspect in aspects do
        aVector_1 = function_1.getAspectVector(aspect)
        aVector_2 = function_2.getAspectVector(aspect)
        if (aVector_1.size() > 0 or aVector_2.size() > 0) then
            fuSim += computeDiceSimilarity(aVector_1, aVector_2)
        else
            fuSim += 1.0
        end if
    end for
    if (function_1.getType == function_2.getType) then
        fuSim += 1.0
    end if
    fuSim = fuSim / 7
    return fuSim
end function
```

Algorithm 3 allows computation of Dice similarity between two vectors. It is used by Algorithm 2 and returns a value spanning the [0, 1] range.

Algorithm 3 Algorithm to compute Dice similarity between vectors

```
function compute_Dice_Similarity(v1, v2)
    diceSim = 0.0
    intersection = 0
    for i in [0,v1.size()-1] do
        for j in [0,v2.size()-1] do
            if (v1(i) == v2(j)) then
                intersection += 1
            end if
        end for
    end for
    diceSim = (2 * intersection) / (v1.size() + v2.size())
    return diceSim
end function
```

Allostatic load assessment: local view and global view. The last step of these guidelines concerns the way to interpret the semantic distance values. As already mentioned, given a cyber-socio-technical system,

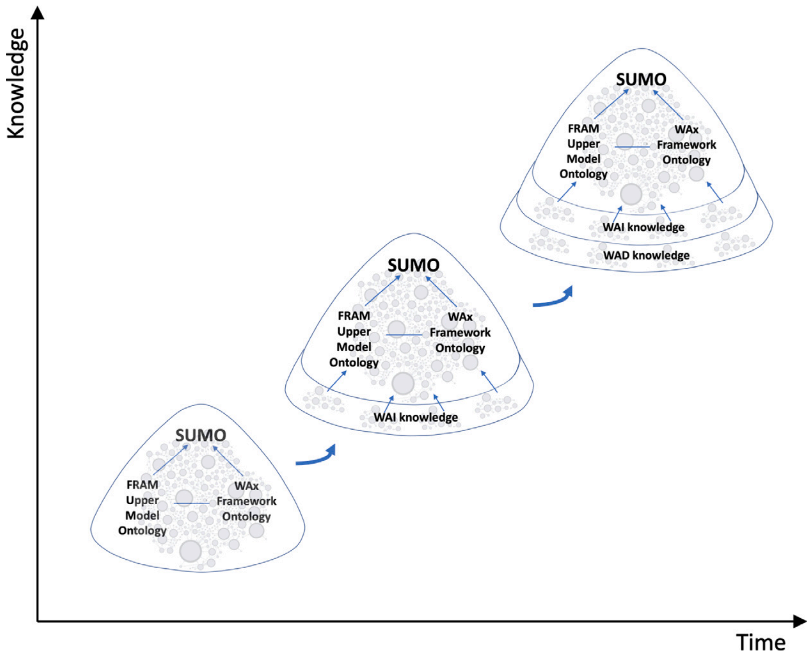


Fig. 5. WAx knowledge enrichment in EPOWAx.

one of its business processes (i), and a pair of WAx entities (j, k) representing it, the allostatic load ($\mathcal{A}_{i,(j,k)}$) can be measured by the complement of 1 of the semantic similarity between the mentioned WAx entities:

$$\mathcal{A}_{i,(j,k)} = 1 - waxss_{i,(j,k)} \tag{1}$$

Values of $\mathcal{A}_{i,(j,k)}$ close to 1 indicate high allostatic load and, hence, high level of perceived organizational tensions in the CSTS under analysis. Values of $\mathcal{A}_{i,(j,k)}$ close to 0 indicate low level of perceived organizational tensions. This simplified approach to measure the allostatic load of a CSTS can be further elaborated taking into account two different perspectives: the *global view* and the *local view*.

Accordingly, given a cyber-socio-technical system where there exist one or more business processes and, for each of them, two or more WAx entities are known, we define the allostatic load in the global view ($\mathcal{A}_{gv}$) as it follows:

$$\mathcal{A}_{gv} = \frac{1}{n} \cdot \sum_{i=0}^{n} \sum_{j=0}^{m} \frac{(1 - waxss_{i,j})}{m} \tag{2}$$

where n is the overall number of CSTS processes, m is the overall number of WAx entities pairs available for the process i, and $waxss_{i,j}$ is the semantic distance between the pair of WAx entities labelled by j available for the process i. A_{gv} is defined in the [0, 1] range.

Allostatic load in the local view can be assessed by multiple indicators including the above mentioned $\mathcal{A}_{i,(j,k)}$ and others derived by some variations of the algorithm to compute semantic similarity between WAx entities (see Algorithm 1) that take into account either only specific functions or only some given aspects. Accordingly, we defined a parametric algorithm to measure semantic similarity between two WAx entities that take into account only given function types (i.e., human, technological, or organizational), and a parametric algorithm to measure semantic similarity between two WAx entities that take into account only given function aspects (i.e., input, output, precondition, resource, constraint, time). The corresponding indicators for allostatic load are, respectively, allostatic load by function type where $\mathcal{A}^{FT}_{i,(j,k)} = 1 - waxss^{FT}_{i,(j,k)}$ and allostatic load by aspect where $\mathcal{A}^{ASP}_{i,(j,k)} = 1 - waxss^{ASP}_{i,(j,k)}$.

The algorithm to compute the WAx semantic similarity by function type is reported in the annex (see Algorithm 4). It is similar to Algorithm 1 but it limits the computation to only some given functions.

For the sake of completion, the algorithms to compute the WAx semantic similarity by aspect are also reported in the annex (see Algorithm 5 and Algorithm 6).

In this paper, we address allostatic load in the local view.

5. Experimentation

The goal of the experimentation was to validate the approach for allostatic load assessment in cyber-socio-technical systems. We addressed its *feasibility*, *reproducibility*, and the *quality of allostatic load results*. Indeed, first, we assessed the allostatic load of a pharmaceutical manufacturing plant due to a packaging process to demonstrate the feasibility of the approach and usefulness and quality of the results. Then, we repeated the experiment for another enterprise in the aluminium sector to demonstrate reproducibility of the approach.

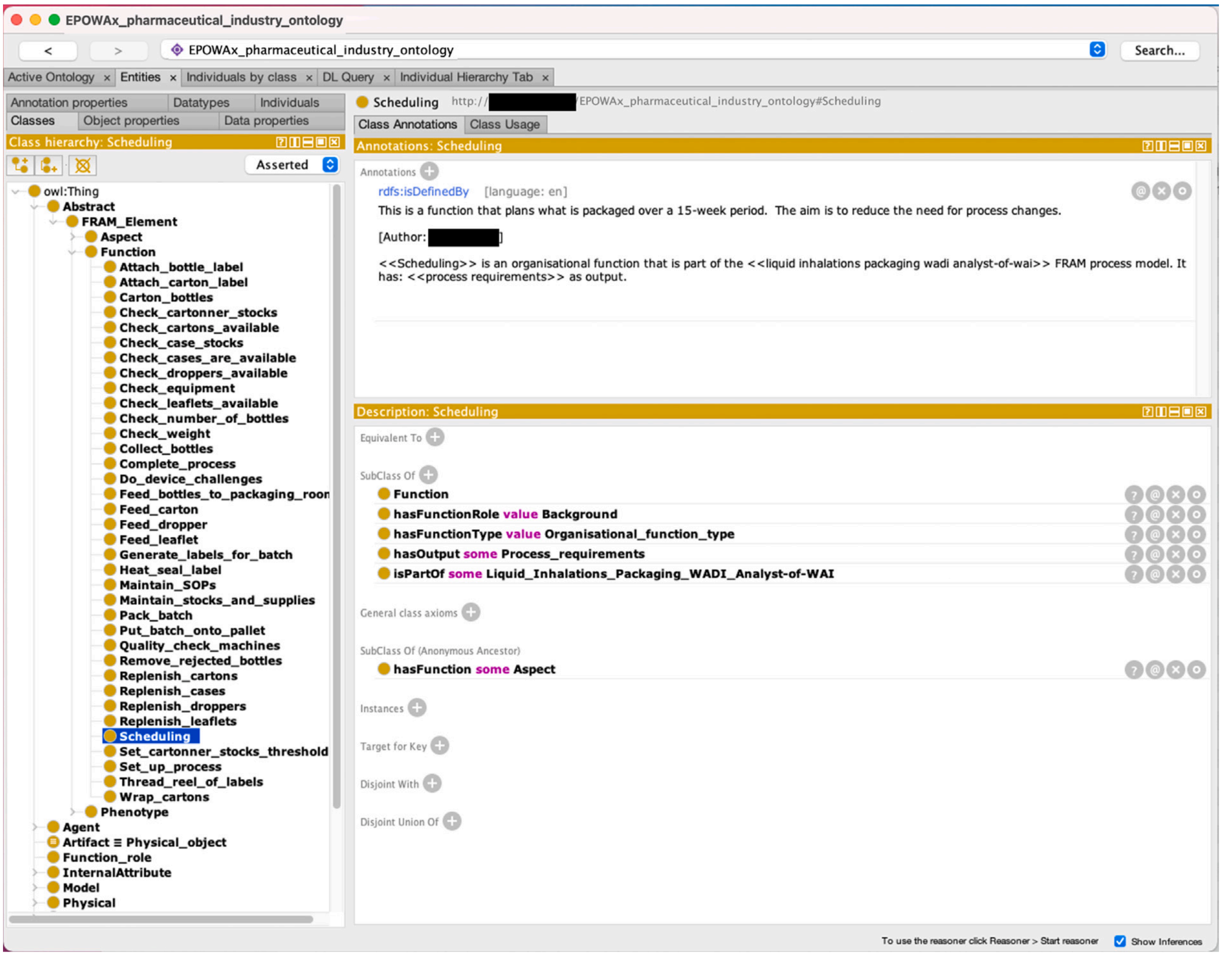
5.1. Case study on a pharmaceutical manufacturing plant

The case study site concerns a pharmaceutical manufacturing plant. It is a so-called “secondary” site, which indicates that it is a lower risk site that produces pharmaceuticals for consumer distribution. The process we selected was one to fill and package liquid inhalation products. The specific agent is a respirator solution, which is used to treat bronchospasms and asthma.

The process consists of two separate, but connected areas: the clean room and the packaging room. The clean room is a sterile environment, where the pharmaceutical product is filled into bottles. The filled bottles then arrive in the packaging area via a conveyer belt. Here, we address what happens in the packaging room.

Bottles arrive in the packaging room from the clean room via the conveyer. Bottles go into the labeller, where a label is attached, which is subsequently heat sealed by going through a heat tunnel. Bottles enter an accumulator, and then get packaged in a carton along with a leaflet and a dropper. Packaged bottles are then weight checked to identify those cartons that have missing leaflets or droppers. Cartons then enter a further labeller. Labelled cartons are wrapped, sealed, and collected as batches into a case. From there, the cases arrive at the end of the production line ready to be put onto a pallet.

The first step of the workflow is related to WAI Elicitation. The site staff produced a virtual walk-through video where they narrated



http://[redacted]EPOWAx_pharmaceutical_industry_ontology#Scheduling

rdfs:isDefinedBy [language: en]

This is a function that plans what is packaged over a 15-week period. The aim is to reduce the need for process changes.

[Author: [redacted]]

<<Scheduling>> is an organisational function that is part of the <<liquid inhalations packaging wadi analyst-of-wai>> FRAM process model. It has: <<process requirements>> as output.

SubClass Of:

Function
hasFunctionRole value Background
hasFunctionType value Organisational_function_type
hasOutput some Process_requirements
isPartOf some Liquid_Inhalations_Packaging_WADI_Analyst-of-WAI

SubClass Of (Anonymous Ancestor):

hasFunction some Aspect

Fig. 6. A screenshot of the EPOWAx ontology including WAI knowledge about the case study in the pharmaceutical sector.

and described the process while video recording the different elements of the process. In addition to the virtual walk-through, we undertook five interviews with site managers as part of the analysis. The focus of the analysis was on the normal operation of the process, and therefore did not consider infrequent or abnormal scenarios such as customized operation for the Chinese market (requiring special labels) or troubleshooting operations. In total, 36 functions were identified during the analysis of the normal operations scenario (instantiation). The process is highly automated, and, hence, a significant number of functions are technological (15 functions). Process operator functions (16 functions) are concerned mostly with ensuring that the equipment can function as intended, e.g. by replenishing materials as and when required. In addition, organizational functions relate to the setup and maintenance of the process (5 functions). The FRAM model of the WAI[6] was built by using the FRAM model visualizer.

Then, a first version of the EPOWAx ontology, including WAI knowledge and the upper model presented in Section 4.2 was automatically built by importing the previously mentioned *.fmv* file in the software tool developed for the purpose. At this stage EPOWAx gathers 317 classes, 52 object properties, and 2261 axioms. A screenshot of the resulting ontology in the Protégé ontology management system is shown in Fig. 6.

The online survey was created by following the step of the above-mentioned guidelines presented in Section 4.3. The analysts decided to address only some functions, which are more relevant for the quality purpose of the project. These are: replenish leaflets, replenish cases, do device challenges, and check equipment. The survey was submitted to the sharp-end operators of the pharmaceutical company by means of the Google Forms web application. Examples of questions are *What resources do you need in order to replenish leaflets in the cartonner?* or "*Do you perform any check or adjustment while replenishing leaflets in the cartonner?*."

After the step concerning the collection of answers from the google forms, we organized a virtual meeting involving the project team, a line manager, and three sharp-end operators. During the workshop, the functions selected for the survey were discussed one by one so to achieve a description of the different functional aspects agreed by all the sharp-end-operators and to widen the understanding of the whole process by the analyst. As an outcome, the definitions of 8 functions of the FRAM WAI were updated and 3 new functions were added to the FRAM model to represent the WAD. The changes for instance, address the need to have explicit time constraints for the operators when replenishing the machines with stocks and supplies, and some specific process-independent resources they need to actually carry out the replenishing case activity and for device checks. The background function *Housekeeping* was added to the FRAM to model supplying such resources. The FRAM WAD model[7] was created accordingly. This latter comprises 39 functions.

Then, the FRAM WAD model was imported in the EPOWAx ontology. The resulting ontology[8] consists of 402 classes, 52 object properties, and 3151 axioms.

---

[6] The FRAM model of the WAI is available as *.fmv* file at [55]

[7] The FRAM model of the WAD is available as *.fmv* file at [55]

[8] The final ontology for the case study on the pharmaceutical manufacturing plant is available at [55]

Table 7
Values of allostatic load in the local view between WAI and WAD entities in the case studies related to the packaging room of a pharmaceutical manufacturing plant and to an enterprise operating in the aluminium sector.

Pharmaceutical manufacturing plant		Enterprise in the aluminium sector	
Allostatic load	Value	Allostatic load	Value
$\mathcal{A}_{1,(WAI,WAD)}$	0.129	$\mathcal{A}_{2,(WAI,WAD)}$	0.2121
$\mathcal{A}^{Hum}_{1,(WAI,WAD)}$	0.1238	$\mathcal{A}^{Hum}_{2,(WAI,WAD)}$	0.068
$\mathcal{A}^{Tech}_{1,(WAI,WAD)}$	0	$\mathcal{A}^{Tech}_{2,(WAI,WAD)}$	0.0536
$\mathcal{A}^{Org}_{1,(WAI,WAD)}$	0.012	$\mathcal{A}^{Org}_{2,(WAI,WAD)}$	0.2121
$\mathcal{A}^{Con}_{1,(WAI,WAD)}$	0.1238	$\mathcal{A}^{Con}_{2,(WAI,WAD)}$	0.2386
$\mathcal{A}^{Inp}_{1,(WAI,WAD)}$	0.085	$\mathcal{A}^{Inp}_{2,(WAI,WAD)}$	0.2150
$\mathcal{A}^{Out}_{1,(WAI,WAD)}$	0.084	$\mathcal{A}^{Out}_{2,(WAI,WAD)}$	0.1932
$\mathcal{A}^{Pre}_{1,(WAI,WAD)}$	0.077	$\mathcal{A}^{Pre}_{2,(WAI,WAD)}$	0.2841
$\mathcal{A}^{Res}_{1,(WAI,WAD)}$	0.154	$\mathcal{A}^{Res}_{2,(WAI,WAD)}$	0.2102
$\mathcal{A}^{Tim}_{1,(WAI,WAD)}$	0.115	$\mathcal{A}^{Tim}_{2,(WAI,WAD)}$	0.0574

As mentioned, we focused on the local view assessment of allostatic load. The allostatic load $\mathcal{A}_{1,(WAI,WAD)}$ is 0.129. Even if the semantic similarity value between the WAI and the WAD is relatively high, there are some differences between them. For this reason, the process indicators could be defined at a more granular level. Therefore, we computed the value of allostatic load by restricting the analysis to one function type and one aspect at a time. First, we considered, respectively, only human functions, technological functions, and organizational functions. The results show (see Table 7) that allostatic load due to technological functions (see $\mathcal{A}^{Tech}_{1,(WAI,WAD)}$) in the two considered WAx entities is null whereas the highest value is due to human functions (see $\mathcal{A}^{Hum}_{1,(WAI,WAD)}$). Also organizational functions contribute to allostatic load (see $\mathcal{A}^{Org}_{1,(WAI,WAD)}$). Then, as reported in Table 7 and Fig. 7, most of the misalignments of the process are due to the different perceptions of sharp-end and blunt-end operators on the needed resources (see $\mathcal{A}^{Res}_{1,(WAI,WAD)}$) and controls (see $\mathcal{A}^{Con}_{1,(WAI,WAD)}$) whereas it is clearer to all which are the inputs (see $\mathcal{A}^{Inp}_{1,(WAI,WAD)}$), the outputs (see $\mathcal{A}^{Out}_{1,(WAI,WAD)}$), and the preconditions (see $\mathcal{A}^{Pre}_{1,(WAI,WAD)}$). Of course, these results should be interpreted bearing in mind the socio-technical dimension of this research, which differs from a pure techno-centric investigation on the technological artifacts. At a more granular level, there could be differences as well between technological functions, which are however outside the scope of our modelling.

The results of this analysis were presented to management during a focus group organized for the purpose of validating the transferability of the methodology to actual users.

Managers pointed out that the methodology was difficult to follow because it requires expertise in FRAM, not to mention the need to adopt data structures such as ontologies that require dedicated staff. For these reasons, the framework turned out not to be easily implemented directly in the company by their staff without first providing them with adequate training. Despite this limitation, reactions on both the quality of the achieved results and the usefulness of the overall approach were generally positive. In particular, it was particularly appreciated that the suggested indicators do not assume a merely safety-oriented perspective but, on the contrary, attempt to integrate the efficiency of the operations carried out (in line with the assumptions of resilience engineering [56–58]).

5.2. *Case study on an enterprise operating in the aluminium sector*

A second case study was completed to demonstrate reproducibility of the overall approach in another industrial sector. In this case, we involved a global manufacturing enterprise operating in the production of semi-finished aluminium products. The enterprise operates in several production sites located in Europe. The one that was involved is an integrated plant with a cast house, rolling mills and finishing lines, for the production of high quality thin rolled aluminum products. Management has identified a set of operations located in support of the actual rolling process as critical to worker safety and productivity. These operations involve the replacement, check, maintenance, and storage of rolling cylinders. The lamination cylinders are heavy objects that are difficult to handle and require a very high degree of surface finish. The areas of the plant affected by the investigated processes conceal potential dangers of all kinds, ranging from crushing to abrasion to falling. Moreover, these activities are crucial to ensure that lamination takes place with the proper requirements (the plant produces, among other things, aluminum film for food use with a thickness of a few microns).

Again, we were able to apply all the steps of the workflow for assessing the allostatic load. The allostatic load in the local view ($\mathcal{A}_{2,(WAI,WAD)}$) is 0.2121 (see Table 7). This means that allostatic load in the second case study is higher than the one in the first one. Concerning allostatic load by function type (see Table 7), we observe that the highest value is due to organizational functions (i.e., $\mathcal{A}^{Org}_{2,(WAI,WAD)}$). Hence, those functions are the ones that are more worthy to be monitored for safety reasons. Finally, we discussed the results of this analysis in a focus group. Similarly to the first case study, the achieved results[9] were appreciated.

6. Conclusion

Higher levels of complexity in cyber-socio-technical systems generate additional management challenges both related to occupational and operational safety, and business processes. Resilience to threats is seen as a positive ability of a system to sustain operations dealing with such complexity, adapting its functioning in spite of both expected and unforeseen situations. However, engineering resilience into a system could cause organizational tensions in the system itself. System indicators are then necessary to assess such levels of complexity in industrial operations. Most of the indicators currently used are those classified as lagging, i.e., measuring failures of the risk control systems in use. Examples can be the number of incidents occurring in a industrial site or the frequency of system faults. However, there is an increasing interest on leading indicators capable to measure the effectiveness of safety activities and risk control systems ex-ante any failure [59,60]. Examples of leading indicators may be the percentage of equipment inspections being performed on the plant, or the percentage of training actions being performed [59].

With the intention of extending decision support systems for CSTS management, in this manuscript, we have presented: (i) a novel leading resilience indicator for CSTS, named allostatic load, to measure the level of organizational tensions (see Fig. 1); (ii) a workflow based on the WAx framework to convert the output of a qualitative analysis (i.e., models of CSTS processes) to the measurement of a quantitative resilience indicator (i.e., allostatic load) (see Fig. 4); (iii) an overarching framework to measure allostatic load that includes an ontology setting, algorithms and software; (iv) an approach to elicit knowledge about the different views existing in real operating CSTS based on a survey automatically generated by a software application; (v) an upper ontology integrating concepts from the WAx, FUM, and SUMO ontologies (see Fig. 3); (vi) a software aimed at automatic ontology engineering starting from CSTS processes modelled with FRAM; (vii) an algorithm and a software leveraging semantics to measure the allostatic load.

Two case studies have been performed to experimentally validate the proposed approach for assessing allostatic load. The former related to the packaging process of a pharmaceutical manufacturing plant and the latter related to an enterprise operating in aluminium production.

---

[9] Experimental data and the final ontology pertaining to the case study on an enterprise operating in the aluminium sector are available at [55]

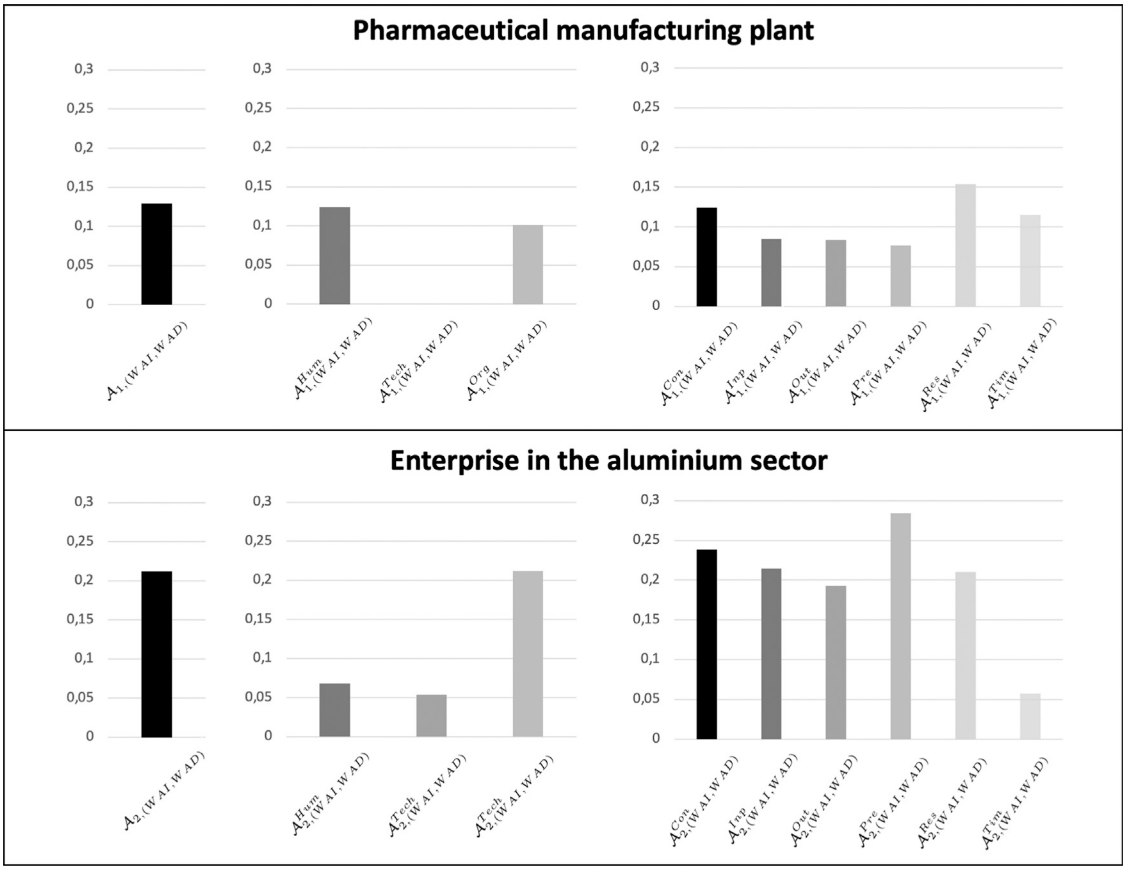


Fig. 7. Histograms of allostatic load in the local view between WAI and WAD entities in the case studies related to the packaging room of a pharmaceutical manufacturing plant and to an enterprise operating in the aluminium sector.

The presented experimentation demonstrates the feasibility and reproducibility of the proposed approach and usefulness and quality of the achieved results.

Conceptually, the assumption underlying the methodology is that there is a gap between Work-As-Imagined and Work-As-Done, and that safety indicators that help monitor this gap and which can provide insights into the realities of Work-As-Done are different from traditional, risk-based safety indicators, which are concerned with the functioning of risk controls (i.e., safety barriers). The allostatic load was defined by leveraging past direct experience in analysing the safety of industrial processes, which, together with current literature [5,7], demonstrated the existence of the different perspectives on the same business processes and suggested to us the need to take this into account quantitatively. It is rooted in a new socio-technical safety perspective called SAFETY II [56,58], which pushes to gather and evaluate significant knowledge about normal work and its effect on safety and production. Consequently, for example, an industry should not wait for an accident to occur to assess how safe a workplace is. We believe that the uncontrolled increase in allostatic load may be related to the number of accidents and lack of performance, especially if there is evidence that safety procedures are not in use in the Work-As-Done processes. Similarly, lack of direct knowledge of blunt-end operators could lead to incorrect process specifications that could cause accidents. We also believe that measuring the allostatic load can inform the CSST under study about its position in terms of margins of manoeuvre and residual capabilities and can improve the situational awareness of the social component.

In principle, our method to compute the allostatic load is flexible and can be applied to other modelling methods, such as IDEF0 [61]. We used FRAM since it is currently widely used by safety analysts. However, the algorithm to compute the allostatic load can be easily adapted to other modelling methods with few changes.

It is worth mentioning that, with respect to existing leading indicators used in resilience engineering works, the allostatic load is a novel ”meta-indicator”, as it remains neutral with respect to a domain or a specific CSTS.

Abbreviations

BPAL	Business Process Abstract Language
BPMN	Business Process Model & Notation
CPSS	Cyber-Physical-Social System
CSTS	Cyber-Socio-Technical System
EPOWAx	Enterprise Production Ontology based on the WAx framework
ETTO	Efficiency-Thoroughness Trade-Off
FMV	FRAM Model Visualizer
FRAM	Functional Resonance Analysis Method
FUM	FRAM Upper Model
FWS	FRAM-WAx-SUMO
HTA	Hierarchical Task Analysis
RAG	Resilience Analysis Grid
RE	Resilience Engineering
SOP	Standard Operating Procedure
SUMO	Suggested Upper Merged Ontology
UML	Unified Modeling Language
WAD	Work-As-Done
WADI	Work-As-DIsclosed
WAI	Work-As-Imagined
WAN	Work-As-Normative
WAP	Work-As-Prescribed
WAx	Work-As-x
WAxSS	WAx Semantic Similarity

CRediT authorship contribution statement

Antonio De Nicola: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Maria Luisa Villani:** Conceptualization, Methodology, Software, Writing – original draft. **Mark Sujan:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **John Watt:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Francesco Costantino:** Writing – review & editing, Funding acquisition. **Andrea Falegnami:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Riccardo Patriarca:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the H(CS)^{2}I project, which was partially funded by the Italian National Institute for Insurance against Accidents at Work (INAIL) and Institution of Occupational Safety and Health (IOSH), UK under the 2018 SAF€RA EU funding scheme.

Annex

Algorithm 4 Algorithm to compute WAx Semantic Similarity by function type.

```
function WASS_BY_FUNCTION_TYPE(wai, wad, pairingVector, functionType)
    waxSim = 0.0
    typePairings = 0
    for i in [0,wai.size()-1] do
        if (pairingVector ≠ null) then
            $fun_1$ = wai[i]
            $fun_2$_Index = pairingVector[i]
            $fun_2$ = wad[$fun_2$_Index]
            if ($fun_1$.getType() == $fun_2$.getType() == functionType) then
                waxSim += computeFunctionSimilarity($fun_1$, $fun_2$)
                typePairings += 1
            end if
        end if
    end for
    if (typePairings != 0) then
        waxSim = waxSim / typePairings
    else
        waxSim = 0.0
    end if
    return waxSim
end function
```

Algorithm 5 Algorithm to compute WAx Semantic Similarity (WASS) by aspect.

```
function WASS_BY_ASPECT(wai, wad, pairingVector, aspect)
    waxSim = 0.0
    pairings = 0
    for i in [0,wai.size()-1] do
        if (pairingVector.size ≠ null) then
            $fun_1$ = wai[i]
            $fun_2$_Index = pairingVector[i]
            $fun_2$ = wad[$fun_2$_Index]
            waxSim+= computeFunctionSimilarityByAspect ($fun_1$, $fun_2$, aspect)
            pairings += 1
        end if
    end for
    waxSim = waxSim / (wai.size() + wad.size() - pairings)
    return waxSim
end function
```

Algorithm 6 Algorithm to compute Semantic Similarity of FRAM functions by aspect.

```
function COMPUTE_FUNCTION_SIMILARITY_BY_ASPECT(function_1, function_2, aspect)
    fuSim = 0.0
    aVector_1 = function_1.getAspectVector(aspect)
    aVector_2 = function_2.getAspectVector(aspect)
    if (aVector_1 > 0 or aVector_2 > 0) then
        fuSim += computeDiceSimilarity(aVector_1, aVector_2)
    end if
    if (function_1.getType()== function_2.getType()) then
        fuSim += 1.0
    end if
    fuSim = fuSim / 2
    return fuSim
end function
```

References

[1] D. Gürdür Broo, Transdisciplinarity and three mindsets for sustainability in the age of cyber-physical systems, J. Ind. Inf. Integr. 27 (2022) 100290, http://dx.doi.org/10.1016/j.jii.2021.100290, URL https://www.sciencedirect.com/science/article/pii/S2452414X2100087X.

[2] D. Gürdür Broo, U. Boman, M. Törngren, Cyber-physical systems research and education in 2030: Scenarios and strategies, J. Ind. Inf. Integr. 21 (2021) 100192, http://dx.doi.org/10.1016/j.jii.2020.100192, URL https://www.sciencedirect.com/science/article/pii/S2452414X20300674.

[3] A. Fayoumi, R. Williams, An integrated socio-technical enterprise modelling: A scenario of healthcare system analysis and design, J. Ind. Inf. Integr. 23 (2021) 100221, http://dx.doi.org/10.1016/j.jii.2021.100221, URL https://www.sciencedirect.com/science/article/pii/S2452414X21000212.

[4] B.A. Yilma, H. Panetto, Y. Naudet, Systemic formalisation of cyber-physical-social system (CPSS): A systematic literature review, Comput. Ind. 129 (2021) 103458, http://dx.doi.org/10.1016/j.compind.2021.103458, URL https://www.sciencedirect.com/science/article/pii/S0166361521000658.

[5] R. Patriarca, A. Falegnami, F. Costantino, G. Di Gravio, A. De Nicola, M.L. Villani, WAx: An integrated conceptual framework for the analysis of cyber-socio-technical systems, Saf. Sci. 136 (2021) 105142, http://dx.doi.org/10.1016/j.ssci.2020.105142, URL https://www.sciencedirect.com/science/article/pii/S0925753520305385.

[6] P.K.R. Maddikunta, Q.-V. Pham, P. B, N. Deepa, K. Dev, T.R. Gadekallu, R. Ruby, M. Liyanage, Industry 5.0: A survey on enabling technologies and potential applications, J. Ind. Inf. Integr. 26 (2022) 100257, http://dx.doi.org/10.1016/j.jii.2021.100257, URL https://www.sciencedirect.com/science/article/pii/S2452414X21000558.

[7] I. Moppett, S. Shorrock, Working out wrong-side blocks, Anaesthesia 73 (2018) 407–420, http://dx.doi.org/10.1111/anae.14165.

[8] M. Sanchez, E. Exposito, J. Aguilar, Autonomic computing in manufacturing process coordination in Industry 4.0 context, J. Ind. Inf. Integr. 19 (2020) 100159, http://dx.doi.org/10.1016/j.jii.2020.100159, URL https://www.sciencedirect.com/science/article/pii/S2452414X20300340.

[9] W.M.P. van der Aalst, Process Mining: Data Science in Action, Springer Berlin Heidelberg, 2016, pp. 1–467, http://dx.doi.org/10.1007/978-3-662-49851-4, URL https://www.scopus.com/inward/record.uri?eid=2-s2.0-84979530122&doi=10.1007%2f978-3-662-49851-4&partnerID=40&md5=2c9677c2cfe2b253453b40c50e86ebb3, Cited by: 1392.

[10] C. dos Santos Garcia, A. Meincheim, E.R. Faria Junior, M.R. Dallagassa, D.M.V. Sato, D.R. Carvalho, E.A.P. Santos, E.E. Scalabrin, Process mining techniques and applications – a systematic mapping study, Expert Syst. Appl. 133 (2019) 260–295, http://dx.doi.org/10.1016/j.eswa.2019.05.003, URL https://www.sciencedirect.com/science/article/pii/S0957417419303161.

[11] E. Hollnagel, FRAM, the Functional Resonance Analysis Method: Modelling Complex Socio-Technical Systems, Ashgate Publishing, Ltd., 2012.

[12] P. Sterling, Allostasis: a new paradigm to explain arousal pathology, in: S. Fisher, J. Reason (Eds.), Handbook of Life Stress, Cognition and Health, John Wiley & Sons, 1988, pp. 629–649.

[13] B.S. McEwen, Protective and damaging effects of stress mediators, N. Engl. J. Med. 338 (3) (1998) 171–179.

[14] A. De Nicola, A. Formica, M. Missikoff, E. Pourabbas, F. Taglino, A parametric similarity method: Comparative experiments based on semantically annotated large datasets, J. Web Semant. 76 (2023) 100773, http://dx.doi.org/10.1016/j.websem.2023.100773, URL https://www.sciencedirect.com/science/article/pii/S1570826823000021.

[15] A. De Nicola, G. Vicoli, M.L. Villani, R. Patriarca, A. Falegnami, Enhancement of safety imagination in socio-technical systems with gamification and computational creativity, in: A.L. Vetere Arellano, Z. Šimić, N. Dechy (Eds.), Enhancing Safety: The Challenge of Foresight. Proceedings of the 53rd ESReDA Seminar Hosted by the European Commission Joint Research Centre 14th-15th 2017, Ispra, Italy, 2018, pp. 158–169.

[16] S. Amir, V. Kant, Sociotechnical resilience: A preliminary concept, Risk Anal. 38 (1) (2018) 8–16, http://dx.doi.org/10.1111/risa.12816, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.12816, URL https://onlinelibrary.wiley.com/doi/abs/10.1111/risa.12816.

[17] S. Dekker, P. Cilliers, J.-H. Hofmeyr, The complexity of failure: Implications of complexity theory for safety investigations, Saf. Sci. 49 (6) (2011) 939–945, http://dx.doi.org/10.1016/j.ssci.2011.01.008, URL https://www.sciencedirect.com/science/article/pii/S0925753511000105.

[18] S. Dekker, Drift into failure: From hunting broken components to understanding complex systems, Aviation Space Environ. Med. 83 (2) (2018) http://dx.doi.org/10.3357/asem.3152.2012, 149–149(1).

[19] A. Falegnami, R. Patriarca, F. Costantino, G. Di Gravio, F. Bilotta, Surveying Work-As-Done in post-operative delirium risk factors collection and diagnosis monitoring, Applied Ergon. 92 (2021) 103347, http://dx.doi.org/10.1016/j.apergo.2020.103347, URL https://www.sciencedirect.com/science/article/pii/S0003687020302957.

[20] E. Hollnagel, D.D. Woods, N. Leveson, Resilience Engineering: Concepts and Precepts, Ashgate Publishing, Ltd., 2006.

[21] C. Perrow, Normal Accidents: Living with High Risk Technologies, Princeton University Press, 2011.

[22] E. Hollnagel, Safety-II in Practice: Developing the Resilience Potentials, Routledge, 2017.

[23] I.W.H. Fung, V.W.Y. Tam, J.O.C. Chu, K.N. Le, A stress-strain model for resilience engineering for construction safety and risk management, Int. J. Constr. Manag. 22 (12) (2022) 2308–2324, http://dx.doi.org/10.1080/15623599.2020.1783602.

[24] E. Hollnagel, RAG – Resilience Analysis Grid, in: E. Hollnagel, J. Pariès, J. Wreathall (Eds.), Resilience Engineering in Practice - a Guidebook, CRC Press, 2011, pp. 275–295.

[25] R.S. Aguilar-Savén, Business process modelling: Review and framework, Int. J. Prod. Econ. 90 (2) (2004) 129–149, http://dx.doi.org/10.1016/S0925-5273(03)00102-6, URL https://www.sciencedirect.com/science/article/pii/S0925527303001026, Production Planning and Control.

[26] F. Taymouri, M.L. Rosa, M. Dumas, F.M. Maggi, Business process variant analysis: Survey and classification, Knowl.-Based Syst. 211 (2021) 106557, http://dx.doi.org/10.1016/j.knosys.2020.106557, URL https://www.sciencedirect.com/science/article/pii/S0950705120306869.

[27] W.M.P. van der Aalst, Process Mining: Data Science in Action, second ed., Springer, Heidelberg, 2016, http://dx.doi.org/10.1007/978-3-662-49851-4.

[28] M. Becker, R. Laue, A comparative survey of business process similarity measures, Comput. Ind. 63 (2) (2012) 148–167.

[29] A. Schoknecht, T. Thaler, P. Fettke, A. Oberweis, R. Laue, Similarity of business process models—a state-of-the-art analysis, ACM Comput. Surv. 50 (4) (2017) 1–33.

[30] S.P. Detro, E.A.P. Santos, H. Panetto, E.D. Loures, M. Lezoche, C.C.M. Barra, Applying process mining and semantic reasoning for process model customisation in healthcare, Enterp. Inf. Syst. 14 (7) (2020) 983–1009, http://dx.doi.org/10.1080/17517575.2019.1632382.

[31] L.R. Dice, Measures of the amount of ecologic association between species, Ecology 26 (3) (1945) 297–302, http://dx.doi.org/10.2307/1932409.

[32] G. Semeraro, P. Basile, R. Basili, M. de Gemmis, C. Ghidini, M. Lenzerini, P. Lops, A. Moschitti, C. Musto, F. Narducci, A. Pipitone, R. Pirrone, P. Poccianti, L. Serafini, Semantic technologies for industry: From knowledge modeling and integration to intelligent applications, Intelligenza Artificiale 7 (2) (2013) 125–137, http://dx.doi.org/10.3233/IA-130054.

[33] I. Weber, J. Hoffmann, J. Mendling, Beyond soundness: on the verification of semantic business process models, Distrib. Parallel Databases 27 (3) (2010) 271–343, http://dx.doi.org/10.1007/s10619-010-7060-9.

[34] A. De Nicola, M. Lezoche, M. Missikoff, An ontological approach to business process modeling, in: B. Prasad (Ed.), Proceedings of the 3rd Indian International Conference on Artificial Intelligence, Pune, India, December 17-19, 2007, IICAI, 2007, pp. 1794–1813.

[35] A. De Nicola, M. Missikoff, F. Smith, Towards a method for business process and informal business rules compliance, J. Softw. Evol. Process. 24 (3) (2012) 341–360, http://dx.doi.org/10.1002/smr.553.

[36] C. Di Francescomarino, Supporting documentation and evolution of crosscutting concerns in business processes, in: H.R. Motahari Nezhad, F. Toumani, Y. Velegrakis (Eds.), Proceedings of the PhD Symposium At the 6th International Conference on Service Oriented Computing (ICSOC 2008), Sydney, Australia, 1 December 2008, in: CEUR Workshop Proceedings, Vol. 421, CEUR-WS.org, 2008, URL http://ceur-ws.org/Vol-421/paper4.pdf.

[37] A.K.A. de Medeiros, C. Pedrinaci, W.M.P. van der Aalst, J. Domingue, M. Song, A. Rozinat, B. Norton, L. Cabral, An outlook on semantic business process mining and monitoring, in: R. Meersman, Z. Tari, P. Herrero (Eds.), On the Move To Meaningful Internet Systems 2007: OTM 2007 Workshops, OTM Confederated International Workshops and Posters, AWeSOMe, CAMS, OTM Academy Doctoral Consortium, MONET, OnToContent, ORM, PerSys, PPN, RDDS, SSWS, and SWWS 2007, Vilamoura, Portugal, November 25-30, 2007, Proceedings, Part II, in: Lecture Notes in Computer Science, Vol. 4806, Springer, 2007, pp. 1244–1255, http://dx.doi.org/10.1007/978-3-540-76890-6_52.

[38] A. Azzini, C. Braghin, E. Damiani, F. Zavatarelli, Using semantic lifting for improving process mining: a data loss prevention system case study, in: R. Accorsi, P. Ceravolo, P. Cudré-Mauroux (Eds.), Proceedings of the 3rd International Symposium on Data-Driven Process Discovery and Analysis, Riva Del Garda, Italy, August 30, 2013, in: CEUR Workshop Proceedings, Vol. 1027, CEUR-WS.org, 2013, pp. 62–73, URL http://ceur-ws.org/Vol-1027/paper5.pdf.

[39] A. De Nicola, T. Di Mascio, M. Lezoche, F. Taglino, Semantic lifting of business process models, in: M. van Sinderen, J.a.P.A. Almeida, L. Ferreira Pires, M. Steen (Eds.), Workshops Proceedings of the 12th International IEEE Enterprise Distributed Object Computing Conference, ECOCW 2008, 16 September 2008, Munich, Germany, IEEE Computer Society, 2008, pp. 120–126, http://dx.doi.org/10.1109/EDOCW.2008.55.

[40] V. Bloemen, S. van Zelst, W. van der Aalst, B. van Dongen, J. van de Pol, Aligning observed and modelled behaviour by maximizing synchronous moves and using milestones, Inf. Syst. (2019) 101456.

[41] I. Nonaka, R. Toyama, N. Konno, SECI, Ba and leadership: A unified model of dynamic knowledge creation, Long Range Plan. 33 (1) (2000) 5–34, http://dx.doi.org/10.1016/S0024-6301(99)00115-6, URL https://www.sciencedirect.com/science/article/pii/S0024630199001156.

[42] E. Hollnagel, The ETTO Principle: Efficiency-Thoroughness Trade-Off: Why Things that Go Right Sometimes Go Wrong, Ashgate Publishing, Ltd., 2009.

[43] A. De Nicola, M. Missikoff, R. Navigli, A software engineering approach to ontology building, Inf. Syst. 34 (2) (2009) 258–275, http://dx.doi.org/10.1016/j.is.2008.07.002, URL http://www.sciencedirect.com/science/article/pii/S0306437908000628.

[44] A. De Nicola, M. Missikoff, A lightweight methodology for rapid ontology engineering, Commun. ACM 59 (3) (2016) 79–86, http://dx.doi.org/10.1145/2818359.

[45] A. De Nicola, M.L. Villani, An ontology of industrial work varieties, in: R. Rodríguez-Rodríguez, Y. Ducq, R.-D. Leon, D. Romero (Eds.), Enterprise Interoperability X - Enterprise Interoperability Through Connected Digital Twins, Springer International Publishing, Cham, 2024.

[46] A. Lališ, R. Patriarca, J. Ahmad, G. Di Gravio, B. Kostov, Functional modeling in safety by means of foundational ontologies, Transp. Res. Procedia 43 (2019) 290–299.

[47] A. Pease, I. Niles, J. Li, The Suggested Upper Merged Ontology: A large ontology for the semantic web and its applications, in: Working Notes of the AAAI-2002 Workshop on Ontologies and the Semantic Web, Vol. 28, 2002, pp. 7–10.

[48] A. De Nicola, M. Villani, A. Falegnami, R. Patriarca, WAx framework ontology, 2023, http://dx.doi.org/10.17632/45k9y2g988.1.

[49] A. Polenghi, I. Roda, M. Macchi, A. Pozzetti, H. Panetto, Knowledge reuse for ontology modelling in maintenance and industrial asset management, J. Ind. Inf. Integr. 27 (2022) 100298, http://dx.doi.org/10.1016/j.jii.2021.100298, URL https://www.sciencedirect.com/science/article/pii/S2452414X21000947.

[50] A.L. Fraga, M. Vegetti, H.P. Leone, Ontology-based solutions for interoperability among product lifecycle management systems: A systematic literature review, J. Ind. Inf. Integr. 20 (2020) 100176, http://dx.doi.org/10.1016/j.jii.2020.100176, URL https://www.sciencedirect.com/science/article/pii/S2452414X20300510.

[51] A. De Nicola, M. Villani, A. Falegnami, R. Patriarca, FWS (FRAM-WAx-SUMO) federated upper ontology model, 2023, http://dx.doi.org/10.17632/rpcjcm9dc2.1.

[52] N.A. Stanton, Hierarchical Task Analysis: Developments, applications, and extensions, Applied Ergon. 37 (1) (2006) 55–79, http://dx.doi.org/10.1016/j.apergo.2005.06.003, URL https://www.sciencedirect.com/science/article/pii/S0003687005000980, Special Issue: Fundamental Reviews.

[53] R. Clay-Williams, J. Hounsgaard, E. Hollnagel, Where the rubber meets the road: using FRAM to align work-as-imagined with work-as-done when implementing clinical guidelines, Implement. Sci. 10 (1) (2015) 125, http://dx.doi.org/10.1186/s13012-015-0317-y.

[54] D. Chandrasekaran, V. Mago, Evolution of semantic similarity - a survey, ACM Comput. Surv. 54 (2) (2021) 1–37.

[55] A. De Nicola, M. Villani, J. Watt, M. Susan, A. Falegnami, R. Patriarca, Measurement of allostatic load in cyber-socio-technical systems: datasets for experiments, 2023, http://dx.doi.org/10.17632/2ghfrf5hwy.1.

[56] E. Hollnagel, Safety-I and Safety-II: the Past and Future of Safety Management, Ashgate Publishing Ltd, 2014, pp. 1–187, URL https://www.scopus.com/inward/record.uri?eid=2-s2.0-84938344362&partnerID=40&md5=9a62c78bbec204c9c11ff90ea0445473, cited By 696.

[57] E. Hollnagel, Resilience engineering: A new understanding of safety, J. Ergonomics Soc. Korea 35 (2016) 185–191, http://dx.doi.org/10.5143/JESK.2016.35.3.185.

[58] D.-H. Ham, Safety-II and resilience engineering in a nutshell: An introductory guide to their concepts and methods, Saf. Health Work 12 (1) (2021) 10–19, http://dx.doi.org/10.1016/j.shaw.2020.11.004, URL https://www.sciencedirect.com/science/article/pii/S2093791120303619.

[59] Health & Safety Executive, Developing Process Safety Indicators: A Step-By-Step Guide for Chemical and Major Hazard Industries, HSE, 2006.

[60] M. Sujan, J. Watt, R. Patriarca, F. Costantino, M.L. Villani, A. De Nicola, Developing leading safety indicators using the functional resonance analysis method, in: M. Parsons, M. Nicholson (Eds.), Systems and Covid-19. Proceedings of the 29th Safety-Critical Systems Symposium (SSS'21) 9th-11th February 2021, SCSC-161, SCSC, 2021, pp. 395–410.

[61] G.J. Colquhoun, R.W. Baines, R. Crossley, A state of the art review of IDEF0, Int. J. Comput. Integr. Manuf. 6 (4) (1993) 252–264, http://dx.doi.org/10.1080/09511929308944576.