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Transportation Research Procedia 43 (2019) 290–299

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Conference on Air Transport – INAIR 2019
GLOBAL TRENDS IN AVIATION

Functional modeling in safety by means of foundational ontologies

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Abstract

Modern theory of safety deals with systemic approach to safety, formalized in form of several systemic prediction models or methods such as FRAM (Functional Resonance Analysis Method) or STAMP (System-Theoretic Accident Model and Processes). The theory of each approach emphasizes different viewpoints to be considered in approaching various industrial safety issues. This paper focuses on FRAM and its functional viewpoint for modern complex sociotechnical systems. The methodology in this paper is based on the utilization of foundational ontologies to conceptualize the core ideas of FRAM, with the focus on the concept of functions as used in theory. The outcomes of the case study in the aviation domain provide for what needs to be determined to properly model functions in FRAM and they allow for better utilization of the method in real-case applications. The results also confirm some previous research, suggesting that modern systemic approach to safety is theoretically grounded on common - or at least complementary - tenets, to be prospectively integrated by means of ontology engineering.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Air Transport – INAIR 2019, GLOBAL TRENDS IN AVIATION

Keywords: aviation safety; socio-technical systems; ontology engineering; safety engineering; resilience engineering

1. Introduction

Modern theory of safety engineering is actively developing, mainly because of the discoveries in technology and science but also because of ever increasing safety standards in current society. There is a continuous tendency to

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Peer-review under responsibility of the scientific committee of the 8th International Conference on Air Transport – INAIR 2019, GLOBAL TRENDS IN AVIATION
10.1016/j.trpro.2019.12.044

develop and improve metrics for the measurement of safety performance of air transport system as indicated by Lintner et al. (2009), Di Gravio et al. (2014) and Di Gravio et al. (2016). The newest models and methods used to explain and predict safety are referred to as systemic as they attempt to evaluate systems as a whole and account for complexity, resonance, emergence and other phenomena typical of system-level analysis. Systemic models and methods of safety are the cutting edge in theory and there are experiments and application research carried to refine and validate the theory. This observation implies that the theory is not finished, nor consolidated, and that various research teams even experiment with possible theory extensions for the purpose of specific safety-related use cases, e.g. Dokas et al. (2013), Salmon et al. (2018) and Li et al. (2019). This provides not only room for desirable experimentation but also room for interpretation variance, hence hindering the effectivity and efficiency of industrial applications of the theory.

This paper focuses on a specific systemic method, i.e. the FRAM (Functional Resonance Analysis Method), described by Hollnagel (2012). FRAM was designed to analyze systems' behaviors and help the analyst to identify possible functional areas, which are more susceptible to resonate, i.e. where variability of functions provided by the systems may combine following uncontrolled and unpredictable patterns. Such combination is considered a resonance, similar as in physics, and it regards significant out-of-range disturbance of a system behavior, which is often associated with loss events (accidents). Basic concept of any modeling with FRAM is a function since the method requires functional representation of a system, which needs to be provided by the analyst. While the foundational principles of FRAM are clear and simple, this is often not the case when particular industrial applications are the scope of its application. Determination of functions and their abstraction is completely up to the analyst and several users are likely to end up with different functional representations with the same system. There are already some solutions available, such as by Patriarca et al. (2017a), and even though it may not always pose a problem from the perspective of the very analysis, it is a limitation which has the potential to severely impact the results of a FRAM analysis.

On the other hand, modern technology and computer science is very sensitive to clear semantics and there already exist tools, which can model reality for different application purposes where semantics is critical. These tools work with modeling languages and ontologies, i.e. metamodels of reality, which aim to disambiguate meaning of different concepts used mostly by software or in human-machine interaction. In this domain, one of the fast-developing areas are foundational ontologies, which provide domain-independent description of reality of interest. In essence, they assure that any domain ontology or specific model of a reality conforms to common human interpretation and as such they are very powerful tool to assure semantics where necessary.

This paper takes the concept of function as used in FRAM and experiments with its representation by means of foundational ontology, namely the Unified Foundational Ontology. The goal is to achieve improved and computer-readable description of what is a function as used in FRAM in order to support future tools and software based on the FRAM itself. The purpose of possible improved semantics is to limit the interpretation variance of FRAM application and modeling by users and to direct the future research towards experimentation with semantically well-based conceptualization of the theory.

2. Methodology

This section reviews the necessary background of FRAM, with the focus on the concept of a function, and defines the notions of the Unified Foundational Ontology (UFO). The practical example is introduced and presented as an UFO-based FRAM model.

2.1. The Functional Resonance Analysis Method

The FRAM was developed by prof. Erik Hollnagel, as a method for analysis of modelling non-trivial socio-technical systems. The FRAM works with the assumption that safety is a system level property and that it should be analyzed in terms of the system's behavior. In this sense, it guides the analyst to first understand how systems normally work and then to use the understanding to explain their potential exposure to failures. Consequently, the theory requires development of functional representation of a system, as opposed to object-based representation as specified by Hollnagel (2012). The basic building elements are functions, which need to be described in terms of their inputs and outputs (the so-called aspects), as depicted in Fig. 1. In the figure, the complete set of function aspects is depicted, where inputs can be further distinguished into *Time*, *Control*, *Precondition*, *Resource*, or *Input*. Every single aspect of a function determines the type of input the function receives from some other upstream function.

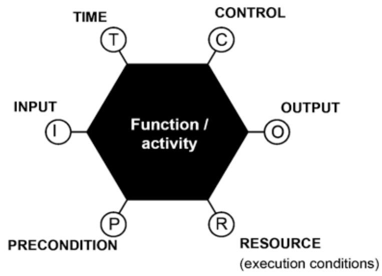

Fig. 1. Representation of a function and its aspects as per the theory of FRAM.

FRAM-based representation of a system, or its part, is then produced as a set of interconnected functions where an output of a function can be any form of input to some other function.

The method is built upon the functional representation, consisting of the following steps: (1) identification and description of functions, (2) identification of variability, (3) aggregation of variability and (4) defining the consequences of the analysis. The main idea is to analyze possible variations of function outputs and their combination within the given functional relationships and search for possible effects. FRAM is grounded in Safety-II described by Hollnagel (2014), i.e. it considers resonance to be the governing principle for emergent outcomes, such as safety, unlike the traditional approach that considers causality instead. Therefore, the main goal is to search for interactions between multiple functions (aggregation of variability), identify those interactions, which have the potential to resonate and help proposing measures for dampening the potential variability combination, and possible resonance. Resonance is a possible effect following variability combination, typically a significant perturbation to system level behavior, that is often associated with loss events (accidents).

According to the FRAM, there are several phenotypes of variability (e.g. variability in time, precision, object, direction, duration etc.) that should be considered when analyzing a system for potential resonance. Here, the method itself reaches a potential limitation, as the evaluation is qualitative and most often relative, i.e. considering only whether the variability aggregation is likely to increase, retain the same or dampen particular function variability in given conditions. Expert assessment and knowledge are needed to conclude any FRAM-based analysis and produce recommendations.

2.2. The Unified Foundational Ontology

Unified Foundational Ontology is one of the latest and actively developed foundational ontologies that was built with several theories, such as formal ontology, philosophical logic, philosophy of language, linguistics and cognitive psychology. It works with universals and particulars, based on the theory of part-whole relation. The ontology has three base layers, named as UFO-A (ontology of endurants), UFO-B (ontology of events) and UFO-C (ontology of social agents). The layers allow for detailed representation of most real world domains for the purpose of various applications. For detailed description of individual layers and concepts of the ontology refer to Guizzardi (2005), Guizzardi et al. (2007) and Guizzardi et al. (2013a).

UFO adopts many successful and well-established concepts used by other foundational ontologies and addresses many aspects of conceptual modeling that were not addressed by other ontologies. Moreover, there are some specific aspects which support its selection over other foundational ontologies for the purpose of this work. The authors of UFO developed OntoUML language, based on the Unified Modeling Language (UML) that resolves many problems inherent to the language and facilitates utilization of UFO-based concepts. There is also a number of support tools available with OntoUML and UML-based tools that can support the conceptualization with UFO.

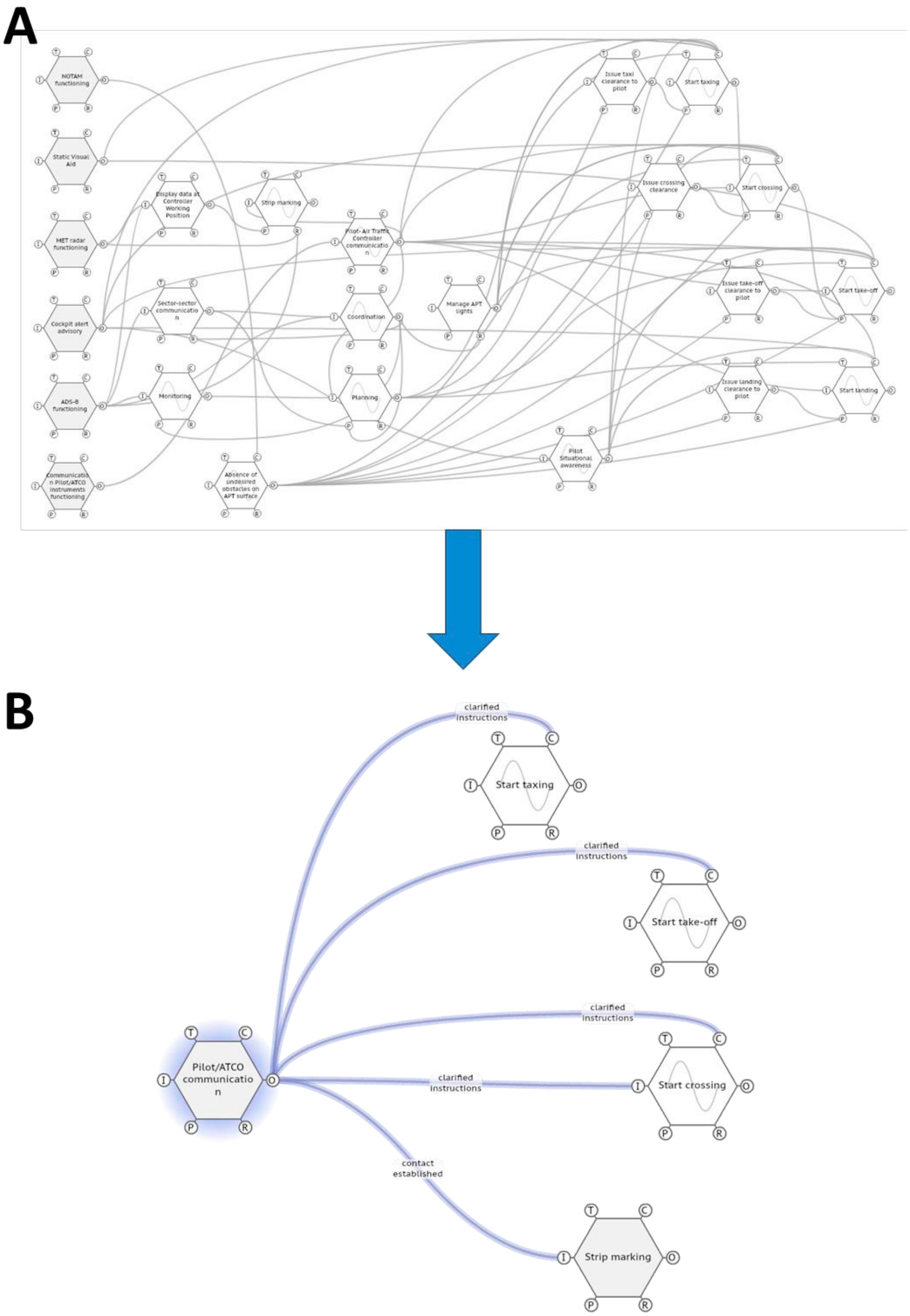

Fig. 2. FRAM model for runway operations: A (complete model), B (model restricted to critical functions). Adapted from Patriarca et al. (2017b).

2.3. *Practical example from aviation domain*

Aviation is a system severely concerned with modern issues of safety, i.e. the need for approaches to deal with tight and non-linear couplings among human, technical and organizational factors. In airports, everyday operation requires collaborative work performed by a large number of interconnected agents, and intertwined functions. In this context, one of the most critical potential scenarios refers to the so-called runway incursion. According to ICAO, a runway incursion is *"any occurrence at an aerodrome involving the incorrect presence of an aircraft vehicle or person on the protected area of a surface designated for the landing and takeoff of aircraft"* (ICAO Doc 4444 – PANS-ATM). For example, a runway incursion can be due to the incorrect entry of an aircraft (or vehicle) onto the runway area, possibly caused by incorrect sequencing for arriving departing or arriving aircraft. There could be several contributory factors to the occurrence, such as weather, aerodrome design, multiple line-ups, the usage of conditional clearance, phraseology, workload, etc. as specified by ICAO (2007).

Following the Air Navigation Service (ANS) Perspective, this paper aims to present a walkthrough example on the usage of FRAM to model everyday work in runway operations and combine its usage with UFO. The paper starts from a previously developed research aimed at modeling runway operations through FRAM and isolating critical functions through a Monte Carlo simulation approach by Patriarca et al. (2017b). The method presented in this paper starts from the original model developed in Patriarca et al. (2017b) (Figure 2A), and proceeds through one of the critical sub-models (Figure 2B) to originally test the applicability of UFO with respect to FRAM analyses.

3. Results

The results include two main achievements: a model (conceptualization) of a function as per the theory of FRAM and an instance model of the practical example from the previous section, produced with the generic model of a function.

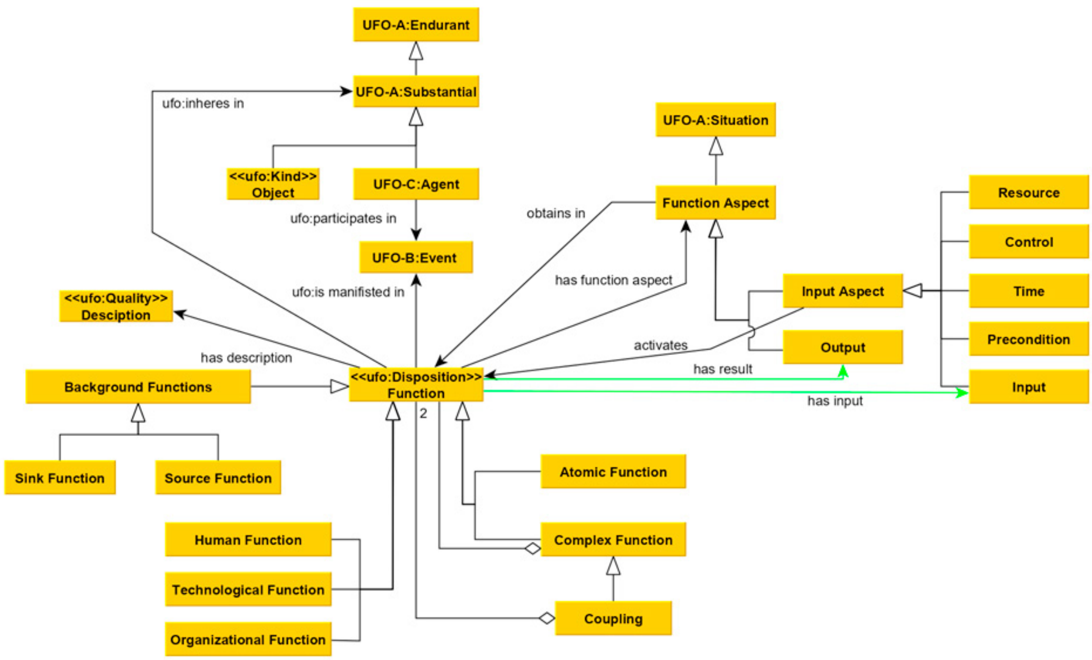

Fig. 3. Conceptualization of a function with UFO ontology.

The generic model of a function is depicted in Fig. 3. In the schema, all concepts reused from UFO start with ufo prefix, non-UFO concepts are either grounded in UFO with particular stereotype or need some explanation. The main concept is a *Function* located in the middle of the schema, which has a stereotype *ufo:Disposition*, i.e. existentially dependent entities that are realizable through the occurrence of an *Event* as specified by Guizzardi and Wagner (2013b). In a figurative sense, this means that a function is typically some capability or ability, something and object or agent can do. Considering a pilot/ATCO communication as a function, this is something that two agents (here pilot and ATCO) can do owing to their capability to listen and talk, and ability to use radio for that purpose. The concept *Function* is then specialized into several other concepts in line with the FRAM principles, be it a *Background Function* concept or distinguishing between a *Human*, *Technological* or *Organizational Function*. All these concepts implicitly inherit the semantics of a *Function*, hence are all considered a disposition.

Similar logic applies as soon as the goal is to consider possible abstraction hierarchy of the functions, as discussed in Patriarca et al. (2017a). Two functions can compose a *Coupling*, which can be abstracted into a *Complex Function* if needed. By contrast, if a *Function* cannot be detailed into higher granularity functions, then this is considered an *Atomic Function*. The pattern reused here follows UFO described by Guizzardi and Wagner (2010).

Following the top section of Fig. 3, the mapping to UFO-grounded concepts is specified, here *Event*, *Agent*, *Substantial* and *Endurant*. This part of the ontology specifies that functions are dispositional properties *manifested* under certain circumstances and through the execution of an *Event* (here Pilot/ATCO communication is manifested in a particular communication, having its start time and end time on particular date) where *Object* or *Agent* can participate in (specific persons with their ID or particular objects like a radio).

Last part in this section is a *Description* concept which is modeled as *ufo:Quality*, i.e. a property that is manifested whenever it exists. In the model, *Description* is essentially a narrative of particular *Function*, making explicit some specific qualities or properties of it.

The right-hand section of Fig. 3 conceptualizes *Function Aspect*, which is modeled as a specialized type of *ufo:Situation*. A situation in UFO regards particular set of objects with their properties, in simple terms a snapshot of them. Be it some *Input Aspect* or *Output* of a Function, they are all modeled as a situation. Considering the practical example from the previous section, frequent output of the function Pilot/ATCO communication are clarified instructions, i.e. a situation when an addressee of an information has received it and understands its content. This is a situation, where the addressee of an information (object) is in some condition (here has some information, knows of something). This conceptualization conforms to the FRAM principles and building steps.

The figure, however, contains some non-UFO relationships, which need to be clarified, namely *has description*, *has input*, *has output*, *has result*, *has function aspect* and *obtains in*. These relationships are all variations of the same type of relationship, which relates two concepts with a type of part-of relationship, that is rather straightforward to understand for domain experts, but not precisely defined yet. The ontology reaches its limit here, thus in the future these relations should be considered for more precise conceptualization. Some of these relations are in green, meaning that similar relations exist with other concepts in this part of the diagram, namely between a *Function* and *Resource*, *Control*, *Time* and *Precondition* but are not made explicit.

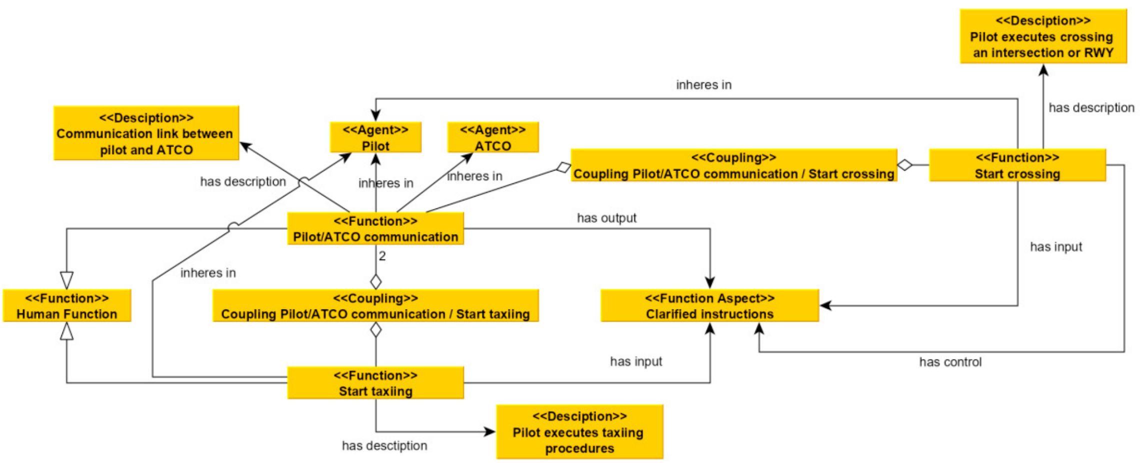

Fig. 4. Conceptualization of the practical example of Pilot/ATCO function with the developed generic UFO-based ontology of a function referring to the model depicted in Fig. 3.

Another result of the study is a particular instantiation model of the practical example from the previous section. The model is shown in Fig. 4. Here, the stereotypes follow domain conceptualization, i.e. the stereotype *Function* relates to the concept *Function* from the previous figure. Similar logic applies to all other stereotypes.

4. Discussion

The conceptualization of a function with the UFO ontology from the previous section, together with the case study example, shows that UFO provides useful conceptual grounding to it. The modeling supports precise definition of the concepts around a function used by FRAM to increase any FRAM-based artefact reusability and common understanding with other users or computers. In other words, it determines the view needed to properly model functions as in FRAM for real-case applications, ensuring semantical coherence. Consequently, the goal was to conceptualize FRAM functions to support future tools and software, which will utilize the theory of FRAM by using UFO.

The results of this work allow analysis of FRAM models in UFO terms, which brings entirely new perspective to the method. Considering the main focus of the paper, a function in FRAM is an activity or simply something that is being done, bearing seemingly clear meaning to majority of people from natural language. UFO considers it as a disposition which is a realizable entity that exists because of certain features (capabilities or vulnerabilities) of a particular object. These functions are manifested in certain events and result in specific situations. As an example, it is possible to consider the function *Start taxiing* from Fig. 4 manifested in particular movement of an aircraft on particular day, time and location, which initiates its taxiing and results in a situation where the aircraft has different location at the airport. As such, it is a disposition since it exists because of the feature of the aircraft to move (its capability in this case). The situation is even more apparent with function aspects, which are hard to explain even in natural language. According to FRAM literature by Hollnagel (2012), function aspects characterize a function, deriving potential relations among them. While from the perspective of the aspect notation, the meaning may be clear (it is generally known what is an input, output, precondition etc.), it is hard to provide acceptably clear and common explanation for all of them simultaneously. The ontology here specifies that all aspects are situations, i.e. snapshots of a set of objects in some state/condition. This delimits the room for how to interpret each of the aspects. Lastly, the conceptualization disambiguates what is a coupling. Whilst this may be intuitively clear for many analysts, further discussion may arise about whether this is a “line” between two functions, thus a separate object representable as another function, or is it a part of the very functions connected by that “line”, i.e. as something that cannot be considered independent of the functions. The ontology model takes the latter perspective, i.e. a coupling is inseparable part of the functions it couples and it specifies that precisely two functions can comprise a coupling. The rest of the conceptualization does not bring any significant discussion about the semantics but rather provides for clear schema where other relevant concepts from the FRAM fit into the ontology.

Another point is that owing to the application of UFO, the ontology model now brings the FRAM method closer to other modern safety engineering theory, by providing a platform for integration of the FRAM-based artefacts with artefacts created based on other methods and safety models. This will ultimately enable integration at the level of the methods and models, in line with the suggestions provided from previous research by Grant et al. (2018) regarding common or at least complementary tenets. The results of the study in this work support future research in this domain.

Lastly, it is important to emphasize that the ontological structure summarized in Fig. 3 remains completely compatible with FRAM principles and building steps. Its development does not imply an additional building step, but it is rather intended to provide support for each building step. Starting from it, it is possible to develop dedicated models like the one showed in Fig. 4 with limited translational efforts. The combined FRAM UFO application is intended to provide faster, simpler and more precise analysis relying on functional resonance principles. Producing a FRAM model through a tool which generates machine-readable information is an added value for future system safety analyses, because it allows integrating safety analyses with pre-existent tools and data sources. Currently a software supporting the FRAM UFO framework is still lacking, but this paper firstly proves its feasibility and potential significance for a number of applications. In practical terms, having a FRAM UFO model may (e.g.) support the definition and exploration of the effects of systems changes as pointed out by Patriarca et al. (2016), combining the benefits of a systemic perspective based to FRAM, through systematic analyses based on UFO. The proposed combined approach may also support the identification and interpretation of data sources to develop leading/lagging indicators which could be used at system level, in line with the results of FRAM analyses. The ontological model is conceived to ensure semantical coherence and reduces interpretation biases of the model itself, further strengthening the value of the proposed results.

5. Conclusions

This paper provided first foundational ontology-based conceptualization of key concepts used in FRAM method, namely the conceptualization of a function and function-relevant concepts. The conceptualization was performed by means of Unified Foundational Ontology (UFO) and provided for basic machine-readable representation, delimiting the interpretation of the selected concepts. As a case study example from the aviation domain, some basic functions performed by air traffic controllers and crew of an aircraft during their operation on airport infrastructure was selected. The case study demonstrated how the ontology can support modeling of real case examples and showed how the proposed ontology disambiguates the concepts regarding function from user's perspective.

The study is limited by the fact that it starts with modeling of only a part of the FRAM method due to practical reasons. Further, the study did not perform in-depth validation and verification of the ontology as this is a long-term task that will need to be performed iteratively with progressive development of the ontology so as with its prospective implementation into a dedicated software tool. It only provides basic conceptualization and case-study example to demonstrate its usability in aviation industry.

The outcomes of this paper, on the other hand, pave the way to future application of an approach combining FRAM and UFO in order to provide formal representation of a complex work domain. A FRAM model has been proved to be a valuable support for representing socio-technical interaction, and through the usage of UFO, it could be formally linked with a variety of data sources even to build some type of software tool to be used organically in multiple organizations. Apart from that, the outcomes support future integration of FRAM-based artifacts with other artifacts based on different safety methods and models, finally having the potential to provide a platform for possible integration of the underlying theory behind modern safety engineering literature.

Future research should further explore the combination of FRAM and UFO, exploring other methodological approaches currently discussed in FRAM literature, for example, the possibility of expanding the FRAM structure through a multi-layer framework developed by Patriarca et al. (2017a), or adding quantitative, or semi-quantitative modelling structures as used in Patriarca et al. (2017b).

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