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Chiara Franciosi[1][a], Adalberto Polenghi[2][b], Mario Lezoche[1][c], Alexandre Voisin[1][d], Irene Roda[2][e] and Marco Macchi[2][f]

[1]Université de Lorraine, CNRS, CRAN UMR 7039, F-54000, Nancy, France

[2]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milan, Italy

{chiara.franciosi, mario.lezoche, alexandre.voisin}@univ-lorraine.fr, {adalberto.polenghi, irene.roda, marco.macchi}@polimi.it

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Abstract: Maintenance is an essential process for guaranteeing the reliability and availability of physical assets towards sustainable performance. The way maintenance could effectively impact on operations management highly relies on available data, whose volume and variety are increasing, challenging how they are stored and processed within an organization. To tackle this issue, ontology engineering seeks for guaranteeing semantic and technical interoperability for shared underlying meaning of concepts and consistent data formats. Despite the growing adoption of ontologies for industrial maintenance, some pitfalls may be envisaged by scientific and industrial practice, specifically referring to the development of multiple non-compatible ontologies that cannot be reused. Therefore, the goal of this research work is to promote semantic interoperability in industrial-maintenance related application. This is achieved by reviewing existing ontologies, later integrated and aligned, to realise a BFO (Basic Formal Ontology)-compliant taxonomy for maintenance, including physical decomposition of systems and maintenance processes. Hence, this research attempts a first step towards a unified taxonomy that, then, is the ground on which ontologies could be built upon so to be consistent each other. In the long run, semantic-based digital twin, referred to as cognitive digital twin, may be consistently established to improve sustainable performance of production systems.

1 INTRODUCTION

Nowadays the attention towards sustainability-related performance is increasing and manufacturing systems and their processes make no exception (Acerbi & Taisch, 2020; Franciosi et al., 2020). Improvement of the energy efficiency while reducing consumed resources are challenging industrial companies to identify novel solutions to meet SGDs (Sustainable Development Goals) as well as reducing costs while keeping the same performance and guarantee operational continuity. In this new, ever-changing context, maintenance could play the lion's share (Franciosi et al., 2021; Holgado et al., 2020; Liyanage, 2007) as it acts as the contact point between the shopfloor and the top management, to make the later more informed about systems status and transmit to the former the medium to long-term objectives of the company. Apart from maintenance, this could be also seen in the wider view of Industrial Asset Management (Niekamp et al., 2015). Nonetheless, the challenges to face are manifold (Iung & Levrat, 2014; Jasiulewicz-Kaczmarek &

[a] https://orcid.org/0000-0002-9983-1386
[b] https://orcid.org/0000-0002-3112-1775
[c] https://orcid.org/0000-0002-3271-1742
[d] https://orcid.org/0000-0002-4637-6826
[e] https://orcid.org/0000-0001-7795-1611
[f] https://orcid.org/0000-0003-3078-6051

Gola, 2019). In the path from data to information, the data management represents a pillar as it allows to acquire, store and distribute data across information systems to support different decision-making processes. The capability to distribute data across users and departments is hence of paramount importance, even though interoperability issues are present. Interoperability could be stratified according to technical, semantic and organizational levels, coherently with the EIF (European Interoperability Framework) (Vernadat, 2010). Indeed, establishing the semantic interoperability between information systems is currently under study as the meaning each concept carried with is as relevant as the value of the same data with respect to the decision-making process (Panetto et al., 2012). For these reasons, several ontologies have been proposed over the years, but there exists incompatibilities that prevent the full exploitation of the maintenance domain-related knowledge formalization (Polenghi, Roda, Macchi, Pozzetti, et al., 2022) and prevent two or more ontologies to work synergistically without applying ontological integration approaches (Izza, 2009). Considering these gaps and relying on the current set of ontology development methodologies, this research work assumes that, to promote the development of compatible ontologies, they must share the same domain-dependent taxonomy of concepts, which should be general enough to be applied to multiple contexts.

Hence, the research question that this work aims at answering is *how to formalise a domain-dependent taxonomy to improve semantic interoperability for industrial maintenance applications?*

In compliance with the above question, the goal of this research work is to define a unified BFO-compliant taxonomy to enhance semantic interoperability for maintenance-related applications. Indeed, this is a first work of a wider project called KARMA (Knowledge-augmented maintenance model for sustainable manufacturing). Overall, the KARMA project aims at extending the use of ontologies to complement data-driven knowledge from the field thanks to sensors through reasoning capabilities. In the long-term the ontology will augment field-level data or information by means of additional static or dynamic knowledge, starting from the condition-based and predictive maintenance towards machine-aware scheduling. Figure 1 visualizes the overall idea of the project.

Within the project, the first steps relate to the conceptualization and knowledge elicitation. Specifically, the selection of one concept, and related meaning, with respect to another one is not straightforward, and it may depend on the specific application. As such, the novelty of this work is to formalise and propose the underlying taxonomy of the ontology. Therefore, in this article, it is shown the reasoning behind the identification and selection of some concepts with respect to others towards a unified BFO-compliant taxonomy.

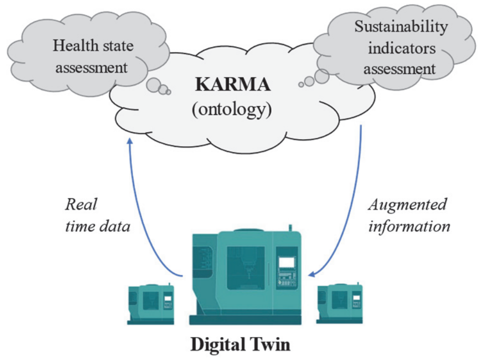

Figure 1: KARMA project overview.

Hence, the paper is structured as follows: Section 2 sets the background for ontology engineering with specific reference to maintenance; Section 3 reviews BFO as relevant, industry-accepted top-level ontology; Section 4 describes the adopted research methodology; Section 5 details out the concepts that will be part of the taxonomy according to three main groups: failure management-related concepts, physical system-related concepts, maintenance process-related concepts. Eventually, some conclusions are drawn based on the findings from the semantic analysis of maintenance-related concepts.

2 ONTOLOGY BACKGROUND

Interoperability can be defined as the ability of two or more systems to share, to understand and to consume information (IEEE, 1990). Interoperability could be tackled at various levels, technical, semantic and organisational (Vernadat, 2010). Our work focuses on the semantic level of interoperability, namely the ability to understand the exchanged information. Information may be defined as data linked to knowledge about this data. It is represented by so-called concepts. A concept is a cognitive unit of meaning (Vyvyan, 2006). At semantic level, an ontology, defined as "an explicit specification of a conceptualization" (Gruber, 1993), represents an answer to guarantee seamless and consistent information exchange between parties and systems (Szejka & Junior, 2017); this is especially perceived in industrial contexts, where a systematic approach in ontology development will define a common and shared IT ecosystems for companies (Ameri et al., 2021), looking for enterprise-based interoperability where distributed systems use multi-domain information and the entire company may have access to it (Panetto, 2007).

However, the development of ontologies is not straightforward, and several are the methodologies that may be adopted, from lightweight ones like Ontology Development 101 (Noy & McGuinness, 2001) to the most demanding, semantic-focused ones like DOGMA (Spyns et al., 2008) and NeOn (Suárez-Figueroa et al., 2015). Also, there exist multiple ontological layers, which represent the levels of details the related ontologies aim at representing. There is no unique view on how many layers should be considered, but at least four are recognised according to scientific literature (IOF and (Polenghi, Roda, Macchi, Pozzetti, et al., 2022)): top-level ontologies, domain independent ontologies, domain dependent ontologies and application ontologies. Top-level ontologies aim at setting the ground for ontological commitment, shaping the reality in very general terms, such as material and immaterial entities, objects, and processes; examples are BFO, DOLCE and SUMO. Domain independent ontologies are those that introduce concepts, like time, or unit of measure that could be applied to any contexts given their generality; domain dependent ontologies are instead already thought for specific contexts. Finally, application ontologies are specific for some contexts, hence they include concepts that are not valid in other situations. From the first (top-level ontologies) one to the last (application ontologies) ones, the specificity and dependency levels on specific contexts increase.

In industry, the use of ontologies may bring advantages and maintenance makes no exception. The potentialities of ontologies for maintenance are manifold and some applications could be in PHA (Process Hazard Analysis) and PHM (Prognostics and Health Management) (Polenghi et al., 2021). Indeed, maintenance-related ontologies have a wide variety of usage, including advanced diagnosis (Chen et al., 2022) and prognosis (May et al., 2022) of failure, FMEA/FMECA knowledge formalisation (Wu et al., 2021), evaluation of system-level impact of failure (Hodkiewicz et al., 2021), maintenance management process formalisation (Karray et al., 2019), joint maintenance and production decisions (Polenghi, Roda, Macchi, & Pozzetti, 2022). All of them rely on the reasoning capabilities of ontologies to augment the information content and empower the decision-making process. As such, ontologies for maintenance are perceived as symbolic AI models that could either improve semantic interoperability, specifying and fixing the meaning each concept has, and exploit the potentialities of non-symbolic AI through logic inference.

Despite the ever-increasing adoption of ontologies for industrial maintenance, some gaps still remain that are worth to be tackled to guarantee semantic interoperability (Polenghi, Roda, Macchi, Pozzetti, et al., 2022) and a wider dissemination and use, amongst which:

1. Alignment with top-level ontologies is not always guaranteed by newly developed ontologies. This reflect in consistencies between ontologies that are difficult to integrate.
2. Knowledge reuse and alignment is not an established practice, even if central in ontology development methodologies. Hence, useful concepts are usually formalised multiple times instead of being reused by already established and tested ontological models.

Therefore, this work aims to align the knowledge present in the BFO-compliant ontologies for industrial maintenance through their comparison, as a first step, to set then the path towards a unified taxonomy based on BFO for maintenance-related ontological applications.

The selection of BFO, as top-level ontology reference, has been made given the newly published ISO 21838-1/2:2021 standard on domain-neutral top-level ontologies and that latest works highly rely on BFO as reference top-level ontology. In this regard, it is worth to introduce briefly BFO in the following section 3, before presenting the methodology in section 4 and the semantic analysis in section 5.

3 BASIC FORMAL ONTOLOGY

The top-level BFO ontology is “a small, upper level ontology that is designed for use in supporting information retrieval, analysis and integration in scientific and other domains” as stated in the official website and described in (Arp et al., 2015). It is top-level as it is domain-independent and does not contain terms specific of some application. Also, it became a standard to build industrial ontologies (ISO 21838). The first level branching of BFO is between continuant and occurrent, where the first ones are three-dimensional entities that persist through time, while the second ones are spread out also in time. From these 2 afore-mentioned concepts, several additional branches are defined. Overall, the first two levels of BFO are reported in Figure 2, but the reader is referred to the book by (Arp et al., 2015) or the ISO 21838-2 for the whole description of BFO.

The formalisation of BFO also enabled the development of domain-independent ontologies that ease the definition of new ontological models as they define more specific concepts than BFO, but enough general to be applied to any domain. Examples of these ontologies are CCO (Common Core Ontologies) and IAO (Information Artifact Ontology) that could be reused in domain-specific ontologies.

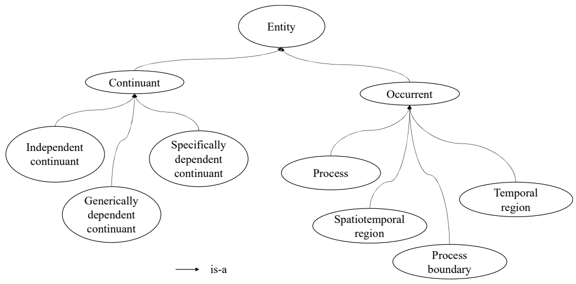

Figure 2: First two levels of BFO taxonomy.

4 RESEARCH METHODOLOGY

The methodology followed to realise a unified BFO-compliant taxonomy for maintenance purposes, starting from the existing BFO-based ontologies, comprises several steps and criteria that allow the identification of relevant sources and the inclusion/exclusion of those that did not fit with current goals and best practices. Indeed, the steps of specification and knowledge elicitation are ground steps as recognised by the scientific literature (Polenghi, Roda, Macchi, Pozzetti, et al., 2022). Hence, to come up with a unified taxonomy, multiple sources must be firstly identified, elaborated and then synthesised, as follows:

1. The first phase includes the identification of relevant ontological and non-ontological sources whose research scope includes industrial maintenance. The search for those sources involves both scientific literature and industrial standard:
   a. Scientific literature was spanned so to identify relevant scientific articles compliant with the following requirements: i) full-text-available article, ii) owl (Web Ontology Language) file available, iii) formal or semi-formal definitions of concepts available, and iv) BFO compliant.
   b. International standards on maintenance so to gather definitions and usage of terms, with agreed-upon semantics.
2. The second phase includes the comparison between the concepts under the semantic point of view via brainstorming sessions among the authors and by leveraging on the use of the concepts in maintenance applications. The goal of this phase is to set the ground towards a taxonomy that integrates knowledge from the identified sources in a unified way.

The methodology was applied to gather and identify those terms that fit with the purpose of creating a BFO-compliant taxonomy for industrial maintenance-related applications.

5 TOWARDS A UNIFIED BFO-COMPLIANT TAXONOMY FOR INDUSTRIAL MAINTENANCE

Three scientific articles providing ontological sources, compliant with the defined requirements, were identified: (Karray et al., 2019), (Montero Jiménez et al., 2021), (Polenghi, Roda, Macchi, & Pozzetti, 2022). Also, the resources publicly made available by IOF (www.industrialontologies.org, Industrial Ontologies Foundry) were considered, namely the ontology on maintenance. Several worldwide recognised standards were considered for the non-ontological sources, such as: IEC 60812:2018, ISO 14226:2006, IEC 60300-3-11:2009.

The most recurring and relevant maintenance-related concepts provided in the analysed ontological and non-ontological sources are then identified and their definitions as well as their positioning in the BFO top-level ontology are evaluated. Several concepts related to (1) the failure management, (2) the physical decomposition of the systems and (3) the maintenance processes are found and compared. As an example, Table 1 reports the comparison among the failure management-related terms, while in the next sub-sections a detailed description of the concepts for the 3-aforementioned is provided.

5.1 Failure Management-related Concepts

Concerning the **FAILURE CAUSE** concept, several coherent definitions from the standards (IEC 60812:2018, ISO 14226:2006, IEC 60300-3-11:2009) were found and reported in Table 1. Regarding the ontological resources, only IOF and (Montero Jiménez et al., 2021) provide the semi-formal definition of failure cause. Anyway, the positioning of the concept in the BFO is different: indeed, according to the IOF, the failure cause is an "occurrent" that has led to a state of failure of machine or a component, i.e. the failure cause is an event that happens, occurs; according to (Montero Jiménez et al., 2021), the failure cause is a "continuant" and, in particular, a descriptive information content entity that describes the cause of a failure mode, hence persists through time as it is seen more as a fixed, never-changing information type. This is aligned with the very same approach to Failure Modes, Effects, and Criticality Analysis (FMECA) by (Montero Jiménez et al., 2021) as they see related data to be stored in the "descriptive information content entity" class; at the same time, some data from the field will be collected during machine operation, therefore, some events related to the "occurrence" class (i.e. IOF definition) are present. Consequently, it is proposed to re-name the concept of failure cause, which is in the descriptive class, as "failure cause description" so to distinguish between the failure cause itself and related information. Therefore, to achieve a complete taxonomy, both concepts should be included.

Concerning the concept of **FAILURE MODE**, the standards IEC 60812:2018, ISO 14226:2006 and IEC 60300-3-11:2009 provide the definition, and all the ontological sources, except for (Karray et al., 2019), defined the concept. In particular, according to IOF, the failure mode is a "realizable entity" that is a consequence of a failure mechanism through which a failure occurs. Also, (Polenghi, Roda, Macchi, & Pozzetti, 2022) positioned this concept in the "realizable entity" class of BFO. Indeed, according to this positioning of the concept in the BFO, when a production process starts, then the failure mode exhibits. Instead, according to (Montero Jiménez et al., 2021), the failure mode is a "Descriptive information content entity" that describes a failure of an item and the corresponding fault that can cause the failure. As for the failure cause concept, (Montero Jiménez et al., 2021) consider the failure mode as an output of the FMECA.

As for the failure cause, the proposal is that both perspectives must be maintained in the ontology: the failure mode exhibits as a "realizable entity" and the failure mode information must be included in the "descriptive information content entity" and related. These two classes should be connected each other because when a failure mode happens, it will be possible to know which other failure modes will happen thanks to the relationships established in the failure mode information and, therefore, even if only one failure mode happens (as a "realizable entity"), it will possible to predict the other failure modes that will occur soon through the inference in the ontology. This means that when the first event of failure mode is occurring, it could imply other failure modes, but it is not possible to understand this only with the "realizable entity" class; whereas, thanks to the relationships among failure modes information established in "descriptive information content entity", it will be possible to predict if other failure modes will exhibit. The general idea is to link the static descriptions, relevant because give the relations between the failure modes, reported in the information content entity, with real data.

The **FAILURE EFFECT/CONSEQUENCE** concept was defined by the standard IEC 60812:2018 and IEC 61882:2016 (Table 1). In the ontological sources, only (Montero Jiménez et al., 2021) provided a semi-formal definition of this concept as: a "Descriptive Information Content Entity" that describes the impacts of a failure in terms of safety, environment, and operation; it is normally measured by rank and it is about an effect that results from a failure and consider the failure effect as an information. Anyway, only the failure effect information is not sufficient to be used in the ontology for making some assessments and reasoning: therefore, it is necessary to relate the information with the "deviation of the flow" (HAZOP-inspired terminology) in the production process. For example, in (Polenghi, Roda, Macchi, & Pozzetti, 2022), they analysed the effect of the failure on the feasibility of the product. Indeed, if we consider the flow at the "asset level", this could be represented by the product, and the deviation of the flow (i.e., the failure effect) is the product unfeasibility.

Concerning the **TRIGGERING EVENT** class, (Karray et al., 2019) define it as a "process" resulting in an action, while (Montero Jiménez et al., 2021) as a "process boundary" (process boundaries are the beginnings and endings of the processes they bound) that is the starting point for a maintenance action. After some brainstorming sessions among the authors, it was deemed to consider the triggering event concept as a process boundary so that: the triggering event triggers the maintenance action, which is connected to the event that detects when a threshold (of whatever nature) is reached, hence the action is requested. Also, the writing of an ontology-based database will consider the event (exceeding of the threshold) and the related maintenance action. Moreover, the database connected with the ontology will be feed with the information related to the event, the exceed of the threshold, not to the process.

Other definitions are provided by IOF that divides the concept of triggering event in **INSPECTION TRIGGERING EVENT**, **MAINTENANCE TRIGGERING EVENT** and **OPERATING TRIGGERING EVENT**, respectively defined as "a process boundary of an Inspection Action that begins a Maintenance Process. An inspection event that causes a maintenance process to be initiated", "a Process Boundary that begins a Maintenance Process through the production of a Maintenance Work Specification", and "a Process Boundary in the operation of a Manufacturing Process that begins a Maintenance Process".

Concerning the concept of **FAILURE**, according to the ISO 14224:2016, it is a loss of ability to perform as required, while ontologically (Montero Jiménez et al., 2021) and IOF the failure is a "process boundary". The related "failure event" is a "process" that precedes the state of failure (Karray et al., 2019). Specifically, according to IOF, a failure event is a terminal process boundary where some process which realizes the initial phase of a material product production process plan ceases, while (Montero Jiménez et al., 2021) define the failure as a triggering event subclass related to corrective maintenance strategy; the impossibility of an item to perform its intended function triggers a maintenance action. After some brainstorming among the authors, a failure can be represented in the ontology as an event, as for the triggering event, specifically a triggering event after the process of degradation.

Other concepts are modelled by (Montero Jiménez et al., 2021) as sub-classes of "triggering event" are: **DEGRADATION THRESHOLD OVERSHOOT**, **FAILURE FORECAST**, **FAULT DETECTION** and **FIXED TIME RECOMMENDATION** (Table 1).

After some brainstorming sessions, the proposal is to re-allocate the concepts that for (Montero Jiménez et al., 2021) are all sub-classes of "triggering event" in the specific concepts provided by IOF of "inspection triggering event", "operating triggering event" and "maintenance triggering event". Therefore, the idea is that all these concepts are process boundaries, but there will be first a class of "triggering event", divided in the three types of triggering event provided by IOF and the concepts of "degradation threshold overshoot", "failure forecast", "fault detection", "fixed time recommendation" and "failure" will be reallocated to the three types of triggering events. Below what proposed in this research work:

1. The concept of "failure" is an "operating triggering event" related to a part of the physical system (e.g. the component).
2. The concept of "degradation overall overshoot" is a "maintenance triggering event", because it is the maintenance department that takes care of the monitoring of the threshold overshooting, while the production is in progress. The concept of "degradation overall overshoot" is strictly interconnected with the condition-based maintenance (CBM) strategy.
3. The concept of "failure forecast" is a "maintenance triggering event".
4. The concept of "fixed time recommendation" is a "maintenance triggering event". We also propose to include the concept of "fixed age recommendation", to consider another possible periodic maintenance strategy.
5. The concept of "fault detection" is a "maintenance triggering event" because it is performed by the predictive maintenance module. The event of fault detection highlights that, even if the failure does not occur, something is happening on the physical system, so the "fault detection" concept can trigger the degradation assessment, which can imply the "degradation overall overshoot". Consequently, the maintenance action can be carried out once the overshoot appears or planned after a prognostic. This is in part coherent with the OSA-CBM (www.mimosa.org/mimosa-osa-cbm/) principles, for which there is first the fault detection, then the diagnostics to understand the type of fault, and then the maintenance action; but, when the maintenance action is not urgent, it is possible to use prognostics. This means that some relationships need to be clarified in the ontology because currently the "fault detection" is allocated as sub-class of "triggering event", therefore should imply directly a maintenance action, but based on MIMOSA OSA-CBM, fault detection does not imply directly a maintenance action.

Finally, (Montero Jiménez et al., 2021) did not explicitly differentiate between the predictive maintenance and the CBM strategies, but they only include the preventive, corrective and predictive.

Therefore, it may be interesting to consider and formalise the difference between CBM and predictive maintenance with proper relationships.

Several definitions of **STATE**, **FUNCTIONAL FAILURE**, **STATE OF FAILURE**, **STATE OF FAILURE COMPONENT**, **STATE OF FAILURE MACHINE** and **STATE OF DEGRADATION** are provided (Table 1). For example, according to (Karray et al., 2019), a "state of failure" is defined as a state during which an artifact is unable to perform its function. This concept is positioned as a sub-class of "state" in the "process" class, whereas IOF defines a "functional failure" as a state in which a physical asset or system is unable to perform a specific function to a desired level of performance, but the concept is still not positioned in the BFO top-level ontology. IOF provides also the definition of "state of failure component" and "state of failure machine", directly as a sub-class of "state". The definition of "state of degradation" is also provided by (Karray et al., 2019) as a state during which an artifact bears an undesirable quality or function and by IOF as a state in which some component endures and is moving towards non-conformity; it describes when a component is in the process of degrading.

Of course, we agreed that the two concepts of "state of failure" and "state of degradation" must be separated because they refer to two different states of the asset (unable to perform the service and reduced capability to provide the service, respectively) as well as two types of information in the FMECA analysis: on the degradation process is possible to perform prognostics (connected with the predictive maintenance), while the failure is a process boundary and, as such, is unpredictable or is the result of a degradation, therefore is not possible to perform prognostic on the failure (connected to the corrective maintenance, but we can consider the concept of failure also in the predictive maintenance).

Based on the several definitions provided by the analysed resources and the brainstorming sessions, our proposal is to consider a macro-class "state" including two sub-classes of "state of failure" and "state of degradation"; in the "state of failure" class, a difference is done between "state of functional failure" related to the asset and "state of physical failure" related to the component.

5.2 Physical System-related Concepts

Several concepts related to the physical decomposition of the systems are provided in the analysed sources: **ITEM**; **MAINTAINABLE ITEM**; **ASSET**; **COMPONENT**; **FUNCTIONAL UNIT**; **PART**; **SYSTEM**; **ASSET PLANT**; **ASSET SYSTEM**; **SENSOR**; **MACHINE**; **MANUFACTURING MACHINE**; **MANUFACTURING TOOL**; **EQUIPMENT**; **PIECE OF EQUIPMENT**; **TOOL**. (Polenghi, Roda, Macchi, & Pozzetti, 2022) and IOF also provide the concept of **PRODUCT**, as physical material entity.

These concepts are positioned in the "independent continuant" BFO class because all the concepts are "material entity", therefore, all the sources agree on the positioning of the concepts in the BFO. The differences are on the level of indentation of the concepts: for example, IOF includes in the ontology many concepts as "system", "component", "maintainable item", "machine"; "manufacturing machine"; "manufacturing tool"; "equipment"; "piece of equipment"; "tool", whereas (Karray et al., 2019) only considers the "asset" that is composed of some "maintainable item".

After reviewing the standards and the scientific literature, that do not provide a unique level of indentation, and based on the authors' experience, the level of indentation can vary based on the industrial context. For this reason, our proposal is coherent with (Karray et al., 2019) , i.e. to consider only two levels, one for the asset and another level for the components; this allow a major generalizability as the component is than related to itself via reflexive relationship. This is also coherent with the proposal done in the failure management-related terms, i.e. "state of functional failure" related to the asset and "state of physical failure" related to the component. The levels should be then adapted based on the industrial context.

5.3 Maintenance Process-related Concepts

Several maintenance process-related terms were analysed: all these concepts are positioned in the BFO "process" class.

(Polenghi, Roda, Macchi, & Pozzetti, 2022) define the **MONITORING PROCESS** as a process to monitor an artifact by measuring a specific phenomenon, while (Montero Jiménez et al., 2021) define the **CONDITION MONITORING** as a process that has as output condition data. The two concepts can be identified as a unique term and one definition can be provide as a process to monitor an artifact by measuring a specific phenomenon and that has as output condition data. A further difference can be done between condition continuous monitoring and condition discrete monitoring (Polenghi, Roda, Macchi, & Pozzetti, 2022).

Concerning the concept of **PROCESS OF DEGRADATION**, IOF and (Karray et al., 2019) define it respectively as a process that results in the loss of ability to perform a function and as a process that results in the loss of a desired quality or function, while (Montero Jiménez et al., 2021) provide the concept of **DEGRADATION ASSESSMENT**

PROCESS defined as a process performed on a physical equipment by a predictive maintenance module to assess degradation until this degradation overshoot a specific threshold. After some brainstorming sessions among the authors, we agreed that the concept of degradation assessment process allows the achievement of the degradation information thanks to the comparison of the measured values with thresholds, enabling the understanding of the magnitude of the degradation and the deviation of the flow, while the process of degradation is more a representation of the process in the real world.

Also, (Montero Jiménez et al., 2021) provide the definition of **FAULT DETECTION PROCESS** as a process performed on a physical equipment by a predictive maintenance module to detect incipient faults, therefore it is automatically performed by a system, whereas the concept of **INSPECTION ACTION**, only defined by the IOF as examination of an item against a specific standard, is generally performed by an operator that manually inserts the data in the information system. IOF puts this last concept in the class "need to be placed", therefore the inspection action is still not positioned in the BFO. Anyway, both concepts of fault detection process and inspection action have to be included in the taxonomy considering all current activities at shopfloor level.

The concept of **MAINTENANCE PROCESS** is also provided by the IOF as a process comprised of maintenance action to retain or restore a maintainable item to perform a function, all activities necessary to retain or restore the functionality of an asset; accordingly, IOF defines also the **MAINTENANCE ACTION** concept as a process to perform work on a component according to a maintenance work order specification; one of more tasks necessary to retain an item in or restore it to a specified condition. The concept of maintenance action is also provided by (Karray et al., 2019) as a process to perform work on an artifact according to a Maintenance Work Order Specification and by (Montero Jiménez et al., 2021) as a process performed on a physical equipment to restore or keep it in its operational state. All the definitions are consistent with each other.

Moreover, the concept of **MAINTENANCE STRATEGY DEVELOPMENT PROCESS** is defined by IOF as a process to produce a maintenance strategy specification, describes the process to produce a maintenance strategy for a maintainable item, and by (Montero Jiménez et al., 2021) as process subclass, which includes all activities and sub-processes to select the right maintenance strategy to apply for the different failure modes of a physical equipment.

Finally, the **PROGNOSTIC PROCESS** is only defined by (Montero Jiménez et al., 2021) as a process performed on a physical equipment by a predictive maintenance module to estimate the time to a future failure of a physical equipment or one of its components.

All these concepts must be then integrated, to be as exhaustive as possible in the taxonomy, taking into account the general classification of the maintenance processes from the standards that can be taken as a reference: for example, MIMOSA OSA-CBM, a standard architecture for moving information in a condition-based maintenance system, or the (BS EN 17007, 2017) reporting a generic description of the maintenance processes, as management, action and support processes.

6 CONCLUSIONS

Semantic interoperability is becoming the new bottleneck for companies willing to exploit the full potentialities of new technologies in exchanging information. Indeed, semantic interoperability does refer to the capability of preserving the meaning of concepts when several systems talk each other. The effect of idiosyncrasies in ontology development is not only a matter to ease IT development, but hugely impacts on decision-making in general and, specifically for this work, for maintenance, and, consequently, for the whole organization. Hence, fixing the semantics becomes a cornerstone to share the meaning underlying various concepts on which decision-makers judge decisions. A first step towards the formalisation of a domain-specific ontology is the definition of a taxonomy of concepts which allows to characterise the features of entities.

Therefore, it is the goal of this research work to pave the way towards a unified BFO-compliant taxonomy for maintenance-related applications. On the one hand, the selection of BFO depends on its diffusion as world-wide recognised, normative-supported top-level ontology. On the other hand, its application to maintenance is due to the new role maintenance is nowadays experiencing in gluing the shopfloor, and related data, with mid to high level decision-making, and vice versa as decisions to be made concrete.

The performed analysis is based on a review of the already existing ontologies that are already BFO-compliant as well as international standards, which already represent an agreed-upon vocabulary.

The result of the analysis is an aid to fix which concepts are relevant to formalise ontologies in the maintenance domain.

Future works include first the semantic validation by interviewing other academic experts and industrial practitioners. Then, after the formalisation of the relationships between entities so to enable the KARMA ontology reasoning and make inference, ontology evaluation tools will be used to identify formal pitfalls in the final ontology release.

The first maintenance subdomain to tackle will be the health assessment to achieve automatic diagnostics for failures. Furthermore, this will be extended to include both production-aware health state definition of machine, thus influenced by the load, as well as machine-aware scheduling, so to account for the health states when schedule production activities.

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Table 1: Failure management-related concepts.

	NON-ONTOLOGICAL RESOURCES	***ONTOLOGICAL RESOURCES***			
CONCEPT	**STANDARDS**	**IOF**	**KARRAY ET AL., 2019**	**MONTERO ET AL., 2021**	**POLENGHI ET AL., 2022**
FAILURE CAUSE	Set of circumstances that leads to failure (IEC 60812 : 2018); Circumstances associated with design, manufacture, installation, use and maintenance that have led to a failure (ISO 14226 : 2006); The circumstances during design, manufacture or use which have led to a failure (IEC 60300-3-11 : 2009)	A BFO:Occurrent that have led to a MNT: State_Of_Failure_Machine or MNT: State_Of_Failure_Component	-	A CCO: Descriptive Information Content Entity that describes the cause of a failure mode. It is about a CCO: Cause that can lead to an OMSSA: Failure	-
FAILURE MODE	Manner in which failure occurs (IEC 60812 : 2018); The effect by which a failure is observed on the failed item (ISO 14226 : 2006); one of the possible states of a failed item for a given required function (IEC 60300-3-11 : 2009). The consequence of the mechanism through which failure occurs (MIL-STD-721-C)	Def. A BFO: Realizable Entity that is the UNK:Consequence of a MNT: FailureMechanism through which the MNT: StateOfFailue occurs	-	It is a CCO: Descriptive information content entity that describes a failure of an item and the corresponding fault that can cause the failure. It is an output of the Failure Modes, Effects, and Criticality Analysis (FMECA)	A BFO:Realizable Entity that inheres in a ORMA :Component

Table 1: Failure management-related concepts (cont.).

	NON-ONTOLOGICAL RESOURCES	*ONTOLOGICAL RESOURCES*			
CONCEPT	**STANDARDS**	**IOF**	**KARRAY ET AL., 2019**	**MONTERO ET AL., 2021**	**POLENGHI ET AL., 2022**
FAILURE EFFECT / CONSEQUENCE	Consequence of a failure, within or beyond the boundary of the failed item (IEC 60812 : 2018); outcome of an event affecting objectives (IEC 61882 : 2016)	-	-	A CCO: Descriptive Information Content Entity that describes the impacts of a failure in terms of safety, environment, and operation. It is normally measured by rank. It is about a CCO: Effect that results from an OMSSA: Failure	-
TRIGGERING EVENT	-		A BFO:process resulting in an action.	A BFO: process boundary that is the starting point for a maintenance action	-
INSPECTION TRIGGERING EVENT	-	A BFO:Process_Boundry boundary of an UNK: Inspection_Action that begins a MNT: Maintenance_Process. An inspection event that causes a maintenance process to be initiated	-	-	-
MAINTENANCE TRIGGERING EVENT	-	Maintenance_Triggering_Event = Def. A BFO:ProcessBoundary that begins a MNT:MaintenanceProcess through the production of a MNT:Maintenance_Work_Specification	-	-	-
OPERATING TRIGGERING EVENT	-	A BFO:Process_Boundary in the operation of a IOF: Manufacturing Process that begins a MNT: Maintenance_Process. An operational event that causes a maintenance process to be initiated	-	-	-
DEGRADATION THRESHOLD OVERSHOOT	-	-	-	A COMSA: triggering event subclass related to predictive maintenance strategy. It is prescribed by a degradation assessment module of a predictive maintenance system.	-
FAILURE FORECAST	-	-	-	A COMSA: triggering event subclass related to predictive maintenance strategy. It is prescribed by a failure forecast module of a predictive maintenance system.	-
FAULT DETECTION	-	-	-	A COMSA: triggering event subclass related to predictive maintenance strategy. It is prescribed by a fault detection module of a predictive maintenance system.	-

Table 1: Failure management-related concepts (cont.).

	NON-ONTOLOGICAL RESOURCES	*ONTOLOGICAL RESOURCES*			
CONCEPT	**STANDARDS**	**IOF**	**KARRAY ET AL., 2019**	**MONTERO ET AL., 2021**	**POLENGHI ET AL., 2022**
FIXED TIME RECOMMENDATION	-	-	-	A COMSA: triggering event subclass related to preventive maintenance strategy. It is prescribed by a preventive maintenance plan. A recommendation based on fixed operation intervals or from fixed basic inspections triggers a maintenance action.	-
FAILURE (FAILURE EVENT)	Loss of ability to perform as required (ISO 14224 : 2016)	a BFO: terminal process boundary where some process which realizes the initial phase of a material product production process plan ceases	A BFO:process that precedes the ROM:State of Failure	An OMSSA: triggering event subclass related to corrective maintenance strategy. The impossibility of an item to perform its intended function triggers a maintenance action	-
STATE	-	-	A BFO:Process in which some BFO:independent continuant endures and one or more of the dependent entities it bears does not change in kind or intensity	-	-
FUNCTIONAL FAILURE	A state in which a physical asset or system is unable to perform a specific function to a desired level of performance (SAE JA 1012)	A state in which a physical asset or system is unable to perform a specific function to a desired level of performance		-	-
STATE OF FAILURE	-	-	A ROM:state during which a CCO:artifact is unable to perform its BFO:function		
STATE OF FAILURE COMPONENT	-	Def. A IOF:State in which some IOF:component endures and does not meet a requirement. Describes when a component is in a failed state	-	-	-
STATE OF FAILURE MACHINE	-	Def. A IOF:State in which some IOF:machine endures and does not meet a requirement. Describes when a machine is in a failed state	-	-	-
STATE OF DEGRADATION	-	Def. A IOF:State in which some IOF:component endures and is moving towards non-conformity. Describes when a component is in the process of degrading	A ROM:state during which a CCO:artifact bears an undesirable BFO:quality or BFO:function.	-	-