

An Ontology to Support Safety Management in Industrial Establishments Handling Dangerous Substances

Elena Stefana^{a,*}, Antonio J. Nakhal A.^b, Francesco Simone^a, Lorenzo Fedele^a, Giulio Di Gravio^a, Riccardo Patriarca^a

^aDepartment of Mechanical and Aerospace Engineering, Sapienza University of Rome, Rome (Italy)

^bDepartment of Engineering and Science, Universitas Mercatorum, Rome (Italy)

elena.stefana@uniroma1.it

Industrial establishments involving dangerous substances shall comply with Seveso Directive in order to control major accident hazards, prevent accidents, and limit adverse consequences for human health and the environment. Recent studies have emphasised the intricate socio-technical nature of such establishments, highlighting the need to adopt systemic and knowledge-based approaches for supporting their safety management. The effective implementation of such approaches can be fostered by the definition of an ontology able to capture all the organisational, technological, and social elements interacting within a Seveso system. This paper aims to develop a novel ontology to support safety management in Seveso establishments by addressing the various actors, organisations, equipment, processes, and their interactions prescribed by the Directive. Such ontology leverages existing ontologies related to Seveso sites and/or industrial plants, and it is intended to serve as a reference for various stakeholders involved in the safety management of industrial Seveso establishments. It provides a formalised and structured description of the relevant concepts and their relations, and facilitates the sharing of up-to-date knowledge around this domain.

1. Introduction

Safety management in industrial establishments handling dangerous substances plays a crucial role in defining measures and procedures to manage unexpected events with potentially devastating consequences for people, organisations, and the environment. This concern led to the drafting of the 2012/18/EU Directive (European Union, 2012), known as the Seveso III Directive. The Directive is grounded on the concept of major accident hazards, and on the implementation of an effective Safety Management System (SMS) to manage industrial establishments involving hazardous substances. To do so, the Directive stresses the importance of information flow at and among different political, organisational, and operational levels, for enhancing safety and transparency in industrial processes within European Union (EU) territories. However, the industrial landscape has radically transformed with the advent of advanced, digital, and human-centred technologies through the promotion of the Industry 4.0 and Industry 5.0 programmes in the EU. This rapidly transformation increased complexity and dynamicity of industrial systems, and stimulated their recognition as complex Socio-Technical Systems (STs), comprising interrelated and interdependent social and technological elements that influence each other to conduct operations and achieve objectives (Elmaraghy et al., 2012). This also caused the introduction of emerging safety risks in STs, which should be properly assessed and managed to assure acceptable safety performance. This appears particularly relevant for industrial plants that use, handle, produce, and/or store hazardous substances, where there is the need to prevent major accidents and limit the consequences for humans. To support the safety management in such industrial establishments, recent studies have proposed the adoption of a systemic perspective (Simone et al., 2025) and the usage of structured tools for organising the knowledge (Nakhal Akel et al., 2025). However, to represent the knowledge characterising the different Seveso establishments and support further systemic analyses, an ontology is required (Nakhal Akel et al., 2025). The ontology potentialities in the safety management and prevention of major accidents are also emphasised by Bragatto et al. (2020).

Indeed, an ontology is a formal explicit description of concepts in a domain and relations among them, which allows sharing common understanding of the structure of information among people, enabling reuse of domain knowledge, making domain assumptions explicit, and analysing domain knowledge (Noy and McGuinness, 2001). In other words, an ontological approach gives a valuable support for a systematic control of the knowledge (Bragatto et al., 2020). To the best of the authors' knowledge, only a limited number of scientific contributions propose ontological approaches for Seveso systems (e.g., Ancione et al., 2024b; Bragatto et al., 2020), which do not properly characterise the entire set of social and technical elements existing in these STSs. In such a context, this paper aims at developing a novel ontology to support safety management in industrial Seveso establishments by addressing the various actors, organisations, equipment, processes, and their interactions prescribed by the Directive.

The remainder of the paper is organised as it follows. Section 2 explains the methodology used to develop the ontology. This latter is described in Section 3. Section 4 summarises key findings and practical implications of this study, also suggesting possible future research directions.

2. Methodology

To develop this proposed ontology, the guide and the process suggested by Noy and McGuinness (2001) have been followed. The ontology development is an iterative process and is composed of seven steps (Noy and McGuinness, 2001), as shown in Figure 1, and briefly described below.

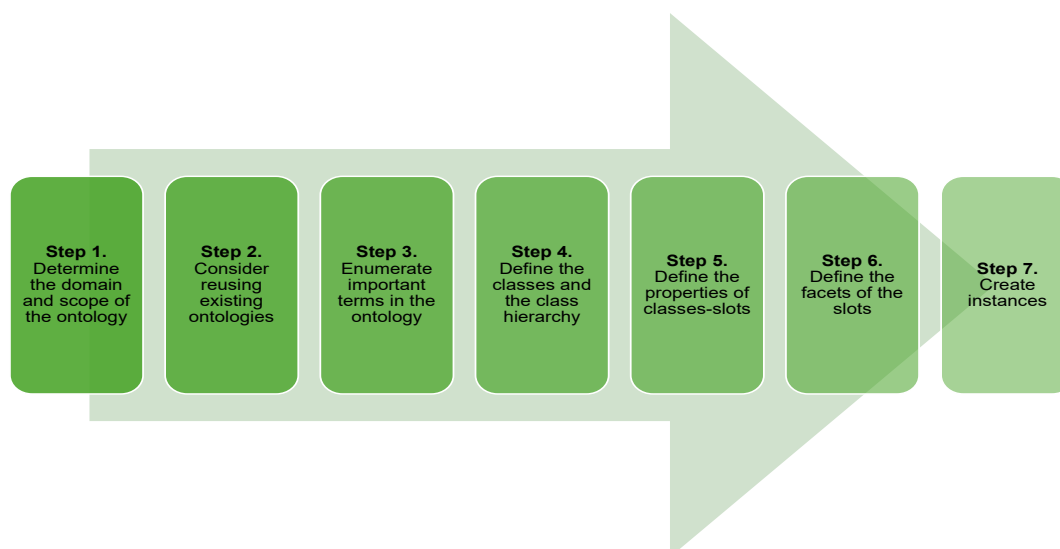


Figure 1: Methodology for developing an ontology, adapted from Noy and McGuinness (2001)

Step 1 permits clarifying which domain will be covered by the ontology, what it will be used for, what questions it will have to answer, and who will adopt it. The ontology developed in this paper is focused on the Seveso Directive and on the processes carried out by regulatory and inspection authorities, industrial operators and managers for assuring compliance with such Directive. It assists in answering the following questions (e.g.): (i) Is there a possibility that an agent different from the plant operator will send the documentation of the accident? To whom?; (ii) Which plant components need further action for their control? Who should collect this information? (iii) Which plant components are subject to inspections? Who is likely to carry them out?

Step 2 requires performing a literature review about existing ontologies to understand if they can be refined and/or extended for the domain and task at hand. Therefore, a review of scientific literature (e.g., in the Scopus database) and technical documents (e.g., international and European standards) was performed to identify interesting contributions answering the research question "Which ontologies or ontology-based approaches exist with regard to Seveso establishments and/or industrial plants?". A total of 16 scientific articles was retrieved from this literature review. Some of them propose ontological approaches investigating some critical issues of Seveso plants: e.g., Bragatto et al. (2020) focus on critical equipment, Ansaldi et al. (2021) on inspections, Ancione et al. (2024a, 2024b) on ageing management. Others develop ontologies for different processes typically occurring in industrial plants: e.g., inspection process planning based on resource capabilities (Solano et al., 2016), maintenance planning for equipment (Xia et al., 2023), smart maintenance (Wang et al., 2024).

Some international standards (e.g., ISO 2016, 2021) were also examined to identify relevant classifications for the industrial domain.

Based on these results, relevant terms and their relationships were identified and enumerated (Step 3). Such terms represented the main themes on which to ground the new proposed ontology. Those terms referring to concepts or objects clearly distinguishable (e.g., apparatus, human resource) were considered classes of the novel developed ontology. The class hierarchy was defined (Step 4) by combining a top-down approach with a bottom-up one: a few general concepts (derived from the objective of the ontology) and specific concepts (derived from the existing ontologies) were preliminarily defined and gradually refined. Step 5 allows detailing the class properties, i.e., the internal structure of the concepts in terms of intrinsic or extrinsic properties, physical or abstract components. Such properties derived from the remaining list of important terms not considered as classes: for each property in the list, it was necessary to determine the class it describes; these properties were considered as slots connected to the classes. Then, the facets of these slots were defined in terms of (e.g.) value type, admissible values, cardinality. Finally, Step 7 is the creation of individual instances of classes in the hierarchy, by choosing a class, creating an individual instance of that class, compiling property values.

Furthermore, the new proposed ontology was developed by involving five experts in the Seveso Directive implementation and inspections in industrial contexts (belonging to Italian inspection authorities and competent authorities) and three industrial operators and safety managers of Italian Seveso establishments.

3. The ontology for Seveso establishments

The application of the methodology summarised in Section 2 permitted obtaining a novel ontology to support safety management in industrial Seveso establishments by addressing the various actors, organisations, equipment, processes, and their interactions prescribed by the Directive and occurred in an industrial setting. Such ontology is comprised of nine classes, 36 properties, and 25 relationships.

3.1 Classes

The classes composing the ontology capture both social and technical elements of a Seveso industrial establishment. They are briefly described in the following, while Table 1 reports the properties of each class.

1. **Organisation:** an organised group of people with a specific purpose related to creating or establishing something. It can be a company, association, or entity (e.g., ISO, plant). This class was inspired by Karray et al. (2012).
2. **Human resource:** a human actor (i.e., person) or a group of them, who performs an activity within an organisation (e.g., maintenance worker, production team). This class was inspired by Ansaldi et al. (2021), Bragatto et al. (2020), ISO 9712 (ISO, 2021), Karray et al., (2012), Solano et al. (2016).
3. **Document:** an element containing information on a specific domain relevant to the plant (e.g., Seveso Directive, procedure for safety management during maintenance). This class was inspired by Ancione et al. (2024a, 2024b), Bragatto et al. (2020), Karray et al. (2012).
4. **Activity:** a specific work assigned or performed as part of one's duties, concerning a part of a process. It is the execution of a task, whether physical or cognitive (e.g., load, setup, calibrate, monitor). This class was inspired by Ansaldi et al., (2021), Karray et al. (2012), Montero Jiménez et al. (2023), Solano et al. (2016), Wang et al., (2024), Xia et al. (2023).
5. **Apparatus:** a device or artifact designed to operate in the industrial process (e.g., tank, valve, pipe). This class was inspired by Ancione et al. (2024a, 2024b), Ansaldi et al. (2021), Bragatto et al. (2020), ISO 14224 (ISO, 2016), Karray et al. (2012), Montero Jiménez et al. (2023), Wang et al. (2024), Xia et al. (2023).
6. **Material:** any physical material used for the realisation of an apparatus (e.g., carbon fibre, steel, copper, iron). This class was inspired by Ancione et al. (2024a, 2024b), Bragatto et al. (2020).
7. **Substance:** a form of matter with a uniform and defined composition with distinctive chemical and physical properties (e.g., fuel oil, methane, hydrogen). This class was inspired by Ancione et al. (2024a, 2024b), Ansaldi et al. (2021).
8. **Operating condition:** a variable describing the operating condition of an industrial process or substance (e.g., temperature, pressure, flow rate). This class was inspired by Ancione et al. (2024b), Montero Jiménez et al. (2023).
9. **Deterioration mechanism:** any physical, chemical, or mechanical process leading to the degradation, damage, or failure of the apparatus over time (e.g., corrosion under insulation, corrosion, mechanical fatigue from pressure, embrittlement). This class was inspired by Ancione et al. (2024a, 2024b), Ansaldi et al. (2021), Bragatto et al. (2020).

Table 1: Properties for each class defined in the new ontology

Class	Property (Type)	Definition
Organisation	Organisation type (string)	Type of organisation with specific regulatory, supervisory, inspection, monitoring, certification, or accreditation roles.
	Geo-political level (string)	Context or geo-political scope of an organisation.
Human resource	Role (string)	Prescribed or expected behaviour of a human resource associated with a particular position or status within the organisation's processes.
	Qualification (string)	Recognition of formal education, training, certifications, and experience that demonstrate an individual's suitability to perform a specific job, activity, or task.
Document	Document type (string)	Type of document relevant to the establishment.
	Date of document issuance (date)	Date of the document, in terms of day, month, and year, when a document is distributed to all interested parties.
	Type of requirement (enumerated)	Mandatory or voluntary nature underlying the issuance of the document.
	Update frequency (number)	Frequency, in months, with which the document must or can be updated.
Activity	Document validity (number)	Temporal period, in months, in which indicates the validity duration of a document.
	Reference process (string)	Sequence of interdependent and connected activities that, at each stage, consume one or more resources to convert inputs into outputs, meeting certain constraints.
Activity	Activity frequency (number)	Frequency, in days, with which an activity is performed within a given time frame, which can be described in terms of time intervals or occurrences.
	Apparatus class (enumerated)	The classification of an apparatus, i.e., equipment or component.
Apparatus	Age in service (number)	Service age or operating time of an apparatus, in years.
	Diameter (number)	Diameter size of an apparatus, in m.
	Length (number)	Length size of an apparatus, in m.
	Height (number)	Height size of an apparatus, in m.
	Width (number)	Width size of an apparatus, in m.
	Thickness (number)	Thickness size of an apparatus, in mm.
Material	Density (number)	Mass per unit volume of the material, in g cm^{-3} .
	Material composition (string)	Chemical composition of the material.
	Elastic modulus (number)	Ability of the material to resist deformation when subjected to stress, in GPa.
	Yield strength (number)	Maximum yield stress that a material can withstand without failure, in MPa.
	Tensile strength (number)	Maximum tensile stress that a material can withstand without failure, in MPa.
Substance	Density (number)	Mass per unit volume of the material, in g cm^{-3} .
	Substance composition (string)	Representation of the molecular structure of the substance.
	Phase (enumerated)	State of the substance, i.e., solid, liquid, or gaseous.
	Viscosity (number)	Resistance to flow of the substance, in cSt.
	Heating value (number)	Amount of heat released during the combustion of a specific quantity of a substance, in MJ kg^{-1} .
Operating condition	Parameter (number)	A parameter related to a specific operating condition.
	Unit (string)	Unit of measurement related to the parameter of the operating condition.
Deterioration mechanism	Consequence (string)	Negative effects of the deterioration mechanism on an apparatus.
	Propagation velocity (number)	Propagation rate of deterioration, in m s^{-1} .
	Visual manifestation (string)	Visible consequences of the deterioration mechanism on an apparatus.
	Class term (string)	Metallurgical manifestation of the deterioration mechanism on an apparatus.
	Detectability (string)	Investigation of the deterioration mechanism on an apparatus.
Measurement technique (string)	Approach adopted to analyse the deterioration mechanism.	

3.2 Relationships between classes

The various classes are linked through relationships. The 25 defined relationships were classified into the following unique 16 types: **belongs_to**, **causes**, **controls**, **describes**, **has**, **has_output**, **interacts_with**, **involves**, **is_assigned_to**, **is_input_of**, **is_made_of**, **is_part_of**, **is_subject_to**, **issues**, **performs**, **prescribes**. Figure 2 graphically links the classes through the relationships.

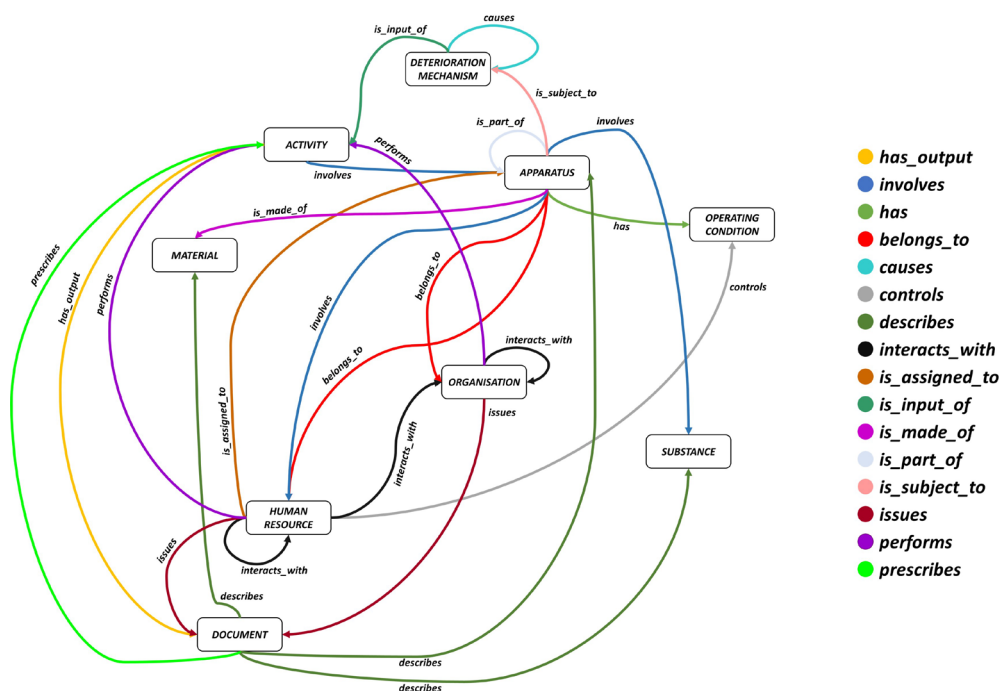


Figure 2: Relationships between the classes

Through the ontology adoption, an exemplary qualitative analysis about typical actors and their relationships in a Seveso industrial establishment could be performed. For instance, the plant operator (**human resource**, role: operator, qualification: experience of 20 years) **interacts_with** the operations team (**human resource**, role: operation team, qualification: safety training, ISO 9712 certification). The operator **performs** operations coordination (**activity**, reference process: management process, activity frequency: 1), and then **issues** an activity plan (**document**, document type: operations plan, date of document issuance: 01/05/2025, type of requirement: voluntary, update frequency: 4, document validity: 1). Such document **prescribes** periodic monitoring (**activity**, reference process: operations process, activity frequency: 1) about the plant equipment. For instance, the operations team **is_assigned_to** the oil pipeline (**apparatus**, apparatus class: component, age in service: 3, diameter: 0.2, length: 3, height: 1, thickness: 20), and **controls** its fuel oil temperature (**operating condition**, parameter: 298.15, unit: K). The pipeline **involves** fuel oil (**substance**, density: 1, substance composition: carbon 86%, hydrogen 13%, sulfur 0.5%, oxygen 0.4%, nitrogen 0.1%, phase: liquid, viscosity: 500, heating value: 42), **is_made_of** API 5L X65 carbon steel (**material**, density: 7, material composition: Mn 1.7%, Cr 0.50%, Ni 0.50%, Mo 0.50%, Cu 0.50%, Si 0.45%, C 0.18%, P 0.025%, S 0.015%, elastic modulus: 210, yield strength: 250, tensile strength: 350), and **is_subject_to** corrosion (**deterioration mechanism**, consequence: minor to medium hole, propagation velocity: 0.01, visual manifestation: uniform, class term: long metallurgical, detectability: easy, measurement technique: ultrasonic testing).

Both the example and the proposed ontology are strictly linked to the scope of the study, i.e., safety management in Seveso establishments handling, manufacturing, using, or storing hazardous substances. The example highlights key components of an industrial plant regulated under the Seveso Directive, though not all actors and processes are included here due to space limitations. Complementary, the ontology enables a case-independent structure and organisation of diverse data sources collected from one or more Seveso establishments, thereby facilitating both the description and the analysis of their operational processes. For instance, the ontology represents a means to perform advanced data semantics investigations, possibly even through the usage of Knowledge Graphs (KGs) to quantify system properties and identify potential weaknesses.

4. Conclusions

The adoption of ontological approaches allows for the structured organisation and formalisation of all relevant knowledge on a specific domain, through the usage of a shared and common dictionary. This paper has proposed a new ontology to support safety management in industrial Seveso establishments handling dangerous substances. It is composed of nine classes, 36 properties, and 25 relationships. This encompasses prior ontologies on critical equipment, inspections, ageing management, maintenance and resource

management in industrial settings, and extends them by explicitly incorporating the social and technical elements within an STS. This ontology may be extended in the future to include other interesting socio-technical elements and most recent technological innovations. Nevertheless, the structured knowledge organisation provided by the proposed ontology may be leveraged for the adoption of advanced data-driven approaches, including machine learning techniques and KGs, enabling further in-depth safety analyses of critical industrial establishments.

Acknowledgments

The authors would like to acknowledge the support of INAIL (National Institute for insurance Against Accidents at Work). This work is funded through the project “RE-SET: Resilience Engineering for Safe Energy Transition” under the INAIL BRIC 2022 funding scheme.

References

- Ancione G., Ansaldi S.M., Bragatto P., Agnello P., Milazzo M.F., 2024a, Ageing Management in Seveso Establishments by an Ontology Application, *Chemical Engineering Transactions*, 111, 91-96.
- Ancione G., Ansaldi S.M., Bragatto P., Agnello P., Milazzo M.F., 2024b, An ontological approach increasing the knowledge about equipment ageing including the effects of current transitions, *Journal of Loss Prevention in the Process Industries*, 92, 105453.
- Ansaldi S.M., Agnello P., Pirone A., Vallerotonda M.R., 2021, Near Miss Archive: A Challenge to Share Knowledge among Inspectors and Improve Seveso Inspections, *Sustainability*, 13, 8456.
- Bragatto P.A., Ansaldi S.M., Agnello P., Di Condina T., Zanzotto F.M., Milazzo M.F., 2020, Ageing management and monitoring of critical equipment at Seveso sites: An ontological approach, *Journal of Loss Prevention in the Process Industries*, 66, 104204.
- Elmaraghy W., Elmaraghy H., Tomiyama T., Monostori L., 2012, Complexity in engineering design and manufacturing, *CIRP Annals - Manufacturing Technology*, 61(2), 793-814.
- European Union, 2012, Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC.
- International Organization for Standardization (ISO), 2016, ISO 14224:2016: Petroleum, petrochemical and natural gas industries - Collection and exchange of reliability and maintenance data for equipment.
- International Organization for Standardization (ISO), 2021, ISO 9712:2021: Non-destructive testing - Qualification and certification of NDT personnel.
- Karray M.H., Chebel-Morello B., Zerhouni N., 2012, A formal ontology for industrial maintenance, *Applied Ontology*, 7, 269-310.
- Montero Jiménez J.J., Vingerhoeds R., Grabot B., Schwartz S., 2023, An ontology model for maintenance strategy selection and assessment, *Journal of Intelligent Manufacturing*, 34, 1369-1387.
- Nakhil Akel A.J., Simone F., Stefana E., Agnello P., Vallerotonda M.R., Ansaldi S.M., Alvino A., Fagnoli M., Di Gravio G., Patriarca R., 2025, A novel representation of the Seveso III Directive to manage dangerous substances in modern industrial plants, *Proceedings of International conference on Safety & Innovation*.
- Noy N.F., McGuinness D.L., 2001, *Ontology Development 101: A Guide to Creating Your First Ontology*.
- Simone F., Nakhil Akel A.J., Stefana E., Di Gravio G., Patriarca R., 2025, Towards dynamic safety control structures in STAMP to manage safety-critical industrial establishments, *Proceedings of the 35th European Safety and Reliability (ESREL) Society for Risk Analysis Europe (SRA-E) 2025 conference*.
- Solano L., Romero F., Rosado P., 2016, An ontology for integrated machining and inspection process planning focusing on resource capabilities, *International Journal of Computer Integrated Manufacturing*, 29, 1-15.
- Wang Y., Cheng Y., Qi Q., Tao F., 2024, IDS-KG: An industrial dataspace-based knowledge graph construction approach for smart maintenance, *Journal of Industrial Information Integration*, 38, 100566.
- Xia L., Liang Y., Leng J., Zheng P., 2023, Maintenance planning recommendation of complex industrial equipment based on knowledge graph and graph neural network, *Reliability Engineering and System Safety*, 232, 109068.