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Towards Enhancing Open Innovation Efficiency: A Method for Ontological Integration of BPMN and EMMO

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***Abstract*—The process of open innovation based on advanced materials involves the collaborative sharing of knowledge, ideas, and resources among different organisations, such as academic institutions, businesses, and government agencies. It is suggested that Business Process Modelling and Notations (BPMN) and Elementary Multiperspective Material Ontology (EMMO) be closely integrated to accelerate the development of new materials and technologies and address complex material challenges. In this paper, we examine the integration of EMMO and BPMN through an initial investigation to streamline workflows, enhance communication, and improve the understanding of materials knowledge. We propose a four-step approach to integrate both ontologies, which involves ontology alignment, mapping, integration, and validation. Our approach supports faster and more cost-effective research and development processes, leading to more effective and innovative solutions.**

I. Introduction

DIGITALISATION efforts in the engineering and materials development domains are today introducing new methods for digital collaboration and open innovation, like the one proposed in VIPCOAT[1]: Development projects implementing digitalisation approaches offer a multi-sided platform to create a collaborative environment to connect modellers (software owners, academia), and translators [1], manufacturers, governmental bodies and society to initiate and implement innovation projects (see Fig.1). To assist industrial end-users in making optimal decisions about materials and process design and manufacturing based on predictive modelling, it is increasingly necessary to examine innovation through a quadruple helix approach, which addresses the need for a *Digital Single Market strategy for Open Innovation 2.0* [2].

In parallel, an enormous amount of materials, manufacturing and processing data are currently generated by high throughput experiments and computations, possessing a significant challenge in terms of data integration, sharing and interoperability. A common ontology lays the foundation for solving these issues, enabling semantic interoperability of models, experiments, software and data, which is vital for using rational development design principles and testing and manufacturing of materials in general.

The aim of this work is to contribute to the current efforts by the European Materials Modelling Council EMMC on establishing common standards for materials modelling through the Elementary Multiperspective Material Ontology (EMMO), e.g.: [3]. The basic idea is to merge Business Decision Support Systems, implemented in terms of the BPMN and DMN standards, with materials modelling workflows by using ontologies as a glue between these hitherto distinct worlds.

Given that a product or a material system is defined by a combination of its physical, chemical and other technical properties, as well as other business-related aspects, such as cost, environmental footprint, and other relevant information to the organisation and the society at large. Therefore, it is essential for companies to gather data on the properties of the materials used in their products and vice versa. For instance, the physical and chemical properties of a protective coating can have a significant impact on production time, resource utilisation, manufacturing cost, sustainability, and toxicity.

[1] https://ms.hereon.de/vipcoat/

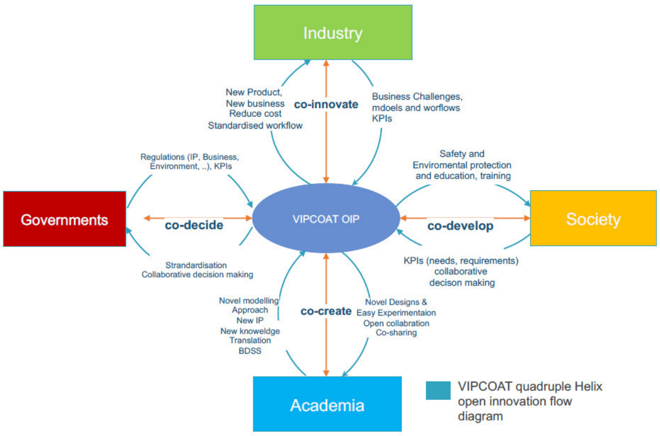

Fig. 1: Four Helix Virtual Open Innovation Framework: Industry, Society, Academia, and Governments

Hence, comprehending the properties of materials is critical to streamlining the manufacturing process, identifying appropriate machinery and equipment, and estimating relevant business indicators for informed decision-making [4]. This integration is particularly important in the context of Open Innovation, where companies collaborate to develop new products and services [5].

BPMN is a crucial tool for Open Innovation processes [6]. BPMN enables organisations to visually depict their business processes and workflows in a standardised format, which fosters more effective communication and collaboration with external stakeholders such as customers, suppliers, and partners. The standardised representation of business processes using BPMN allows for the identification of inefficiencies, redundancies, and bottlenecks in the workflow, leading to streamlined operations and increased efficiency [7]. Moreover, the use of BPMN provides a common language for discussing business processes, making it easier to share ideas and identify opportunities for improvement [5]. As a result, the ontology facilitates collaboration, accelerates innovation, and promotes the sharing of knowledge and best practices between organisations.

Elementary Multiperspective Material Ontology (EMMO), [8], is a comprehensive and versatile ontology for materials science that aims to provide a common language for describing materials and their properties. EMMO was developed by a group of European researchers as a part of the European Materials Modelling Council (EMMC)[2], which recognised the need for a unified approach to materials modelling and interoperability. EMMO is designed to be applicable to all levels of granularity, from atoms and molecules to macroscale materials, and it covers all aspects of materials science, including properties, structures, processes, and applications. EMMO is based on a multiperspective approach, which means it considers different perspectives and scales when describing materials. It provides a hierarchical structure that allows for the description of complex systems and a comprehensive set of classes and relationships for describing materials properties, including chemical composition, crystal structure, thermodynamic and mechanical properties, and more. EMMO is also designed to be extensible. Thus, it can be customised to meet the specific needs of different domains and applications. One of the key strengths of EMMO is its potential to promote interoperability between different materials modelling approaches and software tools. By providing a common language for describing materials and their properties, EMMO can facilitate the integration of models and data from different sources and the development of open standards and interfaces for materials modelling. This, in turn, can accelerate the development of new materials and improve the efficiency of materials design and testing.

In order to bridge the gap between the material science and business domains, this manuscript proposes the use of ontologies to establish a common understanding of the terminology and concepts used in both fields. The integration of the Business Process Model and Notation (BPMN) and the European Materials and Modelling Ontology (EMMO) can facilitate communication and collaboration among stakeholders, ultimately leading to the development of new materials and products. The integration of ontologies can lead to faster and more cost-effective research and development and the creation of innovative solutions to address complex material challenges. The paper aims to answer the research question of *how BPMN can be connected with EMMO* or vice versa, and proposes a concrete approach for integrating ontologies, consisting of conceptual alignments, concept mapping, concept integration, and validation. The proposed approach is applied to a preliminary analysis of integrating BPMN into EMMO. Section II provides an overview of the ontologies, extension mechanisms, and related works, while Section III describes the process of developing the integrated ontology. To know: III-A proposes processes alignment, III-B explains the concept and relationships mapping, III-C yields the integration of the concepts, and finally, III-D formally validates this integration using Incoherence Solving techniques. The paper concludes in Section IV with suggestions for future research areas.

II. Background

This section introduces BPMN and EMMO ontologies, reminds the different ontology extension mechanisms at our disposal, and presents the main related works.

A. BPMN

BPMN stands for Business Process Model and Notation [9]. It is a graphical representation for specifying business processes in a standardised way. BPMN was created by the Business Process Management Initiative (BPMI) and is now maintained by the Object Management Group (OMG)[3].

The primary purpose of BPMN is to provide a standardised notation that is readily understandable by all business stakeholders, including technical and non-technical users. This

[2]https://emmc.eu/

[3]https://www.omg.org/

notation enables clear communication and collaboration between business and technical teams when modelling and analysing processes and supports the execution of processes in a technology-agnostic manner.

BPMN provides a set of graphical elements, such as process, task, gateways, and events, that can be used to model various types of business processes. The notation also supports the modelling of more complex process flows, such as parallel and sequential execution, exception handling, and compensation.

BPMN is a widely adopted standard that helps organisations model, analyse, and improve their business processes, leading to increased efficiency and effectiveness.

B. EMMO

The Elementary Multiperspective Material Ontology (EMMO) is an ontology that provides a standardised and structured representation of the domain of materials science and engineering [10]. An ontology is a type of knowledge representation that defines a common vocabulary and formal model for describing concepts and relationships in a specific domain.

EMMO provides a comprehensive, hierarchical, and interlinked view of the concepts, classes, and relationships that are commonly used in materials science and engineering. It covers a wide range of topics, including material properties, processing techniques, and the relationships between materials and their components. EMMO aims to provide a shared understanding of the concepts and terms used in the field, making it easier for researchers, engineers, and data scientists to collaborate and exchange information.

EMMO is designed to be used as a resource for a variety of applications, including knowledge management, semantic search, and data integration in materials science and engineering. It can also help to integrate diverse data sources and support interdisciplinary research by providing a common vocabulary and conceptual framework. In this paper, we use the EMMO version 1.0.0.bata4 from github. [4]

C. Ontology extension mechanism

According to [11], the integration of two models (metamodels [12] or ontologies [13]) requires resolving three types of heterogeneity: *syntactic*, *semantic* and *structural*. For our integration, only the semantic and structural heterogeneity have been addressed. Indeed, the syntactic heterogeneity aims at analysing the difference between the serialisations of metamodel and, as explained by [14], addresses technical heterogeneity like hardware platforms and operating systems, or access methods, or it addresses the interface heterogeneity like the one which exists if different components are accessible through different access languages [15], [16]. Hence, it is not relevant in the case of this ontological integration.

Structural heterogeneity exists when the same metamodel concepts are modelled differently by each metamodel primitive. This structural heterogeneity has been addressed together with the analysis of the conceptual mapping and the definition of the integration rules. Finally, the semantic heterogeneity represents differences in the meaning of the considered metamodel's elements and must be addressed through elements mapping and integration rules. Regarding the mappings, three situations are possible: no mapping, a mapping of type 1:1, and a mapping of a type n:m (n concepts from one metamodel are mapped with m concepts from the other).

After analysing the heterogeneities, ontology extension mechanisms are applied. Ontology extension mechanisms refer to the ways in which an existing ontology can be expanded or modified to better suit the needs of a particular application or domain. There are several methods that can be used for ontology extension, including:

- Inheritance (generalisation): Inheritance is a refinement, detailing. Generalisation lifts things up. It is an additional level of abstraction. This is a common method of ontology extension in which a new class is defined that inherits properties and characteristics from an existing class. This allows new classes to be defined while reusing existing definitions and knowledge (e.g., in [17], inheritance relationships to extend OWL-S)
- Restriction (specialisation): This is a method of ontology extension in which the definition of an existing class is restricted to exclude certain individuals or objects. This can be used to refine a class's definition to better match a particular application's requirements.
- Extension (by adding axioms): This is a method of ontology extension in which new axioms or statements and rules are added to the ontology to provide additional information or, *a priory*, knowledge.
- Modules and Libraries: This is a method of ontology extension in which ontologies can be packaged as modules or libraries and can be imported or reused in other ontologies.

Each of these methods has its own strengths and limitations, and the appropriate method for a particular extension depends on the application's requirements and the design of the ontology being extended on a case-by-case basis.

D. Related Works

In [18], the proposed approach aims to integrate material modelling with business data and models to develop a Business Decision Support System (BDSS) [6] that assists in the complex decision-making process of selecting and designing polymer-matrix composites. This system combines materials modelling, business tools, and databases into a single workflow, providing a comprehensive solution supporting decision-making. In [7], the authors suggest utilising the BPMN and DMN[5] standards [19] to bridge the gap between business processes, materials science, and engineering workflows in the context of composite material modelling, which can potentially open up new horizons for industrial engineering applications. By using these standards ([20], [19]), it is possible to establish

[4]https://github.com/emmo-repo/EMMO

[5]https://www.omg.org/dmn/

a connection between the diverse domains and provide a more integrated approach to the modelling process, which could lead to improved efficiency and effectiveness in engineering applications.

In line with the previous approach, [21] extends the analysis by incorporating technical key performance indicators (KPIs) and financial KPIs, such as part costs, calculated using cost modelling applications. By including financial KPIs in the analysis, a more comprehensive understanding of the overall performance can be achieved, which can assist in the decision-making process related to product design and development. In [22], the authors discuss the development of an ontology called OSMO, which is an extension of the MODA workflow metadata standard [23], [24] used in European materials modelling projects. OSMO was created as part of the VIMMP project[6] and is connected to the larger effort of ontology engineering by the European Materials Modelling Council, with EMMO as its core. The article explains the purpose, design choices, implementation, and applications of OSMO [22], including its connections to other domain ontologies in computational engineering.

III. Integrating EMMO with BPMN

Merging two ontologies involves the integration of two separate ontologies into a single ontology that reflects the combined knowledge represented by both ontologies [25], [26]. To incorporate BPMN into EMMO, we propose a method, illustrated in Figure 2, that includes the following four steps:

- **Alignment**: This involves identifying and matching the concepts, classes, and relationships in the two ontologies that correspond to each other. This step requires a careful examination of the structure, content, and meaning of the concepts and relationships in both ontologies.
- **Mapping**: This involves creating a mapping between the concepts and relationships in the two ontologies based on the results of the alignment step. This mapping defines how the concepts and relationships in the two ontologies correspond to each other.
- **Integration**: This involves combining the two ontologies into a single ontology, using the mapping as a guide. The resulting merged ontology should reflect the combined knowledge represented by both original ontologies.
- **Validation by Incoherence Solving**: This involves checking the merged ontology to ensure that it is logically consistent and coherent and that it correctly represents the combined knowledge from both original ontologies.

A. Alignment

Conceptual alignment is the process of identifying and establishing the syntactic and structural correspondences between concepts or entities from two or more different sources or domains, should it be at the definition or at the association with other concepts level. To achieve this alignment, we listed all BPMN concepts, including their definition and association,

[6]Virtual Materials Market Place – https://cordis.europa.eu/project/id/760907

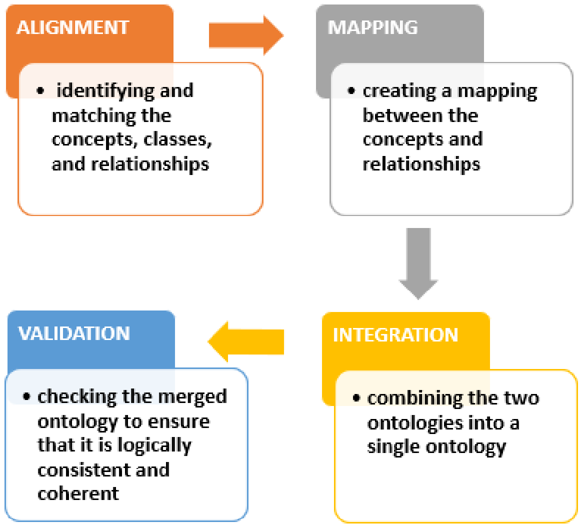

Fig. 2: Four steps of the method used to integrate BPMN into EMMO: Alignment, Mapping, Integration and Validation

and then we looked for correspondence with the EMMO concepts.

After a deep review of all BPMN concepts, we observed that eight concepts from BPMN may be aligned with nine concepts from EMMO. This alignment is possible based on analysing the concepts' names and definitions (syntactic alignment) and their associations with the other concepts (structural alignment).

1) Process vs. IntentionalProcess: The definition of **Process** from BPMN is *a Process describes a sequence or flow of Activities in an organisation with the objective of carrying out work*, although in EMMO, the **Process** is defined by *A whole that is identified according to criteria based on its temporal evolution that is satisfied throughout its time extension* and the **IntentionalProcess** extends the definition with *occurring with the active participation of an agent that drives the process according to a specific objective (intention)*. Both the **Process** and the **IntentionalProcess** are respectively part of and subClass of Process, and are associated with the **Participant**.

2) Participant (BPMN) vs. Participant (EMMO): In BPMN, a **Participant** *represents a specific PartnerEntity (e.g., a company) and/or a more general PartnerRole (e.g., a buyer, seller, or manufacturer) that are Participants in a Collaboration. A Participant is often responsible for the execution of the Process enclosed in a Pool* although in EMMO, this is *an object which is a holistic spatial part of a process. If plays an active role in the process, this is an Agent*. Both are linked to the concept of BPMN and EMMO's **Process**.

3) Activity vs. Elaboration: BPMN defines the **Activity** as a *work that is performed within a Business Process. An Activity can be atomic or non-atomic (compound)*. From the side of EMMO, an Elaboration is *the process in which an agent works with some entities according to some operative* *rules*. Elaboration is a subClass of IntentionalProcess, and Activity is a component of Process (although not represented in BPMN metamodel from [20]). Both also have subClasses ElementaryWork, Computation, Workflow for Activity and, similarly, CallActivity, Task, SubProcess for Elaboration.

4) Task vs. ElementaryWork: The definition of **Task** in BPMN is *an atomic Activity within a Process flow. A Task is used when the work in the Process cannot be broken down to a finer level of detail. Generally, an end-user and/or applications are used to perform the Task when it is executed*. In EMMO, a **ElementyraWork** is *an elaboration that has no elaboration proper parts, according to a specific type*, which means that an ElementaryWork does not break down into smaller pieces of work. **Task** and **ElementaryWork** are respectively subClasses of **Activity** and **Elaboration**.

5) ThrowEvent vs. Status: Throwing events, following BPMN, *are triggers for catching events and are triggered by the process*, which result in **ThrowEvent** and **Status**, following EMMO, consists in *an object which is a holistic temporal part of a process*. Both concepts have no similar association with other modelling concepts.

6) InteractionNode vs. SubProcess and Stage: The alignment between both concepts from both metamodels is more arduous to establish but is real. In BPMN, the **InteractionNode** is *a type of flow object that represents a point in a process where participants interact with each other to exchange information or perform some action*, and in EMMO, the **SubProcess** is *a process which is a holistic spatial part of a process*, and the **Stage** is *a process which is a holistic temporal part of a process*. The semantic analysis of these three definitions does not make it possible to establish an indisputable alignment between the concepts. However, the analysis of associations clearly shows the similarities. Indeed, the InteractionNode is a subClass of Activity and FlowElementaryContainer, and is composed of Artifact and similarly, (1) the SubProcess has SubProcess and is SubClass of Process and (2), the stage has Stage and is SubClass of Process.

7) SequenceFlow and WorkFlow: According to BPMN, the **SequenceFlow** *is used to show the order of Flow Elements in a Process or a Choreography. Each Sequence Flow has only one source and only one target*. For EMMO, the **Workflow** is *an elaboration that has at least two elaborations as proper parts.* At the association level, the SequenceFlow is a subClass of FlowElement (abstract superclass for all elements that can appear in a Process flow), and the WorkFlow is a SubClass of Elaboration.

8) ItemAwareElement and EncodeData: The **ItemAwareElement** in BPMN refers to *several elements that are subject to store or convey items during process execution* and the **EncodedData** are in EMMO *causal object whose properties variation are encoded by an agent and that can be decoded by another agent according to a specific rule.* The ItemAwareElement concept has type DataObject, DataSTore, DataInput and DataOutput, which are type of information, and the EncodedData is a subClass of Data and has subClass Information.

B. Mapping

In order to integrate BPMN concepts and relationships within EMMO, it is necessary to analyse and select the best ontology extension mechanism (detailed in Section II-C) for each conceptual mapping achieved in Section III-A: Inheritance, Restriction, Extension, or Modules and Libraries – knowing that the last method is inappropriate to the purpose of our work.

1) IntentionalProcess: The analyse of the definitions provided in Section III-A1 demonstrates that both metamodels define the IntentionalProcess/Process based on the same arguments, to know: that a process is structured following a sequence of activities and that it aims to reach an objective. BPMN's semantics is richer than EMMO's semantics in that it associates the process to an organisation. Therefore, the preferred extension mechanism is the restriction (EMMO restricts BPMN conceptual semantics).

2) Participant: EMMO's definition of Participant is more generic than the definition of BPMN, which considers that the participant is a human, or an organisation, that is often responsible for the execution of a process. This is more specific than EMMO's point of view, which considers that an object demonstrating a holistic spacial part of the process is a participant. Accordingly, the extension mechanism that fits this alignment is inheritance. First, the BPMN's participant inherits the characteristics of EMMO's participant, and second, the EMMO's participant is extended with two possible statements: the participant is either a human or an organisation.

3) Elaboration: EMMO's definition of Elaboration is semantically a bit different than BPMN's definition of Activity. On one side, BPMN explains that the Activity may be atomic or compound, and on the other side, EMMO stresses the importance of the Elaboration to work following some operative rules. As a result, the most appropriate extension mechanism is inheritance, and the EMMO Elaboration is extended with a composition link from/to the EMMO Elaboration concept.

4) ElementaryWork: Task and ElementaryWork have the same semantics, and both refer to the smallest and indivisible piece of work composing a process. The definition of the Task from BPMN (Section III-A4) is semantically richer in that it stresses the importance of being within a traffic flow and being performed by an end-user or an application. In this case, the ontology extension mechanism used is the extension (BPMN extends EMMO conceptual semantic).

5) Status: The definition of Status in EMMO highlights that this concept stands for an object that reflects a temporal part of a process, whereas BPMN defines ThrowEvent as a trigger for catching events by the process. Although not explicitly embedded in the definition, the Status associated with a process often triggers other events in practice. Therefore, we consider that this Status may be a type of trigger and, by extension, a ThrowEvent. Therefore, the mapping between both concepts is achieved using the restriction mechanism given that EMMO restricts ThrowEvent to Status.

6) SubProcess and Stage: Both concepts represent part of the process (spacial or temporal), such as the InteractionNode from BPMN, which is described as a point in a process. The semantic heterogeneity between both BPMN and EMMO meanings is that the first specialises the finality of the concept to a place (or moment) where participants get together to achieve something or to exchange information. The description of the InteractionNode is consequently semantically more expressive, although both SubProcess and Stage refer to a spacial or a temporal dimension. As a result, the extension mechanism is the restriction since both EMMO's concepts restrict BPMN one. This situation is quite similar to the case of the IntentionalProcess, but because two concepts of EMMO are mapped to one concept of BPMN, it is not necessary to extend the concepts with a dedicated extension mechanism.

7) WorkFlow: Analysing the definitions of the WorkFlow and of the SequenceFlow, we conclude that the equivalence between both concepts is thin and limited. Both concepts are direct or indirect elements of the process that are associated with at least two flowing elements. The SequenceFlow adds a supplementary characteristic which is the existing sequence between the happening of the flowing elements. The extension mechanism preferred is, by the way, the restriction as WorkFlow restricts the SequenceFlow meaning.

8) EncodedData: The ItemAwareElement concept in BPMN represents an abstract concept that may be specialised in many types like DataObject, DataStore, DataInput and DataOutput although the EncodedData concept is well defined and refers to properties variation of an object. This definition restricts by the way the definition of the ItemAwareElement and, as a consequence, the restriction extension mechanism is the one naturally designated.

C. Integration

In the approach used in this work, all concepts from BPMN without EMMO equivalence have been introduced in the integrated EMMO ontology. The main concepts are: Gateway, Events, Artifact, InteractionNode, FlowElementContainer, FlowElement, MessageFlow, DataAssociation, DataOutputAssociation, DataInputAssociation, DataObject, DataOutput, DataInput, CallableElement. Further explanations of those concepts are available in BPMN 2.0 specifications [9].
The integration of BPMN concepts with EMMO equivalence is achieved based on the mapping performed in Section III-B and taking in hand the resolution of potential associations–related issues. This analyses, for each concept is the following:

1) IntentionalProcess: The BPMN process being semantically richer than the IntentionalProcess, we may consider that the IntentionalProcess is a subClass of the BPMN Process concept, which is represented as a **type of** relation in UML. In the integrated ontology, the IntentionalProcess is preserved. Concerning the relationships, two associations which did not exist for the EMMO concept have been added in the integrated version. It consists of (1) the IntentionalProcess **is linked to** Collaboration and (2) the IntentionalProcess **is composed of** Artefact.

2) Participant: EMMO's definition of Participant being more generic, we have maintained the EMMO's Participant concept in the integrated ontology, and we have extended it with an attribute inherited from BPMN, to know: *the Participant is an individual or an organisation that is often responsible for the execution of the Process*. Regarding the relationships, two associations which did not exist for the EMMO concept have been added in the integrated version: (1) the Participant **composes** the Collaboration (2) the Participant is a **type of** InteractionNode.

3) Elaboration: Given the small heterogeneity's existing between Elaboration and Activity and the decision to consider the inheritance extension mechanism, we have maintained the EMMO's Participant concept in the integrated ontology, and we have extended it with a composition link, as explained in Section III-B3, such as an Elaboration **composes** an Elaboration. In parallel, three additional Activity related associations from BPMN have also been included in EMMO Elaboration: (1) an Elaboration **is composed of** DataInputAssociation, (2) an Elaboration **is composed of** DataOutputAssociation, and (3) an Elaboration is a **type of** FlowNode.

4) ElementaryWork: Alike the IntentionalProcess, the ElementaryWork is less rich than the Task semantic from BPMN, and for the same reason, the extension mechanism elected during the mapping step was the extension mechanism. Accordingly, we keep the ElementaryWork in EMMO extended ontology. Concerning the associated relationships, we complete the existing ones with (1) the ElementaryWork is a **type of** InteractioNode, and (2) the ElementaryWork **has type** various kinds of tasks (i.e., ScriptTask, ServiceTask, BusinessRuleTask, ManualTask, SendTask, ReceiveTask and UserTask)

5) Status: EMMOS's definition of Status restricts BPMN's definition of ThrowEvent to a state of a temporal part of a process, and as a result, that a Status is a **type of** ThrowEvent. Accordingly, the Status process is preserved in the EMMO ontology. Concerning the relationships, four associations which previously did not exist in EMMO have been added in the integrated version. It consists of (1) Status is a **type of** Event, (2, 3 and 4) Status **has type** EndEvent, ImplicitThrowEvent and IntermediateThrowEvent.

6) SubProcess and Stage: SubProcess and Stage's definitions, as reviewed in Section III-B6, restrict the definition of InteractionNode. They are both preserved in the EMMO ontology. Moreover, to express that these concepts may correspond to points where participants get together to achieve something or to exchange information, new associations are defined between them and the participants.

7) WorkFlow: Provided the tight analogy between Wokflow from the EMMO ontology and the SequenceFlow from BPMN, our strategy was to use the restriction extension mechanism and, consequently, to preserve the concept of WorkFlow in the integrated ontology. Two associations are needed to complete the ontology integration with some workflow–related semantics coming from BPMN: (1) the WorkFlow **is source**

of and **targets** FlowNode and (2) the WorkFlow is a **type of** FlowElement.

8) EncodedData: EncodedData from EMMO has a precise meaning compared to ItemAwareElement from BPMN, which has more for the purpose of specifying a collection of data. On the opposite, the ItemAwareElement may be of various types described in [20]: DataObject, DataStore, DataOutput and DataInput. Hence, EncodedData will remain in the integrated ontology. Finally, one additional association must be integrated: EncodedData **is source** and **is target** of DataAssociation.

D. Validation by Incoherence Solving

In general, validating a single ontology involves checking whether the ontology adheres to certain principles and standards [27]. Here are the type of validations that can be encountered and applied: syntax validation (*Does the ontology follows the correct syntax and format of the ontology language?*), consistency validation (*Is the ontology internally consistent?*), completeness validation (*Does the ontology covers all the necessary concepts and relationships in the domain?*), coherence validation (*Is the ontology coherent with other ontologies and standards in the same domain?*), usability validation (*Is the ontology easy to use and understand?*), but also the validation of specific ontology criterion such as the accuracy, coverage, scalability, and maintainability.

In the case of the validation of the integration of one ontology with another (BMPN with EMMO), we may assume that the above validation types have been achieved during the design of each specific ontology and that the item left to be validated is merging part itself, to know: Checking for inconsistencies between the ontologies. In general, this can be achieved by using a reasoner that checks for logical consistency (e.g., Pellet [28]), such as whether there are unsatisfiable classes or cycles in the hierarchy.

In the integration of BPMN within EMMO (Figure 3), we illustrate the validation by discussing one type of incoherency manually discovered in the integrated ontology. This incoherence is a cycle in the hierarchy that has been introduced between in the concept of **ElementaryWork** from EMMO and **InteractionNode** from BPMN. Solving this incoherency, in this case, requires a deeper analysis of both source ontologies. Therefore, by analysing EMMO and BPMN, it can be argued that an **ElementaryWork** can be considered a type of **InteractionNode** because an elementary work is a basic process that involves the transformation of materials, energy, or information, often through the application of energy such as heat or mechanical work. This transformation typically involves some kind of interaction between two or more entities, such as a chemical, an electrical or even a nuclear reaction or a physical change in state. Moreover, an **InteractionNode** is a node representing any type of interaction between two or more entities in a business process model. This can include tasks, events, and gateways, which are used to model different types of interactions. Therefore, it can be argued that an elementary work, which represents a basic process that transforms materials, energy, or information, can also be considered an **InteractionNode** because it involves an interaction between two or more entities, even if it is a more fundamental type of interaction compared to other types of nodes. Hence, both **ElementaryWork** and **InteractionNode** represent different types of nodes in a business process model, but an **ElementaryWork** can be seen as a more fundamental type of interaction that involves the transformation of materials, energy, or information, making it a type of **InteractionNode** in a broader sense. As a consequence, the decision was made during the Validation by Incoherence Solving step to keep the link "ElementaryWork is a type of InteractionNode" in the integrated model while removing the link "InteractionNode is a type of ElementaryWork".

IV. CONCLUSIONS AND FUTURE WORKS

This paper enhances the process of open innovation within the materials industry [2]. To achieve this goal, we propose an approach never achieved before that involves integrating two ontologies to unify the innovation process with the processing of materials. Specifically, we utilise the BPMN ontology to support the open innovation process and the EMMO ontology to describe the materials. By merging these two ontologies, we can create a more comprehensive framework that can facilitate collaboration and innovation in the materials industry. This integration aims to streamline the workflow, improve communication, and enhance the understanding of materials, leading to more effective and innovative solutions.

Our proposed approach consists of four key steps: Alignment, Mapping, Integration, and Validation by Incoherence Solving. While alignment and mapping are relatively straightforward, the integration step requires more careful consideration. For instance, we have observed that when the extension mechanism takes the form of a restriction, the BPMN concept is not taken into account. On the other hand, when the extension mechanism is an inheritance, the EMMO concept is extended with the attributes inherited from BPMN. So far, we have not yet encountered a case where the extension mechanism involves a type extension by adding new axioms.

This paper presents a significant step towards achieving open innovation in the materials industry. The ontological integration of BPMN with EMMO can bring about transformative changes to the field by enabling faster and more cost-effective research and development processes and creating innovative material solutions to address complex challenges. Our approach also has the potential to improve communication and streamline workflows, which can lead to greater efficiency and productivity. Moreover, the integration of these two ontologies can enhance the understanding of materials and provide a more detailed description of materials in the innovation process. As a result, organisations can gain a competitive advantage by leveraging this approach and advancing the materials industry with novel and impactful solutions. Overall, our proposed approach has the potential to revolutionise the field of materials science and accelerate progress towards open innovation.

As future works, much must be done to improve ontology and

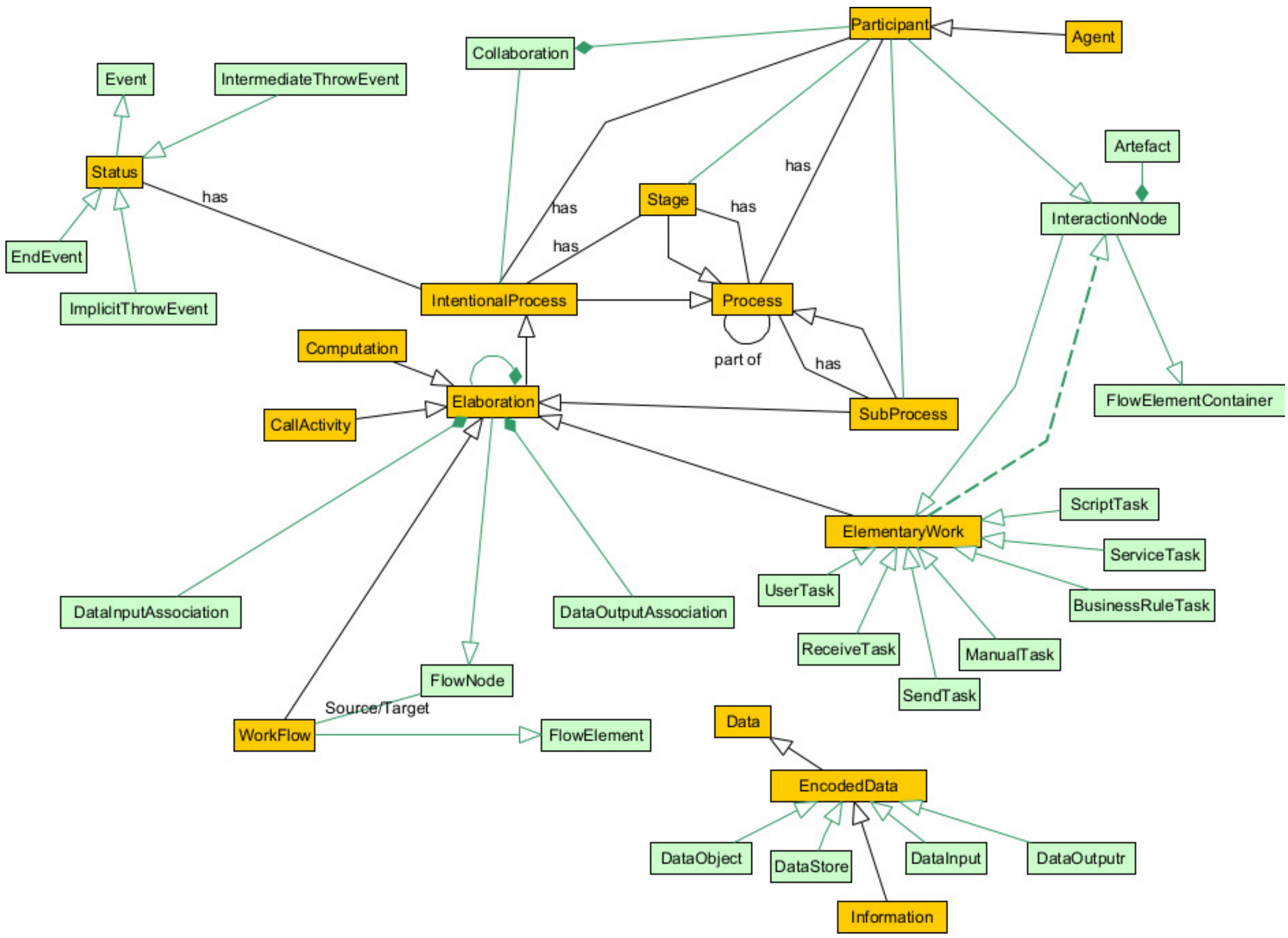

Fig. 3: Integrated BPMN's concepts within EMMO ontology. On this schema, the concepts from EMMO ontology are represented in orange and the concepts from BPMN are in green.

its application in real-world scenarios. Our first priority is to enhance the integration of the two ontologies by potentially considering other concepts that have not yet been integrated. By doing so, we aim to create a more robust and complete ontology that can capture all relevant aspects of the domain. Secondly, we must conduct further analysis to identify potential incoherencies in the integrated ontology. While we have already identified one example of a cyclic association between the ElementaryWork and the InteractionNode, additional review and analysis are necessary to ensure that no remaining incoherencies exist. Thirdly, we plan to validate the ontology by applying it to a real case and observing to what extent it is possible to consider all the dimensions of the real scenario with the integrated ontology. This will allow us to assess the advantages of using the integrated ontology in practice and identify any areas for further improvement. Finally, we aim to deploy the ontology in a software tool like *Protégé* [29] to facilitate its manipulation and representation. This will enable other researchers and practitioners to use the ontology easily and effectively in their own work. Overall, our goal is to create a more comprehensive, coherent, and useful ontology that can help researchers and practitioners better understand and navigate the complex domain. We hope our ongoing efforts will lead to further advancements in the field and contribute to developing more effective tools and applications.

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