A BPMN Extension to Model Inter-Organizational Processes in Industry 4.0

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Abstract

Business processes are increasingly digitized and decentralized in companies adopting Industry 4.0. This paper proposes and evaluates a Business Process Modeling and Notation (BPMN) Extension to deal with this challenge. The proposal results from a design science research project in the coating industry. The proposed extension provides an integrated description of (1) private/shared process elements, (2) local/distributed manufacturing stages, and (3) technology incorporation strategy in the production network. The proposed BPMN extension can be useful for companies certified by the ISO 9001 quality standard that need to disclose their processes and third-party collaborations. Moreover, a comprehensive visualization of processes in Industry 4.0 may contribute to continuous business process improvement in manufacturing networks.

Keywords: Industry 4.0, Inter-Organizational Business Process, BPMN, BPMN Extension, Business Process Management.

1. Introduction

Digital transformation requires a new logic for business process management (BPM). The work of [4] highlights three emerging BPM priorities, namely, agile and more configurable "*light touch routines*," infrastructure flexibility (e.g., increasing adoption of the Internet-of-Things (IoT)), and mindful actors more prepared to make decisions in different parts of the process. Industry 4.0, the high-tech strategy introduced by the German government, is a paradigmatic example of digital transformation [18]. Manufacturing processes now rely on IoT, mobile systems, or artificial intelligence techniques to improve production flows [28]. However, modeling business processes in Industry 4.0 is challenging, requiring new approaches to represent how digitalized companies are changing their operations [6].

The new BPM logic is also extensible to the supply chain. On the one hand, creating a technological infrastructure to decentralize production provides visibility to product flows since the early stages of sourcing raw materials for product use. On the other hand, by requiring more "*effectiveness of communication between actors and favoring data collection and sharing*" [26]. As a result, processes are becoming increasingly "inter-organizational," distributed, and agile, but also more challenging to manage with traditional modeling languages, such as Business Process Modeling and Notation (BPMN) [22]. For example, BPMN cannot represent all the details of Inter-Organizational Business Processes (IOBP) [22] since it lacks the semantics to describe the dependencies of the global control flow of the message exchange [7]. Additional problems are the absence of formal specification of process interfaces and support for alignment with multiple partners.

Aiming to advance the new BPM logic [4] in Industry 4.0, we conducted a design science research project in cooperation with a company that produces technical coatings (e.g., thermal spraying, plasma, laser, or electrodeposition of advanced materials). Technical coatings aim to increase the durability of components and are particularly relevant to process industries (e.g., petrochemical, automotive). Our overall research objective is to create a BPMN extension to model inter-organizational business processes for Industry 4.0 adoption (IOBP 4.0).

The remainder of this paper is structured as follows. Section 2 presents foundational literature in Industry 4.0, IOBP, BPMN, and other related work. We detail the research approach in Section 3, and the results follow in Section 4. Subsequently, we demonstrate (Section 5) and evaluate (Section 6) the adoption of IOBP 4.0 in a real-world setting. The paper closes by stating conclusions, the main limitations, and future work opportunities.

2. Background

2.1. Industry 4.0

Industry 4.0 defines a new digital transformation era in the industry with the adoption of cyber-physical systems (CPS) [13]. This global change was triggered by the development of cloud technologies and the Internet [18], integrating physical assets (e.g., machines, components) and "cyber" capabilities to improve real-time monitoring and control of advanced production processes [21].

Industry 4.0 enables companies to have more flexible manufacturing processes and analyze large amounts of data in real-time, improving their operational decision-making and strategic planning [18]. However, Industry 4.0 is not restricted to internal operations. Digital transformation also extends to the redesign, coordination, and improvement of supply chains, from the early manufacturing stages to the after-sales [19].

The decentralization of manufacturing comes with an associated challenge: horizontal integration, consisting of establishing collaboration networks between companies in the supply chain, sharing resources, and exchanging increasing amounts of data [18]. Moving from single to multi-site manufacturing raises the need to support decentralized decisions and orchestrate technological components (e.g., machines, enterprise systems) that can interact with each other and with workers in real-time, generating more complex data flows and activities [28].

More complex business processes in Industry 4.0 are mobilizing academia to propose process modeling approaches [29]. One of the main goals is to assist managers in moving beyond organizational borders and understanding process-centric work practices that expand to different elements of supply chains [26] while keeping the process compliant and traceable.

2.2. Inter-Organizational Business Processes

IOBP are interrelated and sequential activities shared and executed by two or more trading entities to achieve a business objective of value to the partners [5]. The implementation and execution of IOBP require a certain level of trust between the participating organizations, guaranteed through legal contracts, which specify the responsibilities and obligations agreed by all the participating parties [32].

Currently, IOBP models are created independently by each partner organization, using disconnected documentation and procedures. This approach enables each business partner to focus on its internal activities and develop management activities. Aiming to improve this disjointed approach, [20] proposes a way to merge different process models supporting collaboration in producing components and products by creating a unified perspective of the business process. However, the design of IOBP is problematic:

- The interaction between internal business processes and IOBP requires transparency between business partners [23];
- It is challenging to coordinate IOBP interdependencies (e.g., equipment shared by different partners) [7];

- There is a need to define partner's responsibilities across the different activities in the IOBP flow [1];
- There may exist a semantic gap caused by each business partner having its own internal process language and terminology [22];
- There is a need to deal with the autonomy required by each business partner to design, execute and improve their internal business processes and strategies, which may lead to different paces of digital transformation. Mechanisms are needed to synchronize and reduce the degree of coupling between the external and internal interfaces of the business partners in the IOBP [7];
- There is a need to deal with business partners that are distributed across different geographical locations, each subject to distinct compliance requirements and laws [30];
- Monitoring decentralized activities and decisions in IOBP requires deploying policies that allow traceability of metrics of the several elements (e.g., state of process execution, inventory count in each partner) [10].

Despite the existing contributions for modeling IOBP, the resulting process models are often incomplete [7, 22] and difficult to share within the organizations. Therefore, a new or extended notation (e.g., using BPMN) is necessary to promote the design and execution of IOBP more wholly and effectively.

2.3. BPMN and BPMN Extension Mechanism

Business process models are used to document business processes, enabling their understanding and analysis [2], playing a key role in executing management activities [10].

Business Process Modeling and Notation is an open industry standard for business process modeling. It provides an intuitive and straightforward notation that is readily understandable by all business users [12]. It also has a well-defined language meta-model that simplifies tool integration and model exchangeability [9].

BPMN provides an "*extension by addition*" mechanism that enables the definition and integration of domain-specific concepts [33]. Moreover, BPMN is one of the few process modeling languages that allows extensions, adding domain-specific concepts while ensuring BPMN core elements' validity [25]. Finally, the development of BPMN extensions is generally less costly than developing an entirely new domain-specific modeling language from scratch [9].

According to the BPMN standard [25], the language extension mechanisms is structured as follows:

- Extension – Binds the extension attributes to a standard BPMN model definition;
- ExtensionDefinition – Supports the incorporation of attributes in a specific element or a new element. Composed by several ExtensionAttributeDefinition (name and type);
- ExtensionAttributeDefinition – Defines new attributes as characteristics of a customized element (e.g., string, integer, Boolean);
- ExtensionAttributeValue – Incorporates the attribute value.

The work of [33] suggests a methodology to create BPMN extensions. However, only a few developed BPMN extensions are designed in conformance with OMG's standard [36]. Most are created using meta-model and XML-schema customizations, raising problems in tool integration, comprehensibility, and model exchangeability [9].

Business process models possess two elements more specific to inter-organizational process descriptions: (1) pools representing entities (e.g., organizations) that perform business processes [22], and (2) message flows depicting information exchanges between organizations. However, the standard BPMN elements cannot represent all the details from the IOBP 4.0 domain. Therefore, BPMN extensions emerge as a promising solution [36].

2.4. Related Work: Business Process Modeling in Industry 4.0 and IOBP

Several BPMN extensions have been proposed for Industry 4.0 contexts. PyBPMN [6] is one of the most mentioned, presenting an approach to the specification and management of the resources associated with the business processes supporting cyber-physical systems. Further studies in this field include the modeling of industrial IoT scenarios [14], analysis of business process fragments for manufacturing activities [15], and ubiquitous business process modeling [35]. The study conducted by [37] proposes a BPMN extension for the domain of manufacturing. These authors create a set of elements for representing manufacturing operations and resources, followed by presenting different examples for using them.

BPMN extensions are also available for IOBP. A pioneer contribution was presented by [16], using pools and messages for each organization. The work of [3] presents the design of a BPMN extension for collaborative business processes. The proposal is focused on concepts related to the execution of collaborative tasks, activity privacy, confidentiality, state of progress of activities, and data management. The authors propose a meta-model and a set of new graphical elements for collaborative business processes.

Despite these essential contributions for modeling IOBP and Industry 4.0, an integrated approach to model manufacturing in IOBP scenarios of manufacturing's digital transformation is still necessary to develop. This section's related work can be integrated and extended, serving as the starting point for our research, explained in the next section.

3. Developing an IOBP 4.0 BPMN Extension

We selected design science research (DSR) as the approach to create our extension since it is a problem-solving paradigm that relies on kernel theories to produce inventive artifacts [17]. DSR evolves iteratively, starting with the "*problem identification and motivation, define objectives of a solution, design and development, demonstration, evaluation, and communication*" [27].

Our DSR cycle had a problem-centered initiation [27], including contacts with industry experts and a literature review on the topics of BPMN extensions and Industry 4.0. The next step was designing the IOBP 4.0 extension and demonstrating its utility [17]. The design phase follows the approach proposed by [33] using UML profiles, later improved by [8] with the analysis of the domain and its conceptualization [8]. First, we conceptualized the IOBP 4.0 domain as an ontology, revealing the main domain concepts, relationships, and properties. Then, we conducted an equivalence check to assess if the IOBP 4.0 concepts were semantically equivalent to the standard BPMN elements (e.g., tasks, gateways, data objects).

We instantiated the artifact in a case company adopting Industry 4.0 and decentralized manufacturing. Fig.1 synthesizes our DSR.

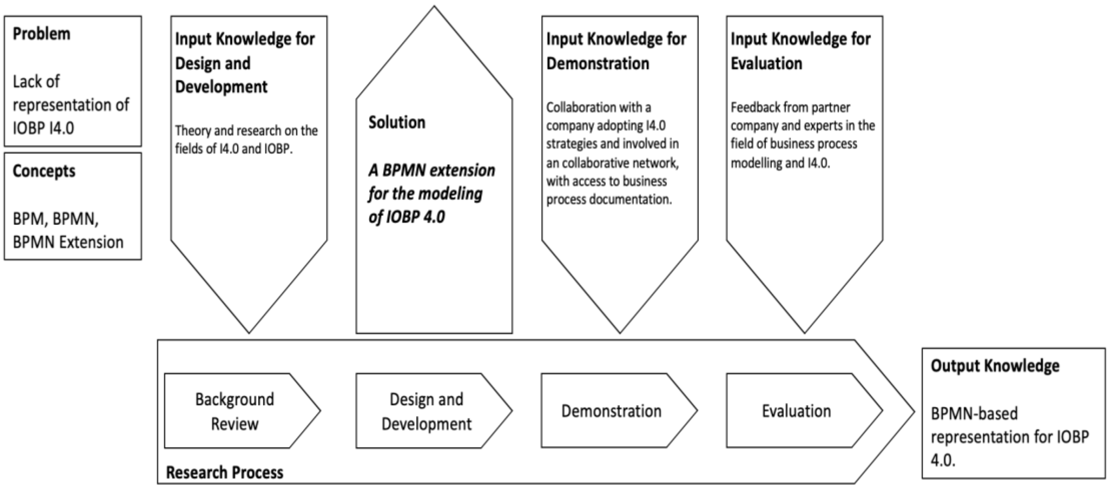


Fig. 1. DSR Grid for IOBP 4.0 (adapted from [11] and [27]).

After confirming the few contributions available for the detailed modeling of IOBP 4.0 (see left of Fig.1, problem description), we identified a BPMN extension as the most promising solution. After its design, we tested it in a real-world case in a technical metal coatings provider adopting Industry 4.0. The case company's mission is to research and develop solutions for the coating of rotary and static industry apparatuses. The case company's operations require some outsourcing, and it is investing in a new coating robot and artificial intelligence models to forecast product failures under operation. Being ISO 9001 certified, the company found our approach interesting to model processes aligned with Industry 4.0 investments. In addition, the company provided process-related documentation, which allowed us to model the process using standard BPMN notation and IOBP 4.0. Section 4 details the artifacts created during our DSR.

4. IOBP 4.0 BPMN Extension Development

We present the domain ontology for Industry 4.0 and IOBP in Section 4.1. Subsequently, we describe the new elements necessary to model IOBP 4.0.

4.1. Domain Ontology

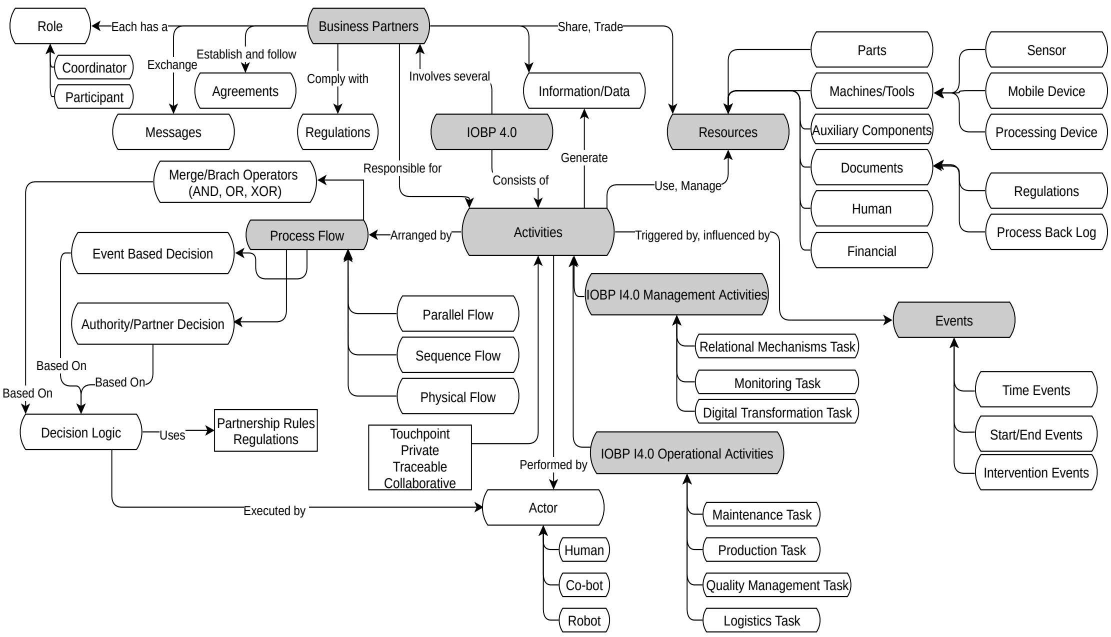


Fig. 2. Domain Ontology of IOBP 4.0.

Fig. 2 depicts the ontology, which we designed to appropriately understand the domain, concepts, and attributes. This domain's central concept is the business process involving two or more business partners (IOBP 4.0, on the top) and their process activities [22].

Each business partner acts in the process (coordinates or participates) according to inter-organizational agreements. Partners must comply with specific regulations (e.g., laws, procedures, standards, contract agreements) [30], exchange information/data (through messages and documents) [7], and may share resources in the manufacturing network (e.g., parts, auxiliary components) [15].

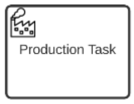
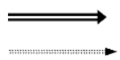
The business partners execute IOBP 4.0 management activities (e.g., relational mechanisms task, monitoring task, digital transformation task), and actors (e.g., human, co-bot, robot) perform IOBP 4.0 operational activities (e.g., maintenance task, production task, quality management task, logistics task), exploiting resources (e.g., parts, auxiliary component, machines, human, financial) [15]. There is a bidirectional impact between activities and events (e.g., time events, start/end events, intervention events) that coexist in business processes [7]. Activities' data may be public or private, requiring traceability [10].

The activities are executed according to the process flow (e.g., parallel flow, partner flow, physical flow), as shown on the left side of Fig. 1. In certain parts of the flow, decisions are made (e.g., gateway, event-based decision, authority/partner decision) about the activities to be executed next, based on a decision logic (e.g., partnership rules/agreement, regulations) [7] executed by actors (e.g., human, co-bot, robot).

4.2. Graphical Representation of IOBP 4.0 BPMN Extension

Table 1 describes the BPMN elements identified in our domain ontology model and their proposed graphical representation. The design team's goal was to uniquely identify each new BPMN element while keeping consistency with those already present in the standard (e.g., in BPMN, a task is represented by a rectangle with rounded corners).

Table 1. Graphical Representation of IOBP 4.0: BPMN Extension Concepts.

BPMN Concept	Domain	Custom Elements	Description	Graphical Representation
Task	**Manufacturing**	**Production Task**	The production task represents a sub-type of task to execute production activities (e.g., assembly, cleaning, handcraft, heat treatment).	
Task	**Manufacturing**	**Quality Management Task**	The quality management task represents a sub-type of task executing quality management activities (e.g., product testing, check non-conformities).	
Task	**Manufacturing**	**Logistics Task**	The logistics task represents a sub-type of task related to logistics activities' execution (e.g., packaging, handling, materials' storage).	
Task	**IOBP and Cyber-Physical**	**Traceable Task**	The traceable task identifies that a specific task is traceable, meaning that a set of metrics is retrieved and registered to execute that task.	
Task	**IOBP**	**Private Task**	The private task represents that a specific task is private, meaning that no information on that task is shared with the partners, being kept confidential.	
Task	**IOBP and Cyber-Physical**	**Touchpoint Task**	The touchpoint task means that it is a region of interest for partners. Information about the task execution/state may be shared.	
Task	**IOBP**	**Collaborative Task**	The collaborative task means that a specific task is executed and managed in collaboration between several business partners.	
Gateway	**IOBP**	**Partner Gateway**	The partner gateway represents a moment in which a specific partner decides the "path" of the activities to be executed in the following steps.	
Intermediate Event	**IOBP**	**Partner Intermediate Event**	The partner intermediate event represents a specific partner's intervention in an activity, started by an authorized partner's decision.	
Process Flow	**Manufacturing**	**Physical Flow**	The physical flow represents the transport/movement of materials (physical objects) between one Flow Element and the next. The transport may occur within (e.g., internal logistics) or between partners.	
Data Object	**IOBP and Cyber-Physical**	**Process Log**	The process log represents data objects to store information retrieved from several traceable tasks and meaningful events.	

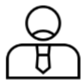
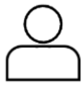
BPMN Concept	Domain	Custom Elements	Description	Graphical Representation
Data Object	**Manufacturing**	**Regulations**	The regulations represent the laws and standards that a specific business partner must follow (e.g., ISO 9001).	
Data Object	**IOBP**	**Private Data Object**	The private data object means that a given data object (or one of its children) is private, meaning that no information on that data is shared with the partners, being kept confidential.	
Data Object	**IOBP**	**Shared Data Object**	The shared data object means that a given data object (or one of its children) is shared: data is accessible to other partners.	
Connected to Task or Flow	**Manufacturing**	**Parts**	Parts are essential elements in industry flows (e.g., parts for coating in our case company). They are used and exchanged between the partners and in manufacturing activities.	
Connected to Task	**Cyber-Physical**	**Processing Devices**	Processing devices are used in process tasks to record information, manage documents, execute algorithms, or analyze data.	
Pool	**IOBP**	**Partnership Manager Pool**	The partnership manager is the main responsible for the execution, monitoring, and management of the IOBP.	
Pool	**IOBP**	**Partnership Participant Pool**	The partnership participant is responsible for executing activities and reporting the agreed information to the partnership manager.	
Task, Gateway	**Cyber-Physical**	**Human Actor**	Represents the tasks and gateways that a human actor may execute.	
Task, Gateway	**Cyber-Physical**	**Co-bot Actor**	Represents the tasks and gateways that a co-bot actor may execute.	
Task, Gateway	**Cyber-Physical**	**Robot Actor**	Represents the tasks and gateways that a robot actor may execute.	
Task, Gateway	**Cyber-Physical**	**Sensor**	Represents sensors used in tasks or incorporated in resources, enabling the retrieval of data and traceability of tasks and resources.	

Table 1 presents 22 elements that compose the IOBP 4.0 extension. The table adapts elements from BPMN extensions proposed for manufacturing (e.g., production task, quality management task, logistics task, parts) [15] and IOBP (e.g., private task, traceable task, collaborative task, private data, shared data) [3]. Our contribution adds a new group of cyber-physical elements that are pillars of Industry 4.0 (e.g., robot actor, human actor, co-bot actor, processing devices, physical flow, sensor) and IOBP elements (e.g., partnership participant pool, partnership manager pool, partner intermediate event, partner gateway, touchpoint task, process log). We developed the BPMN extension elements using Lucidchart [24] and its icon library, aiming to support the representation of the IOBP 4.0 concepts. In Section 5, we demonstrate the use of the IOBP 4.0 extension in the case company.

5. Demonstration

Fig. 3 shows the manufacturing process of the case company modeled using standard BPMN. Two partners (A and B) are involved.

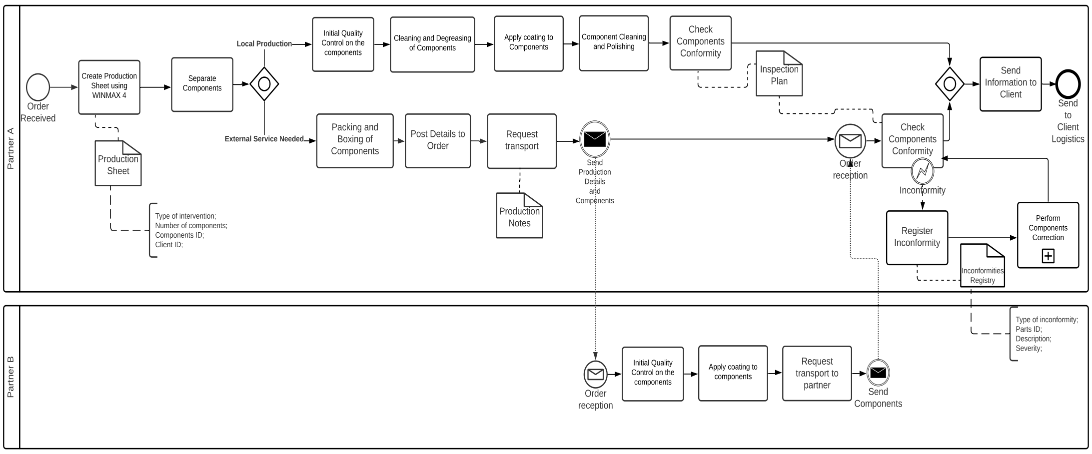


Fig. 3. Coating Process Model using BPMN.

The company coats metal components used in process industries (e.g., energy, oil, and paper). Partner A triggers the business process's execution (event order received), creates the production sheet using specific software, and separates components for internal and/or external production. In the latter, the components need to be sent to partner B. Partner A performs preliminary quality control, followed by the cleaning and degreasing tasks. Afterward, the components follow the (1) coating, (2) cleaning, and (3) polishing. The outsourced components are packed, and the order details are attached before shipment.

Partner B performs a quality check, executes the work (specific coating in which they are experts), and returns the product to Partner A. All the components are submitted to a conformity check before final shipment to the customer. If necessary, partner A deals with the necessary corrections. If the components are in conformance, the client is informed of the process's conclusion, and the components are sent to client logistics.

Fig. 4 shows the same process modeled with the proposed IOBP 4.0 extension.

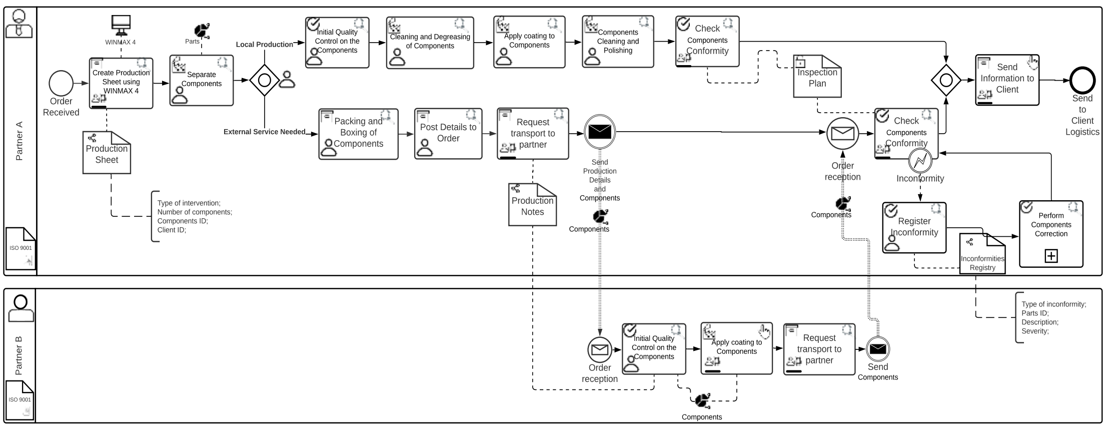


Fig. 4. Coating Process Model using IOBP 4.0 extension.

New layers of information are visible in the extended model of Fig. 4, which cannot be represented with the standard BPMN notation used in Fig. 3. The extension is more precise about process participants' roles (pools), identifies the key manufacturing activities and the digital elements in different parts of the business process: partner A is the business process coordinator, and both partners are IS0-9001 certified (new elements in the pools). Partner A monitors both partners' activities (e.g., initial quality control of the components, request transport to partner) and receives a real-time status of the production (e.g., apply the coating to component). Multiple documents are shared between the partners (e.g., production sheet, production notes), while others are kept private (e.g., inspection plan). The tasks are classified according to the type of operation in the context of quality (e.g., preliminary quality control on the components, check components' conformity, register non-conformity), production (cleaning and degreasing of components, application of coating to components), and logistics (e.g., packing and boxing of components, requesting transport to partner). Robots may partially or fully automate tasks. Examples of IOBP 4.0 use cases are included in Appendix A.

6. Evaluation

The proposed BPMN extension shares the same principles of the standard BPMN and provides an answer to the need to represent inter-organizational business processes in increasingly digitalized manufacturing contexts. Several improvements occur in the model intelligibility and detail of the specification.

Model completeness is one of the most immediate advantages of IOBP 4.0 over the classic BPMN. First, the proposed extension introduces representative elements of the private/shared data and activities (e.g., the inspection plan is a private document, the production sheet is shared among the partners). Second, the new elements, aligned with the core BPMN standard, represent the key manufacturing stages (e.g., apply the coating to components is a production task, check components conformity is a quality management task). Third, the technology strategy on Industry 4.0 becomes visible (e.g., conformity check of the components is executed by humans and robots). Fourth, the entire business process is integrated into a single model instead of disjoint models from different partners, using different notations. The IOBP 4.0 process model can be used as a tool for joint innovation efforts, enabling to identify (internal/external) improvement opportunities by any of the involved organizations. Fifth, the IOBP 4.0 process models can be leveraged for training and onboarding new staff (e.g., making IT experts aware of the existing infrastructure, assisting operators in their contacts with third-party entities). Lastly, the process models can be adopted in internal audits, increasing transparency of the responsibilities, activities, internal/external interactions, and technology investments. Therefore, IOBP 4.0 contributes to an enhanced perception of each partner's contribution.

It is also interesting to contrast the proposed IOBP 4.0 extension with UML. Although there are some similarities with UML activity diagrams, UML is an object-oriented notation primarily focused on modeling and documenting software systems (e.g., web applications, database architecture). Therefore, BPMN extensions may be more accessible to different organizational experts (e.g., business analysts, manufacturing technicians) interested in the design of "as-is" and "to-be" business processes. IOBP 4.0 can be helpful in process improvement initiatives that require a descriptive notation of the domain.

Our evaluation of this real-world case in the coating company also revealed weaknesses in our IOBP 4.0 proposal. First, the additional information increases the complexity and readability of the process models compared to the standard BPMN elements. The absence of clear guidelines regarding what to include may result in overloaded models, more difficult to understand by the practitioners. The problem is not so severe when dealing with quality experts (used to ISO 9001 process models), but other stakeholders (e.g., operators) may face increased difficulties. Second, the current version of the extension does not identify the state of process transformation. For example, if the specific technology (e.g., IoT infrastructure, app, machine learning model used to support decision making) used in activity X is already deployed or under development. Industry 4.0 adoption is dynamic, so it would be essential to identify the maturity of specific elements (e.g., a task executed by a human but might be executed by a robot in the future).

The team identified two main avenues that could lead to overcoming the limitations. First, inspired in the enterprise architecture field and the ArchiMate [34], it would be possible to separate the process model in views (e.g., digital transformation view for showing only the technology, omitting the IOBP-related data; IOBP view hiding the technology layer). Testing the complete process's visualization or only a part of its layers will be interesting. Second, the Industry 4.0 maturity level could be represented by a number (e.g., maturity stage ranging from 1-Explorer to 4-Expert) in each element of IOBP 4.0. Several maturity models could be experimented with to improve IOBP 4.0 (e.g. [31]).

7. Conclusion

This paper reports a DSR cycle aiming at creating and evaluating a BPMN extension to model inter-organizational business processes in the context of Industry 4.0. This cycle included reviewing relevant literature at the intersection of Industry 4.0 and IOBP and the design and evaluation of the proposed BPMN extension in a real-world case. The contributions include (1) a domain ontology of IOBP 4.0, (2) the graphical representation of the IOBP 4.0 extension concepts, and (3) a demonstration of the use of the proposed extension in a real-world case.

For the next steps of the project, the goal is to continue testing the extension with other industrial companies and improve the artifact according to the limitations found in the evaluation, namely, creating IOBP 4.0 views and incorporating a maturity model assessment. In addition, it will also be essential to assess the social implications of using IOBP 4.0 for different partners. IOBP 4.0 can be helpful for standards-certified companies adopting a process approach to management, like ISO 9001, to disclose their processes and third-party collaborations. IOBP 4.0 may also help in the coordination of distributed manufacturing processes that are at the core of Industry 4.0 transformation. In the future, the IOBP 4.0 models can be attached to contractual agreements and become a central tool to collaboratively design, change, and promote shared innovation practices.

There are also limitations in our DSR that we need to state. First, the artifacts produced in this cycle are essential to model IOBP 4.0, but we do not yet have evidence about the proposed approach's benefits to model IOBP 4.0 for the entire collaborative network. Second, the company that participated in our work is not representative of the entire industry. Future DSR cycles need to integrate distinct companies adopting Industry 4.0. Third, the main target of this DSR cycle was manufacturing related IOBP 4.0. However, the model can be extended or adapted to IOBP executed in other relevant sectors and other digital transformation strategies (e.g., health 4.0). Finally, the domain concepts and ontology were identified based on a literature review and process documentation analysis in a single company. It would be interesting to conduct industrial surveys to understand the most relevant layers that could also be added and other elements that may be missing.

Acknowledgements

This work is funded by national funds through the FCT-Foundation for Science and Technology, I.P., within the scope of the project CISUC-UID/CEC/00326/2020 and by European Social Fund, through the Regional Operational Program Centro 2020.

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Appendix A: Examples of IOBP 4.0 Use Cases

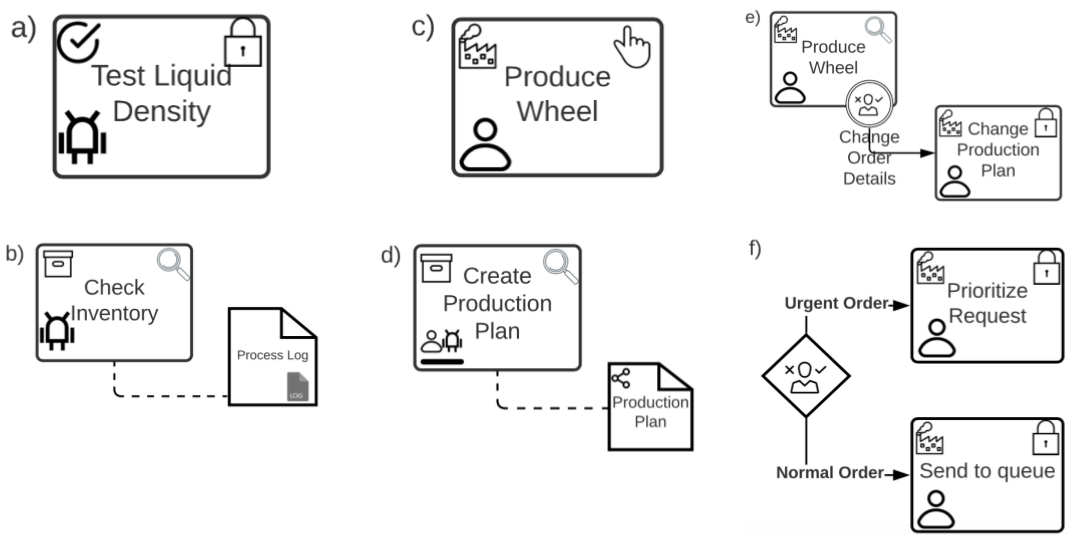

Fig. 5. Examples of IOBP 4.0 Use Cases.

The use case a) included in Fig. 5 presents a private quality management task executed by a robot. Use case b) shows a traceable logistics task executed by a robot and using process log data. Use case c) (in the middle) presents a touchpoint production task executed entirely by hand. Use case d) introduces a traceable logistics task executed by a co-bot. The output is a shared production plan document. Use case e) illustrates a traceable logistics task executed by humans. The partnership manager may intervene during task execution by requesting the change of the order details. Therefore, the production plan is changed in a private production task performed by a worker. Finally, use case f) depicts a priority decision made by the partnership manager.