Vítor Hugo Machado Ribeiro

Inter-Organizational Business Processes in the Industry 4.0 Era

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Dissertation in the context of the Master in Informatics Engineering, Specialization in Software Engineering, advised by Professor João Nuno Lopes Barata, co-advised by Professor Paulo José Osório Rupino da Cunha and presented to the Faculty of Sciences and Technology / Department of Informatics Engineering.

June 2021

Faculty of Sciences and Technology
Department of Informatics Engineering

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Abstract

Industry 4.0 calls for end-to-end digital integration of supply chains and a new boundary-spanning logic of process design. It is a shift from shared operation to shared transformation. Hence, business processes are increasingly digitized and decentralized in companies adopting Industry 4.0. This dissertation proposes and evaluates a Business Process Modelling and Notation (BPMN) extension to deal with these challenges. Design science has been selected as the research approach to identify several attributes and requirements for Inter-Organizational Business Processes in Industry 4.0 (IOBP 4.0), propose a Conceptual Domain Model of the Extension (CDME) and a graphical representation of the extension concepts. 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 dissertation starts with a literature review on inter-organizational business processes, business process management, business process modelling, Industry 4.0, and BPMN. Next, the steps of the design of the IOBP 4.0 BPMN extension are presented, followed by the new extension elements. Next, a proposal of an approach for IOBP 4.0 business process improvement, based on the Plan-Do-Check-Act (PDCA) approach and the proposal of design guidelines for the use of the IOBP 4.0 extension in modelling activities. Finally, a demonstration and evaluation of the extension in two case companies is presented.

The final results of this dissertation are relevant to assist in the industry's digital transformation with increasingly shared, digitalized and decentralized business processes by introducing an extended notation for the modelling of IOBP 4.0. For theory, this work will contribute to the BPM logic of digital transformation: support for coordinated touchpoints, flexible manufacturing and technological infrastructure, and empowered participants. For practice, it proposes an approach to model IOBP 4.0 that ensures manufacturing visibility and supports shared process innovation. Managing the punctuated equilibrium of boundary spanning business processes will be a priority for this decade.

Keywords

Industry 4.0, Digital Transformation, Inter-Organizational Business Processes, Business Process Management, BPMN, BPMN Extension, Collaborative Networks

Resumo

A Indústria 4.0 exige integração digital ponto a ponto das cadeias de abastecimento e uma nova lógica de processo de negócio que ultrapassa os limites das organizações. A mudança é de uma operação partilhada para uma transformação partilhada. Os processos de negócio são cada vez mais digitalizados e descentralizados em empresas que adotam a Indústria 4.0. Esta dissertação propõe e avalia uma extensão de Business Process Modeling and Notation (BPMN) de modo a responder a estes desafios. Como metodologia de trabalho foi selecionado o design science research, de modo a identificar diversos atributos e requisitos para a modelação de processos de negócio inter-organizacionais na Indústria 4.0 (IOBP 4.0), propor um Modelo de Domínio Conceptual da Extensão (CDME) e uma representação gráfica dos conceitos de extensão. A extensão proposta fornece uma descrição integrada de (1) elementos privados/partilhados do processo, (2) fases de produção local/distribuída e (3) estratégia de incorporação de tecnologia na rede de produção.

A dissertação começa com uma revisão da literatura sobre processos de negócio inter-organizacionais, gestão de processos de negócio, modelação de processos de negócio, Indústria 4.0 e BPMN. A seguir, são apresentadas as etapas desenvolvimento da extensão BPMN IOBP 4.0, seguidas dos novos elementos de extensão. De seguida é apresentada uma proposta de abordagem para melhoria de processos de negócio IOBP 4.0, baseada na abordagem Plan-Do-Check-Act (PDCA) e ainda uma proposta de diretrizes para a utilização da extensão IOBP 4.0 em atividades de modelação de processos de negócio. Por fim, é apresentada uma demonstração e avaliação da extensão em duas empresas.

Os resultados finais desta dissertação são de grande importância de modo a prestar auxilio na transformação digital do setor da indústria, com processos de negócio cada vez mais digitais e partilhados. Para a teoria, o trabalho contribui para a lógica de gestão de processos de negócio, na área da transformação digital, recentemente introduzida no campo de SI: suporte para pontos de contato coordenados, infraestrutura tecnológica flexível e participantes capacitados. Para a prática, é proposta uma abordagem para a modelação de IOBP 4.0 que garante a visibilidade das atividades de manufatura e oferece suporte à inovação de processos partilhados. A gestão do equilíbrio pontuado dos processos de negócio que abrangem as fronteiras de diversas organizações será uma prioridade para esta década.

Palavras-Chave

Indústria 4.0, Transformação Digital, Processos de Negócio Inter-Organizacionais, Gestão de Processos de Negócio, BPMN, Extensão BPMN, Redes Colaborativas

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Contents

Acronyms

BAM Business Activity Monitoring

BPM Business Process Management

BPMN Business Process Modelling Notation

BPMS Business Process Management System

CDME Conceptual Domain Model of the Extension

CPS Cyber-Physical Systems

DEI Departamento Engenharia Informática

FCTUC Faculty of Sciences and Technology of the University of Coimbra

FEDS Framework for Evaluation in Design Science Research

I4.0 Industry 4.0

ISG Information Systems Group

IOBP Inter-Organizational Business Process

IOBP 4.0 Inter-Organizational Business Processes in Industry 4.0

IoT Internet of Things

OMG Object Management Group

PDCA Plan-Do-Check-Act

RE Requirements Engineering

UML Unified Modelling Language

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Chapter 1
Introduction

This document reports the work carried out within the curricular unit of Internship/Dissertation, which took place under the supervision of Professor João Nuno Lopes Barata and Professor Paulo José Osório Rupino da Cunha. The dissertation is part of the Masters degree in Informatics Engineering (MEI) with specialization in Software Engineering, in the Department of Informatics Engineering (DEI) of the Faculty of Sciences and Technologies of the University of Coimbra (FCTUC).

Section 1.1 introduces the institutions involved in this project. Section 1.2 presents the context and motivation of this dissertation. Section 1.3 explains the main goals of this dissertation. Section 1.4 presents the tools used in the development of the project. Section 1.5 describes the structure of this document.

1.1 Involved Institutions

The development of this project was proposed by the Information Systems Group (ISG) of the Department of Informatics Engineering of the Faculty of Sciences and Technology of the University of Coimbra (DEI/FCTUC) [1]. External organizations cooperated in the development, testing, and evaluation of the proposed BPMN extension during the second semester.

ALTRI is a leading Portuguese eucalyptus pulp producer and one of the most efficient in Europe [2]. The company owns several factories and lands across the country, raising the need to manage a considerable number of resources and establishment large collaborative networks.

Escudo Iberia [3] is a small technical metal coatings provider. Coatings aim to increase the durability of components and are particularly relevant to process industries (e.g., petrochemical, automotive).

1.2 Context and Motivation

Business process management (BPM) has enabled organizations to move beyond functional boundaries [4]. Much has changed since the pioneer contributions of BPM in the past decades, and the boundaryless nature of business processes has been reinforced. In the era of digital transformation in the industry, cooperation, communication, and integration [5] within and between organizations is a top priority. Therefore, process models representing "how work is done" must support downstream planning of operations, upstream assessment, and decentralized continuous improvement.

Digital transformation requires a new logic for business process management (BPM). The work of [6] 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 [7].

Industry 4.0 is leveraged by multiple technologies such as the Internet of Things (IoT), cyber-physical systems, cloud computing, mobile systems, or artificial intelligence that are shaping the modern smart factory infrastructure [8]. The overall aim is to integrate and digitalize distributed business processes and redesign supply chains [5], [9]. For example, a company may be manufacturing the wheel of a bicycle, while, at the same time, their partners produce frame and saddle area needed to assemble and obtain the bicycle. It is now clear that a new agenda is necessary to promote synergies between BPM and digital innovation in the industry [10], [11]. However, modelling business processes in Industry 4.0 is challenging, requiring new approaches to represent how digitalized companies are changing their operations [12], to represent the new exploited technologies (e.g., machines, sensors, robots) and new activities (e.g., remote activity monitoring, data transmission).

The new BPM logic is also extensible to the supply chain. On the one hand, by creating a technological infrastructure to decentralize production, providing visibility to product flows since the early stages of sourcing raw materials to product use. On the other hand, by requiring more "effectiveness of communication between actors and favoring data collection and sharing" [25]. 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].

The "modular, distributed, collaborative, and product-service-oriented I4.0 architecture" [13] highlights the need to manage Inter-Organizational Business Processes [14]. The study presented by Kunchala, Yu, Yongchareon and Liu [15] is an example of this trend. The authors present an approach to merge different process models collaborating in the production of artefacts. However, the resulting process models are often incomplete (e.g., some parts may be private) and difficult to share in organizations "that operate, cooperate, and compete in a world permeated with digital technology" [16].

Business process models enable the design, documentation, analysis, and optimization of business processes. BPMN is one of the main standards in process modelling, including elements like tasks, events, and data objects [17]. However, BPMN is not able to represent all the details of particular domains (e.g., healthcare, finances) [18], such as inter-organizational practices [19]. Examples of shortcomings are the formal specification of processes interfaces [19] and the semantics of dependencies that describe control flows [20]. The need to align the interests of multiple process partners [19] makes BPMN extensions a promising solution [21], [22].

Contacts with industry managers revealed that rudimentary practices are still the norm, with process models (1) created independently by each organization in the supply chain, (2) supported by separate documentation (e.g., procedures and requirement lists), and (3) lacking a boundaryless approach to the design, improvement, and audit of IOBP. Moreover, despite the ISO 9001 requirements to adopt a process approach [23], the traditional focus of quality audits tends to be the internal documentation, missing crucial details in distributed environments.

1.3 Goals

This project aims to enrich BPMN with an extension and design guidelines to support industrial digital transformation of organizations. More precisely, shaping Inter-Organizational Business Processes in Industry 4.0 (IOBP 4.0), towards a more complete and rigorous representation of these business processes. As previously stated, the main goal is to produce an extension that allows the representation of IOBP, considering the lack of specification in the current BPMN standard and other existing approaches. An evaluation procedure with partner companies is also considered a key point to the development of the extension.

The thresholds of success for this dissertation are fourfold: (1) a comprehensive state-of-the-art on industry 4.0, inter-organizational business processes, BPM and BPMN; (2) the proposal a BPMN extension that can be used to represent inter-organizational business processes in the industry 4.0 era; (3) the testing and evaluation of the proposed BPMN extension in real cases of organizations adopting industry 4.0 and involved in distributed collaborative networks; (4) a set of guidelines for the use of proposed extension in modelling activities.

It is also a goal of this project the production of scientific publications regarding the proposed BPMN extension and an approach to adopt it in industry.

1.4 Tools

For the execution of this project, several tools have been used, to support the activities, from business process modelling to the writing of this dissertation. For the writing of the dissertation, the intermediate report and scientific papers, the Microsoft Word [24] was used. For the creation of business process models in BPMN, the BPMN extension and creation of other necessary diagrams, two tools were used: Lucid Chart [25] and Diagrams [26]. For the remote meetings Skype [27] was used. All the used tools were free of costs, regarding the activation of academic licenses.

1.5 Document Structure

The document is divided in seven chapters, which relate to the work performed during the two semesters of the dissertation. This project evolved in three essential phases. The first one, was concerned with the planning of the work as well as a literature review on relevant concepts of this dissertations (Chapters 2 and 3). The second phase presented the design of the solution to solve the several problems and challenges that exist while modelling inter-organization business processes in the era of I4.0 (Chapter 4). The final phase was concerned with the testing and evaluation of the proposed BPMN extension in two case companies. Figure 1 introduces an overview of the several phase throughout the semesters and the developed chapters in each phase.

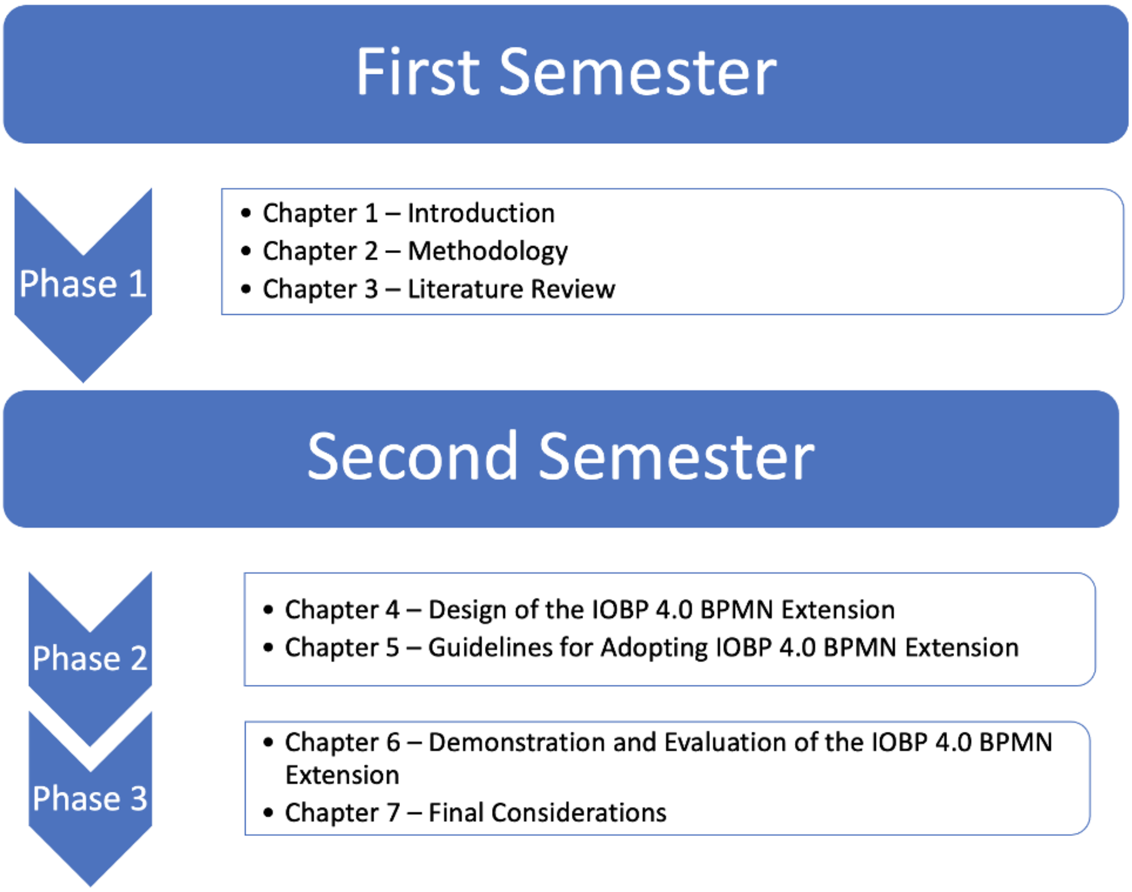


Figure 1 – Overview of the Dissertation's Phases

This dissertation is structured according to the following sections:

- Introduction (Chapter 1): This chapter introduces the context and motivation of this dissertation. Next, the success criteria are stated, followed by the presentation of the involved entities and the structure of this dissertation.
- Methodology (Chapter 2): This chapter presents and describes the temporal planning of this dissertation. Next, is presented the methodology used for the development and evaluation of the solution to address the existing problem, the steps of the literature review, the contacts with the case companies, and the project practices related to the development of the project, time estimation and risk management.
- Literature Review (Chapter 3): This chapter presents a literature review on several important aspects for the development of this dissertation. These concepts are particularly relevant for understanding the context of I4.0, BPM, Inter-Organizational Business Processes, and the challenges that may arise considering these factors.
- Design of the IOBP 4.0 BPMN Extension (Chapter 4): This chapter presents a solution developed to fulfil the existing gap while modelling inter-organizational business processes in the industry 4.0 era. This chapter assumes a key role in summarizing the executed activities to develop the extension, the references found in the literature review and the contacts with industry experts in the case companies. The proposed work extends the standard BPMN with additional concepts, to integrate new information and towards the completion of the models.

- Guidelines for Adopting IOBP 4.0 BPMN Extension (Chapter 5): It introduces an approach for the use of the IOBP 4.0 BPMN extension in business process modelling activities, presenting a set of examples and guidelines for the design of business processes. Then, an approach for the implementation of continuous improvement strategies in IOBP 4.0 is introduced.
- Demonstration and Evaluation of the IOBP 4.0 BPMN Extension (Chapter 6): This chapter refers to the activities performed in the testing, demonstration, and evaluation of the proposed BPMN extension. The several activities executed with the partner companies are presented, focusing on the modelling activities of existing business processes and the retrieval of feedback from the industries' experts. The chapter ends with an analysis of the results and reflection on the impact of the proposed extension in the industry.
- Final Considerations (Chapter 7): This chapter summarizes the final conclusions, providing a critical reflection on all the work developed during this dissertation. The chapter closes with the statement of the limitations and suggestions for future research in the field.

This chapter presented the motivations and goals of this dissertation, followed by the presentation of the overall structure of this document. First, the involved institutions were introduced. Next, the context and motivation of this dissertation were presented, focusing on the introduction of relevant concepts, such as I4.0 and IOBP, the existing problem and its context. Afterwards, the goals of this dissertation and the tools used to execute the several activities are described. Finally, the chapter ends with the introduction of the overall structure of the document, with a description of the content of each chapter.

The next chapter presents the research methodology and planning of this dissertation.

Chapter 2
Methodology

This chapter presents the methodology and the work plan for the dissertation development over two semesters. Section 2.1 describes the work plan. Next, section 2.2 introduces the research methodology, focusing on the literature review process and the methodology selected for the project development. Section 2.3 explains the field intervention and companies collaborating in this project. The chapter ends with the risk management strategy and mitigation plan (Section 2.4).

2.1 Work Plan

This section presents an overview of the work plan, detailing the several tasks developed during the two semesters, from the literature review to the proposal and evaluation of the BPMN extension in real cases.

For the first semester, the following tasks were originally defined in the dissertation proposal:

- [September 2020, duration 1 month] - Research the state-of-the-art: industry 4.0 and BPM, inter-organizational business processes.
- [October 2020, duration 1 month] - Study BPM 2.0 specification and the development of BPMN Extensions.
- [November 2020, duration 1 month] - Initial draft of BPMN extensions for inter-organizational business process modelling in industry 4.0.

The expected results for the first semester were (1) a literature review about the most relevant concepts and methods available to develop BPMN extensions and (2) the intermediate report.

In the first semester, the following tasks were planned and executed:

1. **Planning of the First Semester**: Define the schedule and the structure of the work to be developed in the first semester. The task was executed in 11 days.
2. **Risk Analysis and Monitoring**: Elaboration of the risk management activities on the project scope, considering all the stakeholders, constraints, and restrictions, with the development of mitigation plans, impact evaluation, and probability of each of the identified risks. The task was executed in 72 days.
3. **Literature Review on I4.0**: Understand the foundations of I4.0 and its technology enablers. For example, the Internet of Things, Smart Factories and the requirements to implement these systems, and the impact of I4.0 in organizations. The task was executed in 25 days.
4. **Literature Review on BPM Concepts**: Identify relevant concepts to the development of the BPMN models and extensions. For example, BPM principles, Business Process Modelling principles and a review on technical implementation of extensions in BPMN. The task was executed in 25 days.

5. **Literature Review on IOBP**: Research the opportunities to develop IOBP in the context of I4.0: from the definition of this concept to the several challenges that arise from its development and deployment. This analysis set the basis for the development of the BPMN extension. The task was executed in 25 days.
6. **Study of the BPMN Extension Mechanism and Methodology**: Identify the requirements, examples, and methodologies to develop BPMN extensions. The task was executed in 26 days.
7. **Develop BPMN Extension Drafts**: Development of the first of drafts of the BPMN extension, regarding the first proposal of CDME for IOBP 4.0 and the identification of several domain attributes, based on the literature review. The task took 25 days to be executed.
8. **Writing of the Intermediate Report**: Compilation and presentation of the work developed in the first semester and the planned activities for the second semester. The task was executed in 65 days.
9. **Planning of the Second Semester**: Define the schedule and the structure of the work to be developed in the second semester. Establish contacts with companies to confirm participation in the development and testing of the BPMN extension The task was executed in 15 days.

Figure 2 presents the timeline of the activities planned and executed in the first semester, introducing the time of execution for each activity as well as the dates in which the activities were executed.

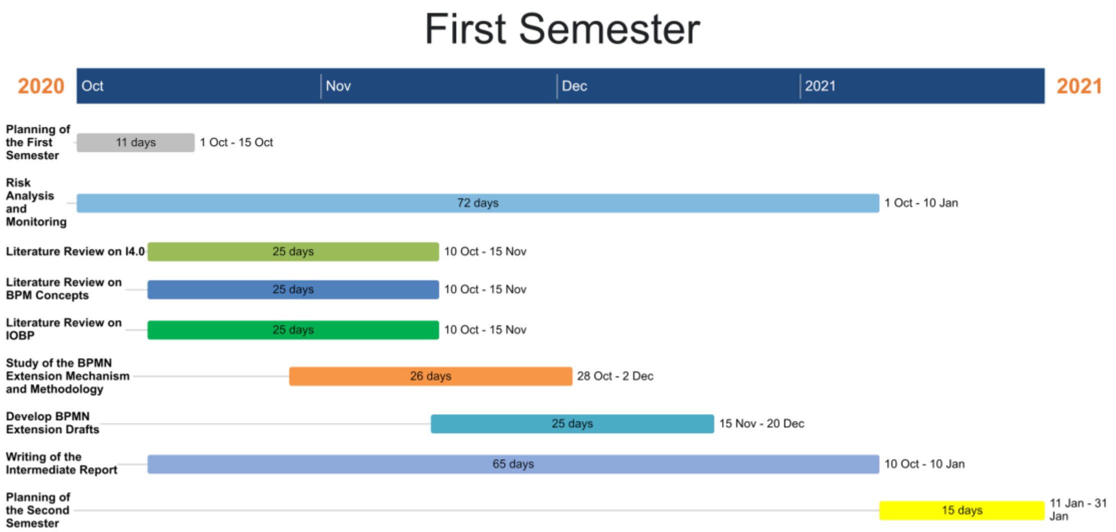


Figure 2 – First Semester Planning

The literature review on BPM, IOBP, and BPMN allowed the identification of some of the gaps to be fulfilled in the development of the extension. Moreover, several attributes and requirements for the modelling of IOBP 4.0 were identified. The study of the BPMN extension mechanism allowed the identification of the key activities to develop an extension and the planning for the second semester. The planned schedule for the first semester was completed on the expected dates.

The first semester ended with the presentation of the intermediate report to the jury of the dissertation.

The initial plan (in the dissertation proposal) for the second semester aimed to propose an approach to model IOBP using the BPMN extension mechanism. Afterward, test it in a real setting with the participation of pilot companies adopting I4.0. The following tasks were defined for the second semester:

- [January 2021, duration 3 months] – Development of an approach to model inter-organizational processes using BPMN 2.0 extensions.
- [April 2021, duration 1 month] – Tests with pilot companies involved with industry 4.0 investments.
- [May 2021, duration 2 months] – Writing of the thesis and submission of a scientific paper explaining the proposed approach to model IOBP in I4.0.

The second semester was dedicated to the development and evaluation of the BPMN extension in collaboration with the partner companies. The following tasks were planned and executed in the second semester:

- **Planning of the Second Semester**: Control the schedule and the structure of the work to be developed during the second semester. The task was executed in 11 days.
- **Risk Analysis and Monitoring**: Risk monitorization on the previously identified risks and the identification of potential new risks. The task was executed in 55 days.
- **Development of the BPMN Extension**: This task was dedicated to the development of the BPMN extension according to the defined methodology, in collaboration with the partner companies. The task was executed in 43 days.
- **Demonstration and Evaluation of the proposed BPMN Extension**: This task involved the testing of the BPMN extension by executing modelling activities and retrieving feedback from the experts in the partner companies certified by the ISO 9001. It was also an objective to analyse the practical adoption of the proposed BPMN extension with the companies. During the testing phase, several adjustments were made to the extension regarding the received feedback from industry experts. The task was executed in 43 days.
- **Writing of the scientific publication #1**: Production of a scientific paper regarding the possibilities of the proposed BPMN extension to support and execute business process improvement activities. The task was executed in 20 days.
- **Writing of the scientific publication #2**: Production of a scientific paper explaining the proposed approach to model IOBP in I4.0 and presenting a case study in one of the partner companies. The task was executed in 34 days.
- **Writing of the dissertation**: Writing of the dissertation, reporting the developed BPMN extension and all the activities that supported the study. The task was executed in 105 days.

Figure 3 presents the timeline of the activities planned and executed in the second semester, introducing the time of execution for each activity as well as the dates in which the activities were executed.

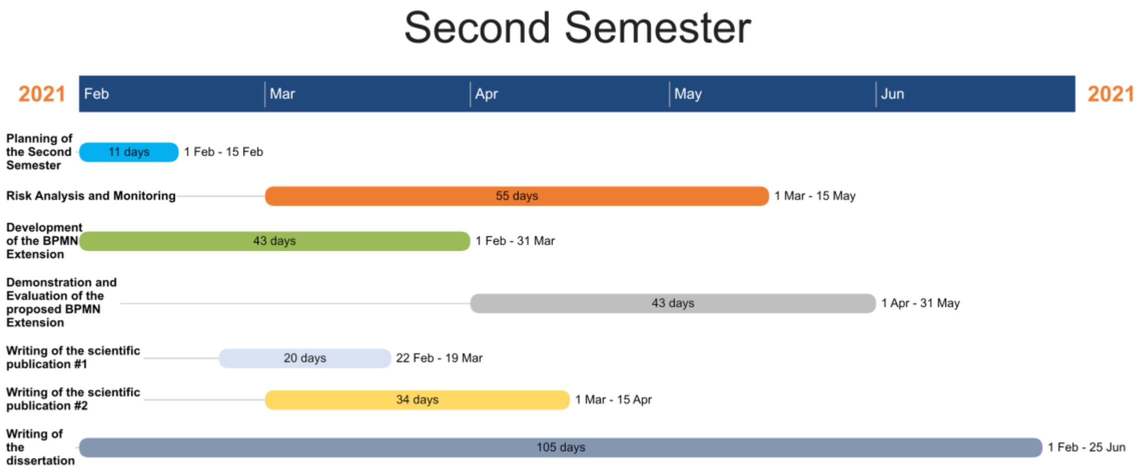


Figure 3 – Second Semester Planning

Despite the changes in the initial planning, the objectives for the second semester were accomplished with no relevant delays.

During the development of this dissertation the writing of a research diary and week report provided support for the monitorization of the development of the work.

2.2 Research Methodology

2.2.1 Literature Review Process

The literature review was an essential step for the development of this dissertation, regarding the need to identify the requirements for modelling IOBP 4.0. In a first phase, there was the need to do some research on the field of I4.0, BPM, and IOBP. This step also allowed us to search existing approaches to model I4.0 and IOBP scenarios. Secondly, the literature review allowed us to do research on the BPMN extension mechanism, to understand how it works and to identify approaches for the design of BPMN extensions.

The sources for the literature review included scientific articles, journals, books and conference proceedings in the field of Information Systems. The main search database was Google Scholar, where it was intended to find a diverse portfolio of documents with a great number of results, with different levels of importance and recognition, exploring the several approaches on the topics and recent works. The search approach using Google Scholar excluded citations and patents. The keywords used at this stage were:

- "BPMN extension" AND ("industry 4.0" OR "digital transformation") – 80 results in Google Scholar
- "BPMN extension" AND ("inter-organizational business process" OR "interorganizational business process") – 10 results in Google Scholar
- "industry 4.0" – 3220000 results in Google Scholar
- "inter organizational business process" OR "inter-organizational business process" OR "inter organizational business process" OR "inter-organisational business process" – 1020 results in Google Scholar
- "business process management" – 3310000 results in Google Scholar

- "business process models" – 3440000 results in Google Scholar
- "BPMN" – 50 000 results in Google Scholar
- "BPMN extension" – 18000 results in Google Scholar

The literature review focused on articles that presented works in the fields of industry 4.0, BPM, IOBP, and BPMN, with a greater number of citations (sorted by relevance, without restrictions on publication date). The research revealed the importance of concepts like industry 4.0 and BPM in current research in both academia and industry, with a great number of works being presented.

However, the field of BPMN extensions for I4.0 and IOBP revealed as an almost unexplored subject. By combining both BPMN extension and IOBP, only 10 hits were found, in which none of these specifically addressed the context of the BPMN extension to be developed, enhancing the importance and innovation of this project. The research of both BPMN extension and I4.0 returned only 80 hits, in which the field of manufacturing and collaborative networks was insufficiently addressed.

With such a wide range of information, it was necessary to define the concepts of higher interest for this dissertation in fields of industry 4.0, BPM and IOBP. This division of the search allowed us to focus on the synergies of industry 4.0, BPM and IOBP, such as collaborative networks and decentralized operations. This division also enabled a better organization of the research, improved access to the documents, and focus on the most important documentation.

Figure 4 introduces the literature review sequence of this project.

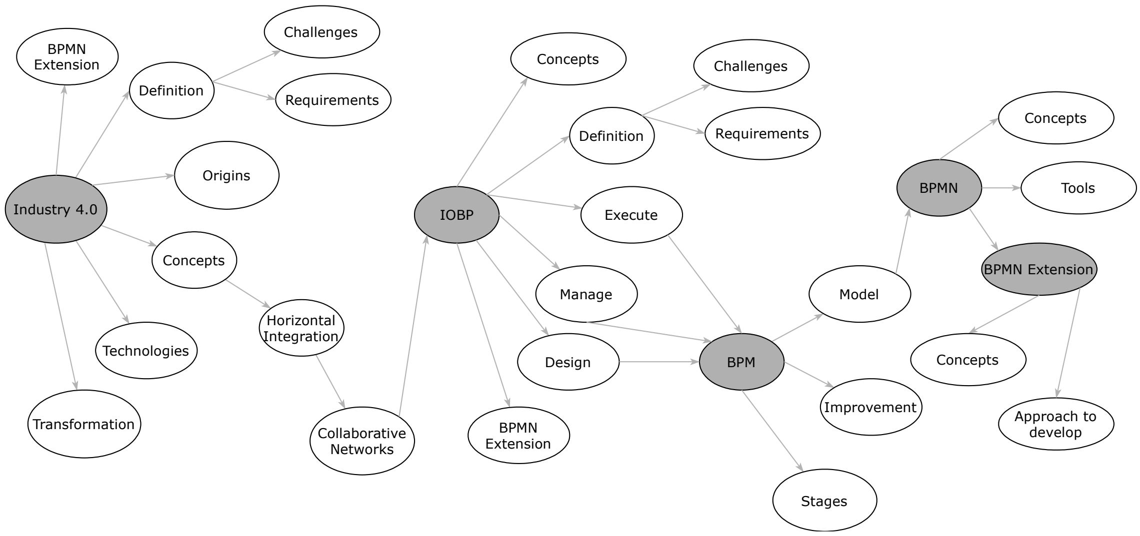


Figure 4 – Literature Review Sequence

Figure 4 summarizes the stages of the review process, starting from the basic industry 4.0 concepts (on the left of figure 4), the exploited technologies, requirements for the modelling and possibilities enabled by the horizontal integration, such as the collaborative networks. The research on IOBP followed, aiming to identify the requirements and challenges for managing and modelling IOBP. The research on the BPM field focused on the stages and approaches to the BPM life cycle and the importance of modelling activities. The search in the field of BPMN focused on the concepts related to the BPMN extension mechanism and the characteristics of the notation. The literature review contributed to the analysis and the understanding of the IOBP 4.0 domain towards the identification of key aspects to be considered while modelling business processes in that context. It was also possible to analyse other contributions in the field of I4.0 and IOBP modelling, intending to identify points for improvement or missing aspects. The literature review also contributed to the study of the BPMN extension fundamentals and the existing approaches to create BPMN extensions.

2.2.2 Design Science Research

The dual goal to develop a new approach to model IOBP in I4.0 and the intervention in real settings required a guiding research approach. Design science research (DSR) was selected since it is a problem-solving paradigm that relies on kernel theories to produce innovative artefacts intended to solve identified organizational problems [28], which is the case of this project as stated in Section 1.2.

DSR consists of a rigorous process to design artefacts to solve observed problems, make research contributions, evaluate the designs, and communicate the results to appropriate audiences [28]. These artefacts may include models, methods, and instantiations, according to the identified problem and context of the situation [28].

In our case, this artefact assumes a main role and importance in DSR, as the research should lead to the production of an artefact created to address the identified problem. Further, the artefact should be relevant to the solution of an important business problem, and its utility, quality, and efficiency must be rigorously evaluated [28], [29]. The development of the artefact should be a search process that draws from existing theories and knowledge to come up with a solution to a defined problem and should be effectively communicated to the appropriate audiences [28], [29].

The authors in [29] suggest an iterative process starting with the problem identification and motivation, define objectives of a solution, design and development, demonstration, evaluation, and communication. The research may involve multiple cycles and entry points that, in the current stage of this project, is the problem-centred initiation. This methodology involves six essential activities, of *Problem Identification and Motivation* (1), *Define the objectives for a solution* (2), *Design and Development* (3), *Demonstration* (4), *Evaluation* (5), *Communication* (6), presented in the following paragraphs and in figure 5 [29]:

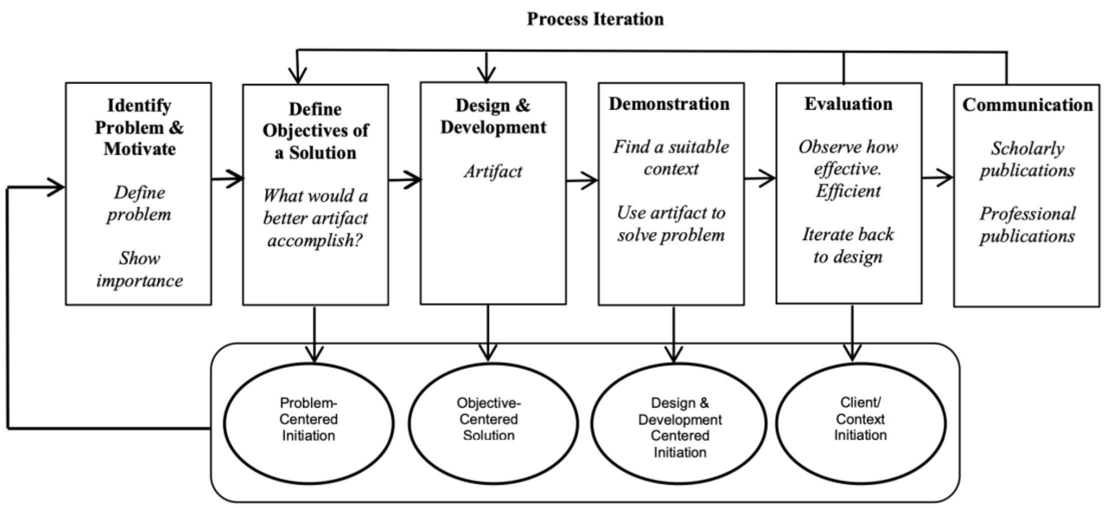


Figure 5 – Design Science Research Methodology Process Model [29]

Problem Identification and Motivation (1) is aimed at defining the specific research problem and justifies the value and importance of a solution. With the problem definition being used to develop an artefact that can effectively provide a solution, it may be useful to fragment the problem conceptually so that the solution can capture its full scope and complexity.

Define the objectives for a solution (2) is aimed to determine the objectives of a solution, based on the problem definition and knowledge of what is possible and feasible in that context. The objectives can be quantitative (the terms in which a desirable solution would be better than current ones) or qualitative (the description of how the new artefact is expected to support solutions to problems not previously addressed).

Design and Development (3) is aimed at creating the artefact. These artefacts may be constructs, models, instantiations, or methods. This phase is also important in determining the artefact's desired functionalities and its architecture. After this, the artefact can be developed and created.

Demonstration (4) is aimed at demonstrating the use of the artefact to solve selected instances of the problem. This step may involve experimentation, pilot studies, case studies, simulations, or proof of concept, according to the context of the problem. For the demonstration, it is required knowledge on how to use the artefact and solve the problem.

Evaluation (5) is aimed at measuring and evaluating how well the designed artefact supports a solution to the problem. This activity may involve comparing the objectives of a solution to actual observed results from the use of the artefact in the demonstration, as previously explained. This phase requires knowledge of relevant metrics and analysis, regarding the comparison approaches and validation mechanisms used (from performance measures to simulations), depending on the nature of the problem venue and the artefact. This phase provides the necessary feedback to produce eventual adjustments and improvements on the proposed artefact, by going back to activity 3.

Communication (6) is aimed at communicating the problem and its importance, the artefact and its utility, the rigor of its design, and its effectiveness to researchers and other relevant audiences.

Despite the process being structured in sequential order, there is no expectation that it should always proceed that way. Depending on the context of the problem and the advances of artefacts, the starting point can vary. In a problem-centred approach, it is common to start with phase one (Problem Identification and Motivation) and refine the objectives before developing the artefacts. An objective-centred solution could be triggered by a company need that can be addressed by developing an artefact for well-known problems. A design and development-centred approach would probably start at step three. A client/context initiated solution may be based on observing a practical solution that worked and would start at activity four [29]. Figure 5 presents the cycle by [29], with several identified phases and entry points.

According to [30], there are six core dimensions for the planning and communication of a DSR project: problem description, solution description, key concepts, input knowledge, output knowledge, and research process. Due to the complex nature of DSR projects, the authors propose a high-level characterization of a DSR project using these six dimensions. The main objectives are to improve "*how DSR projects are scoped, align stakeholders, and to facilitate continuous questioning and readjustment of the project's scope*" [30]. The authors suggest the representation of the six core dimensions in the form of a DSR Grid, allowing a one-page visualization of a DSR project, that is easily adjustable and extendable to the various purposes and contexts of DSR projects. Figure 6 presents the DSR Grid for the development of the IOBP 4.0 BPMN extension.

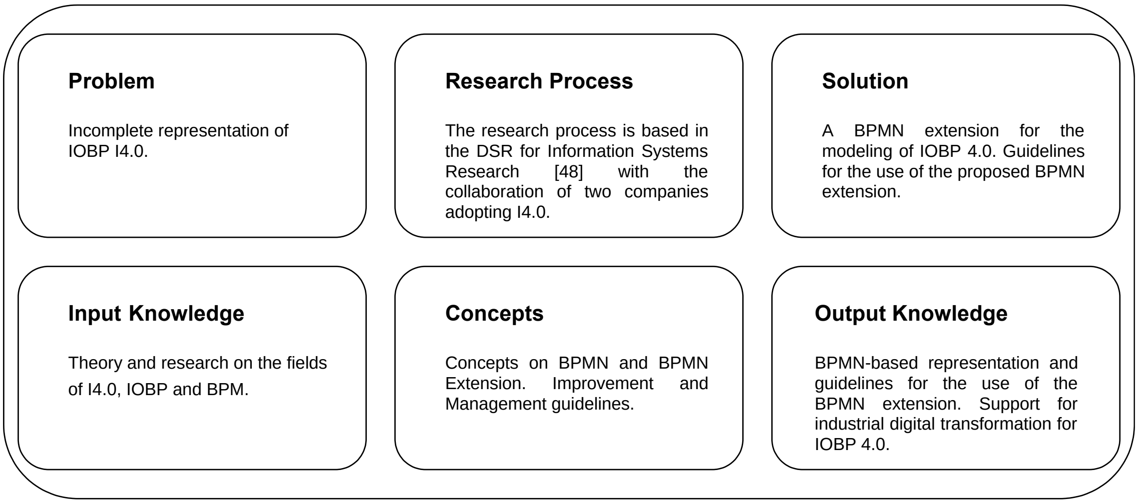


Figure 6 – DSR Grid [30]

The following lines present the six core dimension of the DSR project according to [30]:

- Problem Description: DSR starts with the characterization of the identified problem. Initially, the problem is stated and positioned the problem in a problem space. Then, the problem is described by identifying the domain, the stakeholders, time and place, and goodness criteria.
- Input Knowledge: DSR is supported on existing knowledge that will be used for design. The three essential categories of input knowledge are (1) the kernel theories, (2) the design theories, and (3) design entities. Kernel theories provide theoretical grounding for the artefact [31], which frequently originate outside the IS discipline and suggest novel techniques or approaches to IS design problems [32]. A design theory is a set of principles and knowledge that describes and guides the development of a design artefact to attain a specific goal in the material world [33]. Design entities are design artefacts like constructs, models, design processes, and artefact evolution processes, that are the result of design processes but that can also be applied in design processes [30].
- Research Process: DSR evolves iteratively to create the solution. Therefore, this includes all the activities performed in a DRS project, starting from the literature review, followed by the design and ultimately the evaluation phase.
- Key Concepts: DSR should focus on the concepts used to describe the research, as well as the problem and solution space in which the DSR project focuses, the concepts used to describe the process, and input and output knowledge.
- Solution Description: DSR will deliver mechanisms to create and deploy new solutions. Moreover, it is necessary to be positioned in solution space, by characterizing its representation as a construct, a model, a method, or a design theory.
- Output Knowledge: DSR produces design knowledge obtained from the design process and from the proposed solution.

Figure 7 presents the synthetization of the several stages developed during the DSR project, as well as the outputs and inputs of each of the phase, based on the DSR Grid [30].

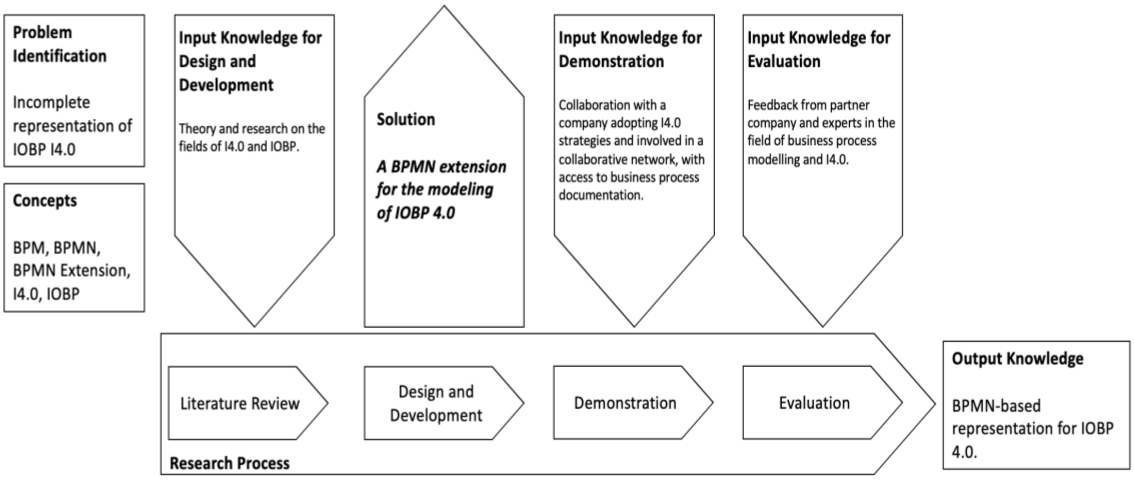


Figure 7 – Design Science Research Methodology Process Model (adapted from [30] and [29]).

The DSR cycle had a problem-centred initiation [29], including contacts with industry experts and a literature review during the first semester. *Problem Identification and Motivation* (1) was the starting point. The activity *Define the objectives for a solution* (2) was also completed during the first semester, with the identification of the requirements for the modelling of industry 4.0 and IOBP scenarios to be fulfilled with the extension. The *Design and Development* (3) started in the first semester, with the elaboration of the drafts regarding the Conceptual Domain Model of the Extension (CDME) and the identification of some of the attributes to be considered in the extension development. At the beginning of the second semester, the development of the extension continued. The *Design and Development* (3) followed the approach proposed by [34] using UML profiles, later improved by [35] with the analysis of the domain and its synthetization [35]. 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). After the equivalence check, the CDME was designed concerning the created domain ontology and the equivalence check. After concluding the design step, it was time to test and evaluate the extension in real-world cases. The *Demonstration* (4) was executed with the two companies, by executing modelling activities with the existing processes. The work with the companies focused on modelling of business processes using the standard BPMN notation and IOBP 4.0 extension, allowing us to test several possibilities and retrieve feedback from experts. The *Evaluation* (5) was executed almost parallelly with the *Demonstration* (4) activities, since the evaluation process took into consideration the results and conclusions of the studies developed in the organizations, to address back to activity 3 and addressing identified problems. The *Communication* (6) activity was fulfilled with the presentation of the results in this dissertation and a scientific publication.

2.3 Field Work

The fieldwork took place in two partner companies. The goal was to establish contacts with industry experts and access valuable business process documentation, allowing the testing and evaluation of the BPMN extension. The first company works on the paper pulp production field. The second company works on the field of coatings.

Altri group [2] is a leading European producer in the pulp sector, being one of the most efficient producers in Europe of bleached eucalyptus pulp. Currently, Altri has three pulp mills – Celbi, Caima and Celtejo – with a nominal annual capacity of more than one million tons. The company is recognized as one of the world's most efficient producers of eucalyptus pulp, being the first in Europe in its industry to receive certification from its Energy Management System, according to ISO 50001 [36]. The company is also ISO 9001 certified. For better forest management, Altri – through its subsidiary Greenvolt – produces electricity from forest biomass, having a total of five power plants. The company is recognized for the high quality of its products, having excellent customer service. Altri is listed in the PSI-20, "a free float market capitalization weighted index that reflects the performance of the maximal 20 most actively traded shares listed on Euronext Lisbon, and is the most widely used indicator of the Portuguese stock market."[37]. The contact for the project development was the IT manager of Altri.

Escudo Iberia [3] provides services with the execution of all types of new solutions in the area of coatings. The company's activity is based on the research and development of solutions for the treatment of industrial components for both rotary and static equipment, as a result of the product specification or R&D operations. By applying the coatings, the goal is to increase the duration of the components and consequent reliability, with a reduction of costs and an increase in overall productivity. The company has established some partnerships for the execution of a specific operation that is not yet available in Escudo Iberia. The company is ISO 9001 certified. The contact for the project development was the industrial manager of Escudo Iberia.

The contacts and meetings with the companies took place remotely. The initial stages aimed to obtain information about the companies' integration in collaborative networks, the existence of decentralized decisions in their supply chain, and shared manufacturing activities. After defining their most relevant IOBP, the companies provided restricted access to their process documentation and process maps. The documentation was used to model the business processes using the standard BPMN and using the extension, for comparison purposes. The business process models were then sent to the companies, which provided feedback on the representation. Their feedback was important to evaluate the acceptance of the extension by the practitioners and proceed with adjustments to the proposed approach.

2.4 Modelling Tool Selection

Several tools are available to model business processes and produce extensions using BPMN, from open source to paid applications, each one having a different set of available functionalities. The available tools offer a great range of functionalities and possibilities to the users, from modelling activities to simulation and integration of Microsoft Office and cloud services. These modelling tools integrate various languages (e.g., UML, BPMN, BPML) to define interactions in a business process. The BPMN tool serves as a repository for business process models. Moreover, its selection is essential for the success of modelling projects [38]. Therefore, the project included an extensive test of different tools.

The tools were selected according to the possibility of accessing a free trial and on the reviews of several websites. Six modelling tools were selected: Microsoft Visio [39], IBM Blueworks [40], Draw IO [26], Lucidchart [25], SmartDraw [41], and Modelio [42]. The applications were then tested, by executing some simple modelling activities and verifying the essential functionalities needed for the project:

- Present the complete set of BPMN 2.0 elements and specification.
- Allow the creation of customized BPMN elements.
- Allow the export of the models in several formats (e.g., PDF, PNG, JPEG).
- Allow the integration of the models in Office applications (e.g., Word, Power Point, Excel).
- Allow the use of collaborative functionalities, such as the simultaneous edition and sharing mechanism.

Table 1 introduces a comparison of the several modelling tools according to the defined criteria. The table resumes the conclusions of the testing activities, that supported the decision of the tool to use in the remaining of the project.

Table 1 – Modelling Tools Comparison

Aspect/Tool	Visio	IBM Blueworks	Draw IO	Lucidchart	Smart Draw	Modelio
BPMN	Yes	No	Yes	Yes	Yes	Yes
Custom Elements	Yes	No	Yes	Yes	Yes	No
Cloud Storage	Yes	Yes	No	Yes	Yes	No
Deployment	Local / Cloud	Cloud	Cloud	Local / Cloud	Local / Cloud	Local
Compatible Models	Yes	No	No	Yes	Yes	No
Price	15€ month per user	44€ month per user*	Free	8,95€ month per user*	99€ year per user	Free
Office Compatibility	Yes	No	No	Yes	Yes	No
Collaboration	Yes	Yes	Yes	Yes	Only Sharing	Not available
Icon Library	Yes	No	No	Yes	No	No

*Educational license available

After reflecting on the testing results, the Lucidchart tool was chosen. The tool presented a complete range of functionalities, allowing the creation of customized BPMN elements by using the available icon library. The application presents the complete BPMN set of elements. The application allows the exporting of models in several types of formats (e.g., PDF, PNG) as well as their integration in Microsoft Office tools (e.g., Word, Power Point). Collaborative functionalities are available, allowing simultaneous edition and an easy sharing mechanism. The application has a free educational license. Appendix A presents a detailed comparison of the tools tested during this work.

2.5 Risk Analysis

Risk management is often defined as the process of identifying, analysing, and responding to any risk that arises over a project by taking a set of actions that help in reducing the probability and the magnitude of the impact of a determined event [43]. Risks may affect the development of a project, causing potential impacts in terms of finances, schedule, or reputation [44].

The first activity is to identify the set of risks that may affect the project. After the identification, the risks must be assessed in terms of probability of occurrence. The magnitude of the consequences of each risk is also evaluated, considering the possible impact on the outcome of the project. Having assessed the impact and probability of each risk, a mitigation plan was developed to eliminate or minimize the impact of that risk. The following classification was considered in this project:

- In terms of probability:
  - High probability – five points.
  - Medium probability – three points.
  - Low probability – one point.
- In terms of impact:
  - Critical impact – five points.
  - Moderate impact – three points.
  - Low impact – one point.

The risk analysis and monitoring were important activities conducted since the first semester. After an initial analysis on the risks, a monitorization of the risks was executed in two days of each week of the project development. In total, seven risks were identified and monitored:

- Focus on Unrelated Topics: The field of Business Process Modelling is vast. It is important to keep the focus on the scope of the research, avoiding unwanted results. The literature review should focus on the synergies of industry 4.0 and IOBP, as well as on relevant concepts for the modelling activities. Periodic reviews of the state of the BPMN extension, to check its equivalence with the domains of IOBP and industry 4.0 can also be considered.
- Imprecise Methodologies to Develop BPMN Extension: There is a lack of available documentation and works on the field of BPMN extensions, which may create difficulties in understanding some of the approaches for the creation of BPMN extensions. Consider works of BPMN extensions in other fields and contacting the advisor for help in understanding the concepts should contribute to the mitigation of this risk.
- Imprecise Scope of the Requirements Analysis: Most of the approaches to develop BPMN extensions include a requirements domain analysis and elicitation phase with the possibility of not identifying all the requirements in this phase and/or identify some in previous phases. The requirements analysis and elicitation must involve a series of iterations, to produce a complete set of requirements.
- Lack of Availability from Partners: Companies and organizations are interested in collaborating to the development of this project, but they may have overwork in critical moments for the research. This may affect the schedule of the project. To mitigate this risk, it is important to establish several communication channels, to promote better and efficient communication and consider alternative organizations to participate in the study.

- Uncertain Utility of the BPMN Extension: Considering that the proposed BPMN extension will the developed and evaluated in organizations, the utility of the extension should be considered, to produce an extension with real value for the companies. To mitigate this risk, consider retrieving feedback from the industry experts in the several steps of the development and evaluation, to consider eventual changes to the extension and keep it according to the needs of the industry.
- Imprecise Evaluation of the BPMN Extension: Considering that the proposed BPMN extension needs to be properly evaluated, there is the need to dedicate some time to the evaluation process. The process of evaluating in organizations can be very time-consuming. The activity needs to be properly planned and executed.
- Difficulties to Access Companies' Documentation: Considering the need to access process documentation in the companies to execute the demonstration and evaluation, there is the risk of access to the documentation being denied. There is the need to guarantee access in proper time or guarantee alternative companies to participate in the studies. Consider companies that are participating (or have participated) in projects with DEI.

The following tables present the characterization of the previously identified risks.

Table 2 – Risk 1, Focus on Unrelated Topics.

Focus on Unrelated Topics	
ID	R1
Date of Identification	October 2020
Description	The fields of BPM and Business Process Modelling has several connections of a great number of domains. It is important to keep the focus on the scope of the research, avoiding unwanted results.
Impact	Low
Probability	Low
Discrimination	1
Risk control and resolution	The literature review should focus on concepts with impact in the modelling activities, such as manufacturing and collaborative contexts . Consider periodic reviews of the state of the BPMN extension, to check its equivalence with the domains of IOBP and I4.0.
Date of Resolution	March 2021

Table 3 – Risk 2, Imprecise Methodologies to Develop BPMN Extension.

Imprecise Methodologies to Develop BPMN Extension	
ID	R2
Date of Identification	November 2020

Description	The BPMN extension mechanism is recent and there is a lack of available documentation regarding this aspect, may create difficulties in understanding some of the methodologies and planning the activities to develop the extension.
Impact	Medium
Probability	Medium
Discrimination	9
Risk control and resolution	DSR has been select as the methodology to develop this project. It is a well-established methodology, that has identified several steps to develop and evaluate artefacts in the field of Information Systems. This methodology is frequently used in scientific papers and information systems thesis [45]. Consider other contributions in the field of BPMN extensions.
Date of Resolution	February 2021

Table 4 – Risk 3, Imprecise Scope of the Requirements Analysis.

Imprecise Scope of the Requirements Analysis	
ID	R3
Date of Identification	November 2020
Description	Most of the approaches to develop BPMN extensions include a Requirements Domain analysis and elicitation phase. There is the possibility of not identifying all the requirements in this phase and/or identify some in previous phases, by relying mostly in a literature review.
Impact	Medium
Probability	Medium
Discrimination	9
Risk control and resolution	The requirements analysis and elicitation must involve a series of iterations, to produce a complete set of requirements. The partner companies may be involved to identify the requirements.
Date of Resolution	April 2021

Table 5 – Risk 4, Lack of Availability from Partners.

Lack of Availability from Partners	
ID	R4
Date of Identification	October 2020
Description	Companies and organizations are interested in collaborating to the development of this project, but they may have overwork in critical moments for the research. This may affect the schedule of the project.
Impact	Medium
Probability	Medium
Discrimination	9
Risk control and resolution	It is important to establish several communication channels, to promote better and efficient communication. Communicate with some time in advance the need for a meeting or a collaboration. Consider the alternative organizations to participate in the study. Consider companies that are participating (or have participated) in other studies with DEI or CISUC.
Date of Resolution	April 2021

Table 6 – Risk 5, Uncertain Utility of the BPMN Extension.

Uncertain Utility of the BPMN Extension	
ID	R5
Date of Identification	November 2020
Description	Considering that the proposed BPMN extension will the developed and evaluated in organizations, the utility of the extension should be considered, to understand the real value of the extension for companies.
Impact	Medium
Probability	Medium
Discrimination	9
Risk control and resolution	Retrieve feedback from the industry experts in the several steps of the development and evaluation of the extension, to consider eventual changes to the extension and keep it according to the needs of the industry.
Date of Resolution	May 2021

Table 7 – Risk 6, Imprecise Evaluation of the BPMN Extension.

Imprecise Evaluation of the BPMN Extension	
ID	R6
Date of Identification	January 2021
Description	The process of evaluating the proposed BPMN extension in organizations can be very time-consuming, regarding the complexity of such a task.
Impact	High
Probability	Medium
Discrimination	15
Risk control and resolution	The evaluation process should be carefully planned, with precise and efficient tasks, that may streamline the evaluation process and produce realistic and concrete results. Consider the contribution and opinions of experts in the partner companies.
Date of Resolution	May 2021

Table 8 – Risk 7, Difficulties to Acess Companies' Documentations.

Difficulties to Access Companies' Documentation	
ID	R7
Date of Identification	January 2021
Description	Considering the need to access process documentation in the companies to execute the demonstration and evaluation, there is the risk of the access to the documentation being denied.
Impact	High
Probability	Medium
Discrimination	15
Risk control and resolution	Access to the needed documentation should be required in time, to avoid delays. Alternative companies should be considered for the project. Consider companies that are participating (or have participated) in other studies with DEI or CISUC.
Date of resolution	April 2021

Figure 8 introduces the risk matrix of this project.

SCALE OF PROBABILITY / SCALE OF IMPACT	Low Impact - 1	Moderate Impact - 3	Critical Impact - 5
Low Probability - 1	LOW - 1 Risk 1	LOW - 3	MEDIUM - 5
Medium Probability - 3	LOW - 3	MEDIUM - 9 Risk 2 Risk 3 Risk 4 Risk 5	HIGH - 15 Risk 6 Risk 7
High Probability - 5	MEDIUM - 5	HIGH - 15	HIGH - 25

Figure 8 – 3x3 Risk Matrix of the Project

The scale of impact is set on the horizontal axis and the scale of probability is set on the vertical axis. According to the discrimination value (scale of impact multiplying by the scale of probability), each of the risks is placed in the corresponding cell. One risk was classified as low, six risks were classified as medium, and one risk was classified as high.

This chapter presented the most important aspects related to the methodology and work plan. DSR was selected as the research methodology for this project. First, a review of relevant literature was conducted, to understand the concepts of I4.0, IOBP, and BPM. The goal was to properly understand the existing challenges and problems in modelling IOBP 4.0. Second, the proposal of a BPMN extension for the modelling of IOBP 4.0. Finally, the testing and evaluation of the proposed extension in real-world cases. The chapter presented the risk analysis and monitorization as well as the developed work plan across the two semesters.

The next chapter presents the literature review on concepts related to I4.0, BPM, IOBP, and BPMN.

Chapter 3
Literature Review

This chapter presents a literature review about key concepts related to I4.0, BPM, IOBP, and BPMN. These concepts have great relevance for understanding the problem, establishing the basis for the requirements, and domain analysis. Section 3.1 presents the paradigm of I4.0 and its challenges. Section 3.2 explains the concepts related to BPM, introducing the activities involved and the importance of this discipline in organizations. Section 3.3 describes the concepts associated with inter-organizational business processes, the challenges that may arise in the implementation, and the importance of collaborative networks. Section 3.4 provides an overview of business process models and the importance of models for organizations and Business Process Design. Section 3.5 presents the BPMN with an overview of the notation and its characteristics. Section 3.6 introduces the BPMN extension mechanism, offering its fundamental features and the possibilities enabled by this mechanism. Section 3.7 offers a review of related work in the field of IOBP and I4.0 modelling.

3.1 Industry 4.0

I4.0 is a new industrial age enabled by digital technologies that allow the integration between manufacturing operations systems and information and communication technologies, creating the so-called Cyber-Physical Systems (CPS) [46][47]. According to Lee [48], Cyber-Physical Systems (CPS) "*are integrations of computation and physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa*" [48].

The digitalization of organizations combined with the increasing development of Internet and cloud platforms triggered a new industrial age [7]. The increasing installation of sensors in physical objects [5] allowed the retrieval of data in several states and units, essential to develop important BPM activities. The technological advances of last years were the core enabler for the development of these embedded and connected systems [5], [7]. These systems are aimed at monitoring and controlling the several types of equipment, machinery, and products distributed in several places. Well-defined feedback cycles are defined, collecting a significant amount of data from the several places and devices (generating big data), while updating the virtual models with the information of the physical processes [46], [49].

This ongoing revolution has enabled new possibilities for companies, from production to product development and collaboration networks. I4.0 allows companies to have more flexible manufacturing processes and analyse large amounts of data in real-time, improving their strategic planning and operational decision-making [7]. The data retrieved from machines, sensors and products enables the measure and analysis in real-time of key performance indicators. Concerning the field of integration, new possibilities have been raised in terms of horizontal, vertical, and end-to-end integration. Vertical integration consists of integrating the various IT systems levels (e.g., the actuator and sensor, control, production management, manufacturing, and execution) in different hierarchical levels of an organization, representing the integration between the production and the management levels in a factory [7]. One of the most critical aspects enabled by I4.0 is horizontal integration, consisting of establishing collaboration networks between enterprises inside a supply chain, with resource and real-time information exchange [5], [7].

Horizontal and vertical integrations enabled the development of end-to-end solutions with integration of engineering in the whole value chain of a product, from its development until after-sales [5], [7], [46]. Industry and manufacturing have acquired new characteristics. The communication between machines and products has enabled the reconfiguration and flexibilization of production lines, allowing the production of customized products [5]. The acquired information across several activities has revealed vital for the companies to have more support for decision-making (more data, insights). This allows a faster adaptation for several events that could be critical for the company [41] by having complete and precise information. The retrieved data can also be essential for optimizing resources and increasing productivity across several business processes and collaboration networks.

Regarding the purpose of this dissertation, horizontal integration is one of the key concepts deeply involved with the creation of collaboration networks and IOBP. One of the most promising visions in Industry 4.0 is decentralized production networks [5]. The move from a single site to multi-site manufacturing comes with 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 dataflow activities [8]. Furthermore, collaborative networks are considered a core enabler of I4.0 strategies [50], promoting autonomous teams of humans and machines equipped with advanced computing power and artificial intelligence [8]. Hence, horizontal integration and collaborative networks among organizations allow the sharing of resources and the capacity to quickly adapt to changes in the market and seize new opportunities [5].

In I4.0, business processes become more dependent on flexible manufacturing, enabling the partial or complete digitalization and integration of business processes [7]. However, when parts of the manufacturing processes are enacted in different locations/settings, it is necessary to deal with moments of disruption and stability [51], not restricted to one organization, as presented in the following sections.

3.2 Business Process Management

BPM is "the art and science of overseeing how work is performed in an organization to ensure consistent outcomes and to take advantage of improvement opportunities" [52]. For the last years, BPM has become a well-established discipline with a defined set of principles, practices, methods, and tools that combine knowledge from the areas of information technology, information systems, management sciences, and industrial engineering to promote the improvement of business processes [52]–[54]. BPM has enabled the development and execution of several important activities to organizations such as the syntactic verification of business process models, the automatic discovery of process models from raw data [53], process automation and process analysis to operations management and the organization of work [53], process analysis and process simulation.

Process, infrastructure, and people are fundamental building blocks of the BPM culture [55]–[58]. First, organizations should focus on the lifecycle of *Process Identification* (1), *Process*

Discovery (2), *Process Analysis* (3), *Process Redesign* (4), *Process Implementation* (5), *Process Monitoring and Controlling* (6), in which the process models assume a key role [52]. The business processes are continuously analysed, that in final stages of each cycle may evolve to new or optimized versions of the business processes [59]. In terms of infrastructure, the aim is to promote the alignment between the business process goals and the infrastructures, mainly through technology with the automation of the business processes [60]. Finally, people participate in the business processes, each with a specified role and activities to execute. The main assumption is that actors within an existing business process are procedural and are consequently expected to follow the processes as documented and modelled [10].

BPM is often associated with software to manage, control and support business processes within an organization. This gave rise to a new type of technology, called BPM Systems (BPMS), which can connect with a variety of legacy systems and emerging technologies, from cloud networks, to sensors, operating machinery, and mobile devices [53]. BPMS can be defined according to Weske [54] as a "*generic software system that is driven by explicit process representations to coordinate the enactment of business processes acting as a central agent that controls the execution of process activities, ensuring the coordination of activities as defined by the process model – like a conductor centrally controlling the musicians in an orchestra*" [54].

BPMS have been heavily adopted by industry for efficiently and effectively supporting the execution of organization's business processes [61]. The use of these systems has been growing over the years, being a key enabler tool to do Business Activity Monitoring (BAM), providing essential data to coordinators.

BPM has drastically changed how enterprises are modelled [62], fostering quality, product offering, and customer service [53]. The popularity of the process approach in industry increased with its integration in the ISO 9001 quality management standard [63]. The PDCA (Plan-Do-Check-Act) cycle is known as an iterative four-step management approach used for controlling and continuously improving processes and products [64], [65], taking particular importance in solving quality problems, reviews for process improvement, and implementing new solutions, being an extremely versatile model. It can be successfully applied in any business, from medium to large organizations [66]. PDCA is an example of a successful process approach used across industry.

Yet, the complexity of BPM in the era of digital transformation needs to balance traditional stability and predictability of work practices with the emerging uncertainty and dynamic nature of change [10], [51], [67], [68]. The infrastructure must support process exploitation and leverage exploration capabilities to take advantage of digital transformation. However, people may not always follow processes as expected [69]. Several studies point to significant advantages in applying BPM procedures, with an emerging competitive advantage, collaborative advantages, and increasing organizational performance [70],[71],[72].

The process-oriented organisational approach used to design, analyse and improve business processes has allowed organizations to manage and improve more effectively their organizational performance [73]. Recent studies at the intersection of industry 4.0 and BPM revealed the necessity to move beyond "the organization" and understand process-centric work practices that expand to different elements of supply chains [74], offer new sociotechnical drivers for BPM [75], and incorporate process deviations [76], while keeping the process compliant and traceable.

3.3 Inter-Organizational Business Processes

3.3.1 Inter-Organizational Business Processes Fundamentals

Inter-organizational business processes are a set of interrelated and sequential activities that are shared and executed by two or more partners to achieve a business objective that is of value to the business partners [77].

I4.0 is proving to be a real challenge for companies that must reorganize and reshape their processes with digital technologies. However, with the implementation of CPS and cooperation networks, organizations need to reshape their internal processes and how they communicate, deliver elements, and share information with partner organizations – business processes that go beyond one organization that cross several organizations. New business models and redesigned business processes are necessary to allow the individualization of production, horizontal integration in collaborative networks, and end-to-end digital integration [5]. Collaboration between companies, like in supply chains, is considered necessary in a business environment, where companies focus on their competitive advantage. Each business partner executes only the operations for which they have expertise, complementing their offering through other partners and suppliers [20], creating key partnerships that can keep the companies competitive in the market. The growing importance of cooperation results from globalization combined with the globalization and the Internet advances [20]. Collaboration networks are providing "significant opportunities at strategic level, as well as significant challenges at tactical level, in order to properly combine flexible and effective inter-organization collaborations with traditional internally managed processes" [12]. The possibilities of designing and implementing IOBP have been enhanced by developing networked business environments, bringing new ways and opportunities for interaction among the organizations, eliminating the time and space gap between the several business partners [78].

According to [79], the implementation of collaborative business processes "has accelerated in recent years as a consequence of both the new challenges posed to companies by the fast changing market conditions and the new developments in the information and communication technologies sector". By integrating and participating in these key partnerships, the organizations seek to acquire a larger (apparent) dimension, access to new or broader markets, new knowledge, the sharing of risks and resources, and achieving higher agility [79]. The involvement of several organizations and people working in these key partnerships and environments can also potentiate and induce innovation, create new value by confronting ideas and practices, combine resources and technologies, and create synergies [79]. The implementation and execution of IOBP require a certain level of trust between the several participating organizations. This trust is traditionally guaranteed solely through legal contracts, which specify the collection of responsibilities and obligations agreed upon by all the participating parties [80].

Significant advantages arise from the development, automatization, and implementation of inter-organizational business processes. In internal business processes, we have only one organization participating, monitoring, controlling, acting, and a centralized point of decisions. In contrast, in distributed business processes, we have more than one participating organization, resulting in the need to track and get data and resources from different places, enhancing the difficulty to create and manage these partnerships [20]. The establishment of these cooperation partnerships and inter-organizational business processes have raised some challenges to business process design:

- The existence of an interaction between IOBP and internal business processes in organizations raises awareness in terms of information sharing since companies are reluctant to share information and data (related to competitive advantage and business secrecy). It is essential to establish a transparent process to share the data between the organizations [81], [82].
- The need for interaction between inter-organizational business processes and internal business processes in organizations implies changes in internal business process organization and the necessity to integrate external processes, allowing more precise coordination and clarifying interdependencies [14].
- The need for a clear definition of responsibilities across the different companies and activities in the IOBP flow [83].
- The specific communication and internal language/specification of each organization, creating a gap in terms of semantics between the companies. This raises the need to establish a semantics alignment between the organizations that cooperate in a given business process [84].
- The freedom and autonomy that each organization may require to implement their strategies, leading to different paces. It is important to establish mechanisms for synchronization and reducing the degree of coupling between the internal and external interfaces of the organizations in the IOBP [85].
- Developing a partnership across several organizations is a great challenge and requires a significant investment from companies. In addition, the design and implementation of these collaborations and business processes may consume a lot of time and resources. Therefore, it is important to establish strategies to make this process more agile, reducing the bilateral negotiation and adaptation efforts from organizations, fostering the alignment of the inter-organizational business processes along with the multiple partners [77], [86].
- The decentralized activities in IOBP raise the need to change the existing monitoring strategies. It is essential to establish policies that allow the traceability and monitoring of the several metrics of the several distributed activities [61].
- The decentralized nature of collaborative networks often implies that several business partners are distributed across different geographical locations, each subject to various compliance requirements and laws. It is essential to establish mechanisms that allow several partners to deal with different regulations and compliance requirements and eventual changes in them [87].

The challenges mentioned above are more frequent for digital innovation [10], [15]. However, despite the important solutions recently proposed to synthesize different processes in a unified visualization [15], we could not find an approach in the literature that adopts or extends a standard process model notation (e.g., BPMN) to assist the transformation of IOBP since the early steps of its design.

3.3.2 Procurement Business Process: An Example of an IOBP

The Procurement activities correspond to the process of finding and agreeing to terms and acquiring goods, services, or works from an external source, often via a tendering or competitive bidding process [88]. The Procurement processes are widespread in industry to seek the most suited partners for specific needs. In the last couple of years, new trends have emerged regarding the digital transformation in industry, enabling the possibility of automatic procurement activities and the outsourcing of procurement.

This section presents a Procurement example created by [89] to explain the concept of IOBP and some of the main characteristics and differences compared with internal business processes. The Procurement application concerns two organizations (in this case, two companies) – a buyer and a seller working in collaboration and need to interlace their business processes. The Buyer sends an initial request for a quote to the Seller. The Seller checks if the requested product is offered, verifying if it is featured in their product catalog. If so, then the stock information is required to see if the product is available in stock. If the product is out of stock, product information is needed to check if the product can be produced or not. In cases of either having the product in stock or producing the product, the Seller needs to calculate its price and send back a quote to the Buyer. If the Seller's requested product is not offered and cannot be produced, a rejection is sent back to the Buyer. If the ordered product has received a quote, the buyer checks if the price corresponds to the price limit set; if so, it sends a PO to the Seller. The Seller then verifies the credibility of the Buyer. If the customer credibility is positive, the Seller returns an order response to the Buyer [89]. Figure 9 presents a graphical representation of the Procurement process, with the several activities executed and the flow.

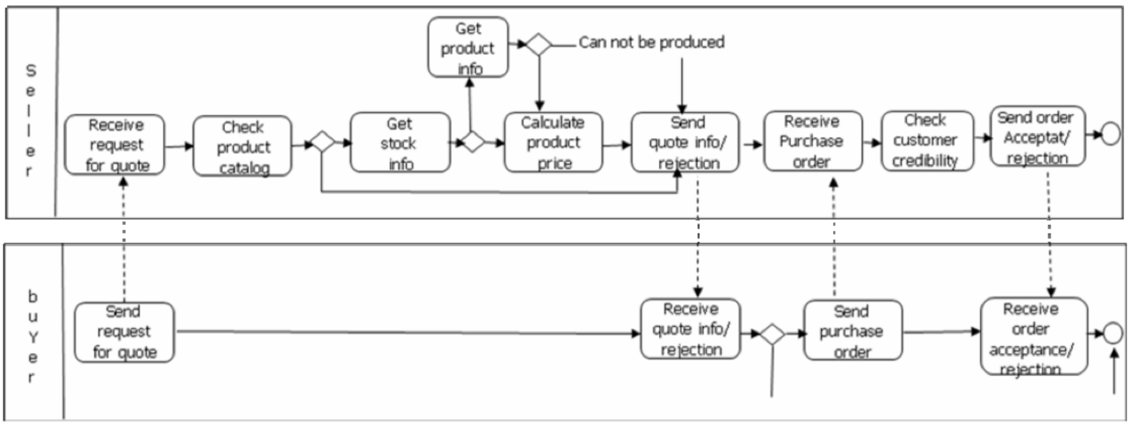


Figure 9 – The case of Procurement IOBP [89]

The presented example introduced the several activities, events, and decisions that concern the Procurement business process. Each organization has to implement and manage not only their internal processes (private processes) but also their external behaviour (public processes), highlighting the need to distinguish between internal and external activities of business processes [89]. Furthermore, regarding the existence activities and decisions that are executed by the several partners (not exclusive of one), there is the need to represent the collaborative parts.

Figures 10 and 11 introduce the possible set and combination of private (internal or executable), public (abstract or view), and collaborative (inter-organizational) business process parts.

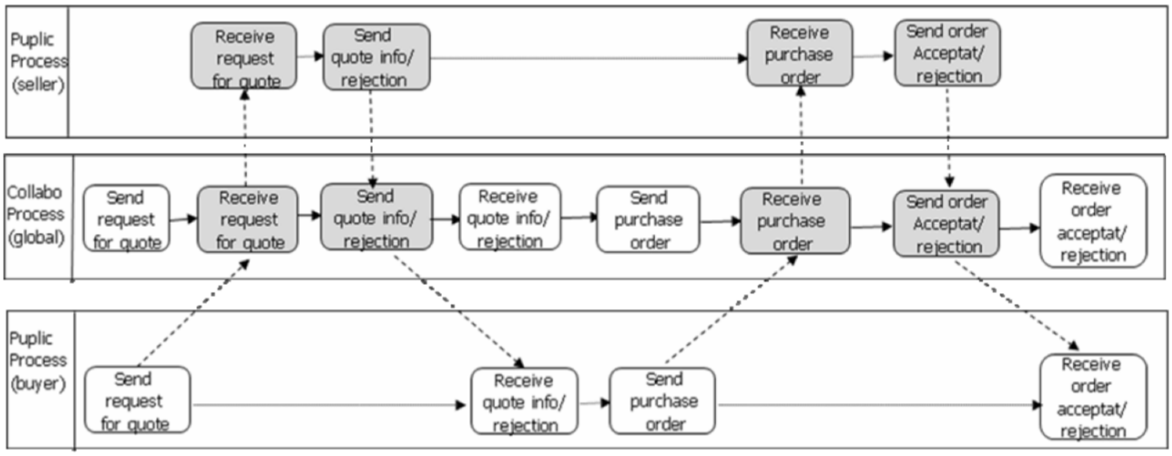


Figure 10 – The case of Procurement IOBP [89]

Figure 10 illustrates a combination of both public and collaborative (inter-organizational) business process, regarding the execution of activities separately or in collaboration. The collaborative business process elements define the interactions (represented by the vertical dashed arrows in figure 10) between two or more organizations. These interactions occur between the defined public processes and are defined as a sequence of messages and/or other material input/output exchange as depicted in figure 10. The collaborations between the involved parties are modelled as interaction patterns between their roles. It is shown by two or more public processes communicating with each other.

Figure 10 also presents the public activities that are elements of the public process, which abstracts information from one or more private processes, enabling companies to hide critical information from unauthorized business partners. This allows the establishment of an interface to the outside world, allowing the extraction of the kind of information necessary for implementing and managing the interactions between the several partners. According to a previously defined message exchange protocol, a public process defines an external message exchange of an organization with its partners. Then, a public process can be seen as a general interaction description of one or more private processes from one partner's perspective. The Seller’s public activities are represented in grey, and Buyer’s public activities are described in white in figure 10.

Figure 11 aims to introduce and explain the concept of private parts in business processes.

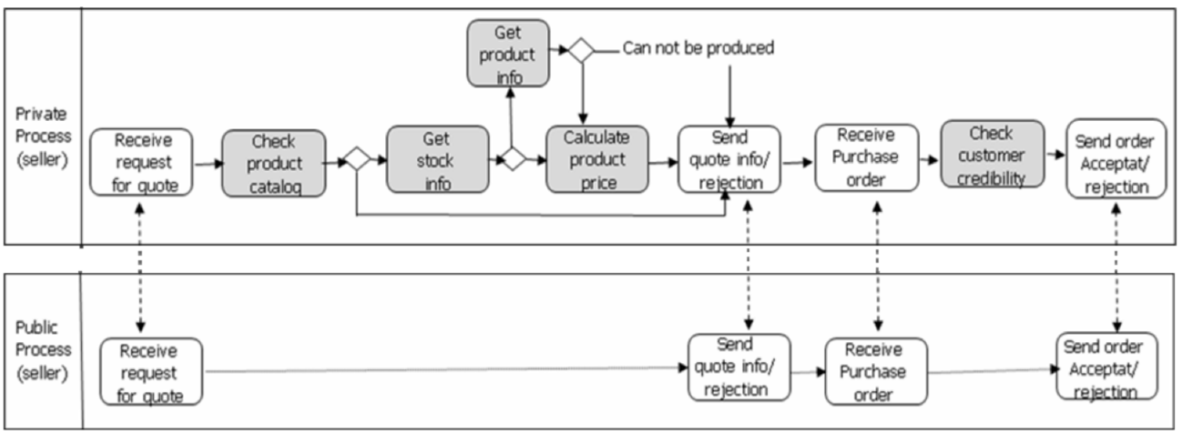


Figure 11 – The case of Procurement IOBP [89]

Private Process parts are procedures that are internal to an organization. They contain data and information that organizations pretend to protect by default (private activities are represented in grey and public activities are represented in white in figure 11) either by compliance requirements or competitive advantages. On the private process level, organizations model their internal business processes according to a modelling approach that is the most suitable for internal demands independently of the modelling methodologies used by the business partners [90]. In the example of the Procurement IOBP, the Seller wants to hide the "Check product catalog", "Get stock info", "Get product info", "Calculate product price", and "Check customer credibility" activities from the Buyer, has shown in figure 11.

The example presented above reinforces some of the previously mentioned challenges while managing and implementing IOBP. Companies need to set mechanisms that allow transparent communication and information sharing, control access to restricted information, manage the internal and external business process interfaces, and combine efforts to execute and manage decentralized activities and decisions.

3.4 Business Process Models

Business process models are essential to document business processes [91]. They describe behavioural aspects of a system, with the graphical representation of process flow, tasks, activities, and events. The models are also essential to identify and optimize business processes, allowing for tracking and tracing eventual problems, identify points of potential automation and measure costs (time, money, resources), more transparency, and enhancing the standardization of procedures through the implementation of the best-practices. A business process model aims to capture or represent the different ways in which a process instance can be handled [57].

Business process modelling enables a shared understanding and a comprehensive analysis of a business process [92]. Business process models play a crucial role at different stages of BPM, for instance, a blueprint for the design, a template for enactment, a benchmark for monitoring, or a schema for analysis [61]. Business Process Models have enabled the precise real-time monitoring of business processes, with the identified tasks and responsibilities. In addition, process modelling is an instrument for coping with the high complexity of process planning and controlling [91], simplifying complex situations and enhancing communication in organizations. For the last years, attention has been raised to the possibility of using business process models in software development projects, mainly in the requirements analysis and elicitation phase [93].

Business Process Models are often used to promote process reorganization, certification, activity-based costing, or human resource planning [91]. Other examples include the conceptual modelling of business processes to facilitate the development of software that supports an organization's business processes and permits the analysis and reengineering or improvement of business processes [92].

The complexity and dynamic nature of organizations, companies, and markets imply the need to create and manage models necessary for understanding their behaviour, design new systems, or improve the operation of existing ones [94]. Several business process modelling techniques and frameworks have been proposed to assist modelling activities. However, no single method or framework can be thought of as better or worse than the others by default [95]. Furthermore, the goals, context, and objectives of a particular study will impact the uses to which a model will be put and therefore influence the requirements posed on the process representation formalisms to be applied in a specific situation [96].

Process modelling techniques differ in the extent to which their constructs highlight the information [95] regarding the representation of how and when activities are executed, resources flows, or relevant events. A process modelling technique should be capable of representing one or more of the following "process perspectives" [95], [97]:

- Functional perspective: Represents what elements of the business process (generally activities and tasks) are being performed.
- Behavioural perspective: Represents when activities are performed (for example, sequencing), as well as aspects of how they are achieved through feedback loops, iteration, decision-making conditions, entry and exit criteria, and so on.
- Organizational perspective: Represents where and by whom activities are performed (the responsible, for example), the physical communication mechanisms used to transfer entities, and the physical media and locations used for storing entities.
- Informational perspective: Represents the informational entities (data, artefacts) produced or manipulated by a process and their relationships.

The important role of business process modelling in software-intensive information systems can explain the resurgent interests in software systems design. Business process models assume a unique role in these complex software systems, with many of these systems being driven by the models [98]. This tendency has been noticeable for the last years with the growth of research in business process modelling, attracting more and more attention year after year [99].

Business process modelling is the basis of process-centric systems implementations, especially in the case of Enterprise Resource Planning systems [99], on the key elements of the BPM culture, enabling the monitorization and logging of business processes [57] and in the creation and implementation of BPM Systems [54].

In the last years, several frameworks and languages emerged to establish standards and foundations for the creation of business process models and the establishment of BPM culture. For example, Event-driven Process Chains (EPC), Business Process Modelling Notation (BPMN), or UN/CEFACT´s Modelling Methodology (UMM).

Despite the existing contributions for modelling IOBP, the resulting process models are often incomplete [14], [20] 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 in a more effective and complete way.

3.5 Business Process Modelling & Notation

BPMN is an open industry standard for business process modelling. The main goal of BPMN is to provide a notation that is readily understandable by all business users, including the business analysts who sketch the initial drafts of the processes, the technical developers responsible for actually implementing them, the business staff deploying and monitoring such processes, and the operators and collaborators [100], [101].

BPMN enables the interaction between the different departments and persons across an organization, to communicate in a unique language and reduce semantic gaps between them all. BPMN has been playing a key role in supporting the BPM activities to both technical users and business users, with a very intuitive and straightforward notation to all users being implemented in the systems and process modelling. Despite its simplicity, BPMN can represent very complex cases, for example, in manufacturing [102]. Another advantage is that BPMN has a well-defined language meta-model that facilitates model exchangeability [103] and tool integration [104]. Moreover, the BPMN meta-model contains a specification of elements for the definition of language extensions [21], which is particularly useful for adapting to new contexts. Diagrams can be shared across organizations and partners using an XML-based interchange format.

The process models in BPMN are characterized by a set of elements [105], [106]:

- Flow objects: the activities, gateways, events. They represent the several steps and events involved in a process. The three main flow objects:
    - Events: Events are the circular symbols that serve as a trigger of action: initiating the instance, intermediate step, or end point of a particular process. Incoming messages, errors, exceptions, or timers are examples of events.
    - Activities: Activities are the rounded rectangles illustrating a specific task performed by a person, software, or machinery that may occur once or multiples times. Tasks and sub-processes are examples of activities.
    - Gateways: Gateways are the diamond-shaped elements that map decision points, determining the "direction" that a process shall turn next, according to the input and type of gateway. Exclusive, parallel, and event-based are examples of gateways.
- Connecting objects: The elements are used to connect the objects and represent the flow of the process. The main three elements are:
    - Sequence Flows: Sequence Flows are represented as a straight line with an arrow. They represent the order in which activities are performed, mapping the sequence flow.
    - Message Flows: Message flows are represented by a dashed line with a circle at the start and an arrow at the end. It means the transmission of messages that flow across "pools" or departments.
    - Associations: Associations are represented by a dotted line, associating an artefact or text to an event, activity, or gateway.
- Swim lanes: Swim lanes are represented as rectangles, with pools represented by the major rectangles and swim lanes symbolized by the rectangles inside pools. The pools represent the main process participants (e.g., different companies, different departments in the same company). Swim lanes point to the activities and flow for a particular role or participant, defining who is responsible for what parts of the process.
- Artefacts: Artefacts allow the addition of attributes, essential aspects in the process, and data that is used in specific tasks or gateways. The three primary artefacts are:
    - Annotations: Annotations provide further explanation to a part of a diagram.
    - Data objects: Data objects represent data elements that are necessary for an activity (need to be accessed, changed, or deleted).
    - Groups: Groups represent a logical grouping of activities with a specific goal or general denomination.

Figure 12 presents several of the core elements of the BPMN notation.

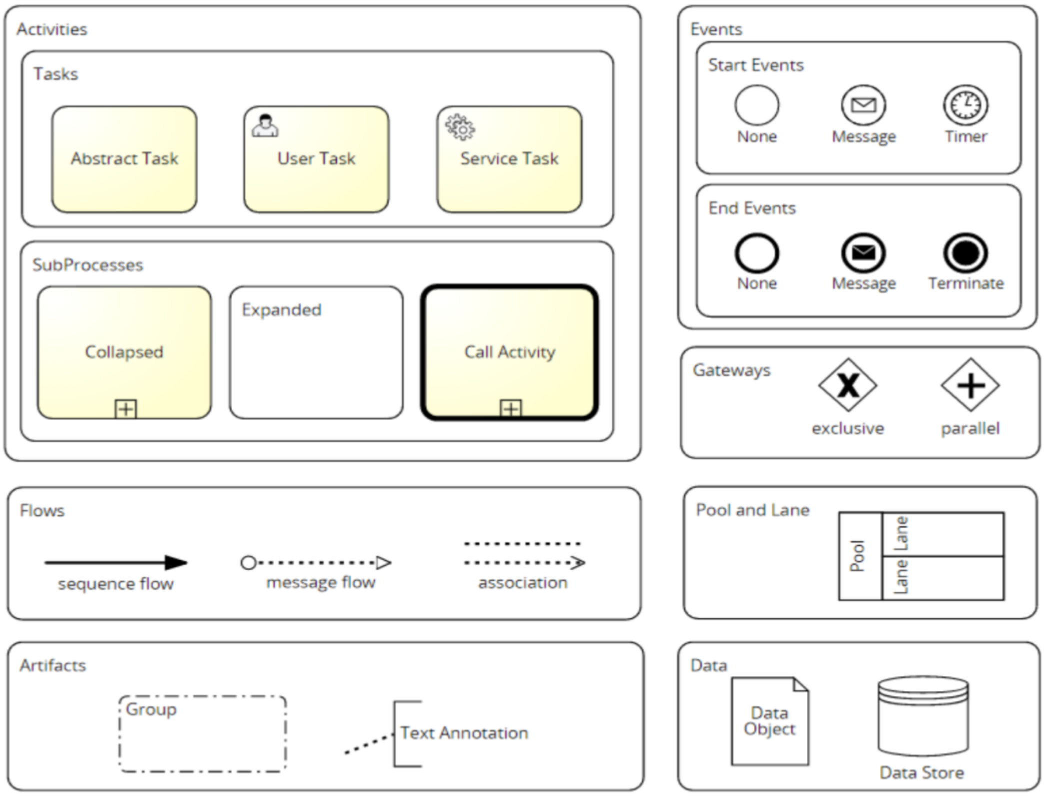


Figure 12 – Core Set of BPMN Elements [107]

BPMN allows the modelling of three different types of business processes using three essential sub-models [100], [105], [106]:

- Private or internal business processes: Private business processes are focused on internal/organization-specific processes. These are business processes that don't cross pools or organizational boundaries.
- Abstract or public business processes: Abstract business processes represent interactions between a private business process and other processes or participants. A participant is a resource that performs the work represented by a workflow activity instance. It shows only those activities involved in the interactions between two or more participants, presenting the sequence of messages needed to interact with the private process. The private/internal business process is not revealed, being kept secret.
- Collaboration or global business processes: Collaboration business processes represent the set of activities describing – among other elements – message exchange between two or more business processes, showing the interactions between two or more business entities.

For the last years, the use of BPMN has been increasing, with companies and adopting this language and with more BPM Systems allowing the use of these process models. Some known BPM Systems like *Signavio* [108], *IBM BPM* [109] and *Bizagi* [110] support BPMN process modelling. The BPMN2.0 version has also changed how models can be shared and transferred between different applications and users. This version introduces an XML-based interchange format for BPMN processes, allowing the storage of both process models (containing the semantics) and process diagrams (the visual representation of the process models). This mechanism enables users to access the diagrams using different tools, allowing the exporting, and importing shared diagrams across organizations and partners. We can also consider that BPMN is embedded into a consistent framework that enables the integrated transformation of BPMN process models to BPEL workflow models [100]. Furthermore, the current version of BPMN includes an extensibility mechanism for both process model extensions and graphical extensions [100], introduced in section 3.6.

Business process models created with BPMN possess two elements more specific to inter-organizational process descriptions: (1) pools, representing entities (e.g., organizations, business partners) that perform business processes [14], and (2) message flows depicting information exchanges between organizations. Additionally, BPMN is one of the few modelling languages that allows the creation of extension elements to incorporate additional details. Regarding the representation of IOBP 4.0 scenarios using BPMN, the notation it lacks in terms of semantics to describe the dependencies of the global control flow of the message exchange [20]. Additional problems are the absence of formal specification of process interfaces and support for alignment with multiple partners. Therefore, BPMN extensions emerge as a promising solution [21].

3.6 BPMN Extension Mechanism

3.6.1 BPMN Extension Fundamentals

The BPMN modelling language provides a set of generic business process elements independent from a specific domain. However, both in academic and industry contexts, it is often necessary to extend BPMN with custom concepts to represent characteristics of a particular vertical field, such as health care, finances, or industry [104]. This mechanism allows the users to benefit from the simpleness and objectiveness from BPMN and includes the specific elements of their context.

BPMN is one of the few modelling languages that allows the use of this kind of extensibility mechanism. More specifically, it allows the extensibility of the BPMN metamodel, allowing BPMN adopters to attach additional attributes and elements to standard and existing BPMN elements [105]. The mechanism is established as an extension by addition format. Groups of attributes and elements are attached to standard BPMN elements that enable the definition and integration of domain-specific concepts and ensure the validity of the BPMN core elements to create valid BPMN extensions [111]. The BPMN extension mechanism is built to ensure model core validity while adding domain-specific concepts, context, and properties [112]. According to OMG's (Object Management Group) BPMN specification, an extension is composed of four elements [105]:

- ExtensionAttributeDefinition - Defines new attributes for the characteristics of a modified element.
- ExtensionAttributeValue - Contains the attribute value.
- ExtensionDefinition - Named group of new attributes that BPMN elements can use. It may be a new element or the addition of attributes to a specific element. Consists of several ExtensionAttributeDefinition (name and type).
- Extension - This element binds and imports the extension definition and its attributes to a BPMN model definition, allowing all the extension elements to become accessible for BPMN elements.

Reusing the BPMN kernel and extending the language with domain-specific concepts is expected to be less expensive than developing and deploying an entirely new domain-specific modelling language from scratch [22]. However, besides the definition of the extensibility mechanism and the requirements to comply with the BPMN meta model, currently, there is no standard methodology to develop BPMN extensions [21].

Several studies indicate that only a minority of the developed BPMN extensions are designed in conformance to the stated extension standard defined by OMG [21], [112]. Instead, most extensions are designed in an ad-hoc methodology by meta model customization, which may cause difficulties in terms of comprehensibility, tool integration, and model exchangeability. The missing of standard methodical guidance, syntactical shortcomings and inaccuracies of the extension mechanism itself provoke these issues [104], [112].

The work of [34] proposes a methodology for the development of valid BPMN extensions [34], that according to [21], is one of the most used methodologies to develop useful BPMN extensions [21].

Figure 13 presents an excerpt of the standard BPMN meta-model, containing all relevant classes and relationships of the extension mechanism [112].

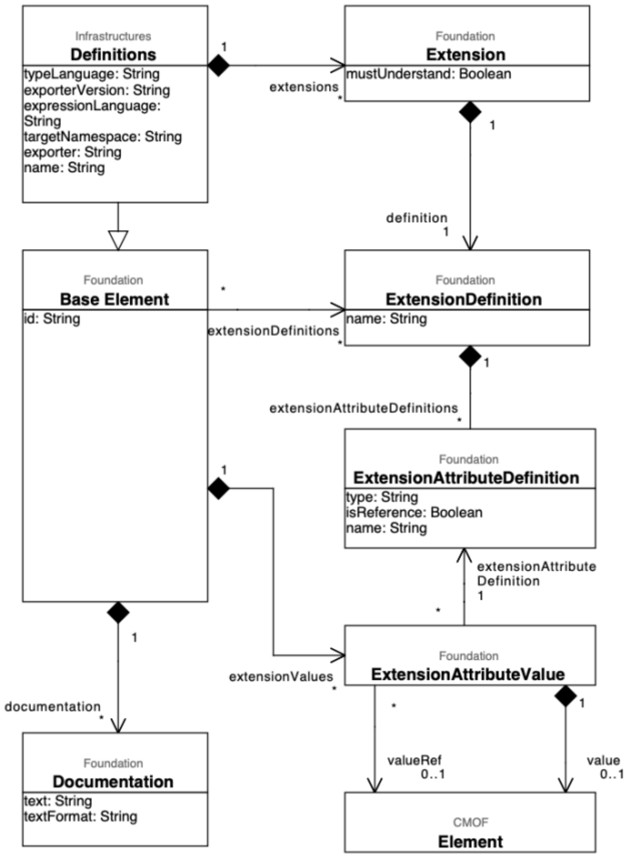


Figure 13 – BPMN Extension Meta-Model [112]

Figure 13 summarizes the previously introduced elements, regarding the elements that compose an extension, according to OMG's BPMN specification [105]. The *Extension* is the element that binds and imports the extension definition and its attributes to a BPMN model definition. The *ExtensionDefinition* is the group of new attributes that BPMN elements can use. It may be a new element or the addition of attributes to a specific element. It is composed of several *ExtensionAttributeDefinition*. Each *ExtensionAttributeDefinition* represents an attribute, being defined, and characterized (*ExtensionAttributeDefinition*) and may have an assigned value (*ExtensionAttributeValue*).

3.6.2 uBPMN, an Example of BPMN Extension Research

Yousfi et al. [113] proposed a BPMN extension for modelling ubiquitous business processes. According to [114], "*a ubiquitous business process is a location-independent business process that turns its business environment into a source of data and/or a target of outcome with the least of human interventions*". Ubiquitous capabilities are strongly related to the use of Automatic Identification and Data Capture devices in several operations (e.g., location-tracking, activity sensing), such has sensors, bar-code readers and QR-Code readers [113].

Their main motivation was that BPMN lacks in several aspects regarding the representation of the business that uses ubiquitous computing technology: to define or constrain the elements of the workflow (e.g., scan the bar-code to update the package status, read the RFID tag to generate the invoice, read the RFID tag to identify, sensor's operations) [113], existing in the sectors of logistics, manufacturing and delivery services.

Regarding the development of the BPMN extension, the authors used an approach based on Stroppi et al. [34], using UML profiles, and later improved by Braun and Schlieter [18], with some adaptions and simplifications. The authors started their work by developing a literature review on concepts related to ubiquitous business processes and related to BPMN extensions and their development. The ubiquitous business processes concepts and elements were analysed to identify the requirements and the domain context. Based on these requirements and domain analysis, the authors identified the several attributes and elements to be extended, by extending the BPMN Meta-Object meta-model.

After extending the BPMN meta-model and identifying all the relevant elements, the authors produced the extended notation of the XML Schema Definition of BPMN. The proposed BPMN extension was tested and validated with several use cases and studies in real-life examples, enhancing its accuracy and correctness in representing the cases. The extension proposed by the authors follows the same outline and recommendations as set by the Object Management Group for BPMN. Therefore, it provides a valid example that can be adapted in our project to the context of IOBP 4.0.

Figure 14 presents part of the Meta-Object Facility (MOF) meta-model describing the concepts related to the newly identified tasks - Sensor, Reader, Image, Audio, and Collector [113]. Each of the new tasks is defined and described by a set of attributes.

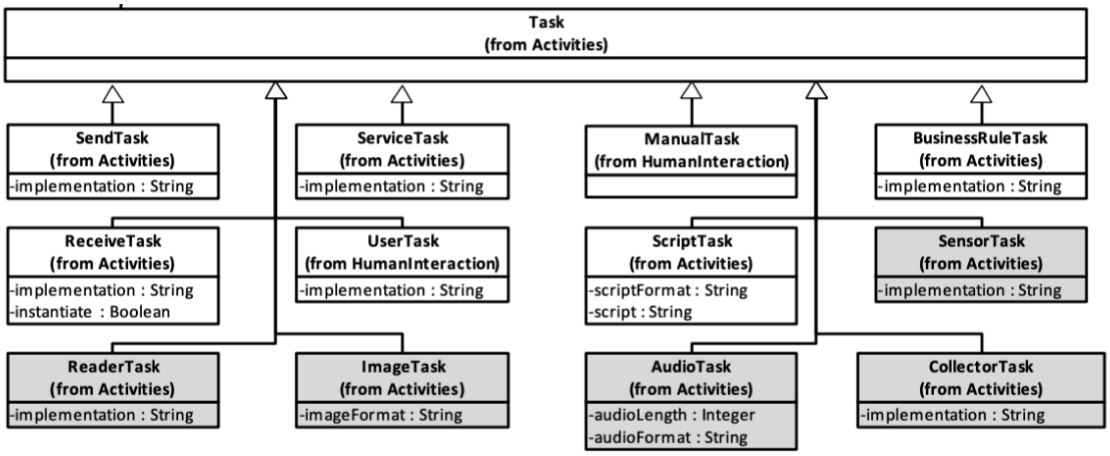


Figure 14 – uBPMN Meta-Model [113]

Figure 15 corresponds to part of the XSD file of uBPMN, extending the standard BPMN notation. This specific part of the file presents some of the tasks mentioned in the uBPMN Meta-Model (Figure 15), more specifically, the Sensor Task and Reader Task. The notation refers to the standard elements to be extended and the new attributes characterizing those new elements.

```
<xsd:element name="sensorTask" type="tSensorTask" substitutionGroup="flowElement"/>
<xsd:complexType name="tSensorTask">
   <xsd:complexContent>
      <xsd:extension base="tTask">
         <xsd:attribute name="implementation" type="tImplementation" default="##unspecified"/>
      </xsd:extension>
   </xsd:complexContent>
</xsd:complexType>

<xsd:element name="readerTask" type="tReaderTask" substitutionGroup="flowElement"/>
<xsd:complexType name="tReaderTask">
   <xsd:complexContent>
      <xsd:extension base="tTask">
         <xsd:attribute name="implementation" type="tImplementation" default="##unspecified"/>
      </xsd:extension>
   </xsd:complexContent>
</xsd:complexType>
```

Figure 15 – uBPMN XSD [113]

Figure 16 presents some of the new created tasks, introducing the graphical representation of the new concepts to be incorporated in the models to be developed. One of the most important goals for actors developing extensions is the graphical representation of the new proposed elements, making it easier to present to audiences and stakeholders.

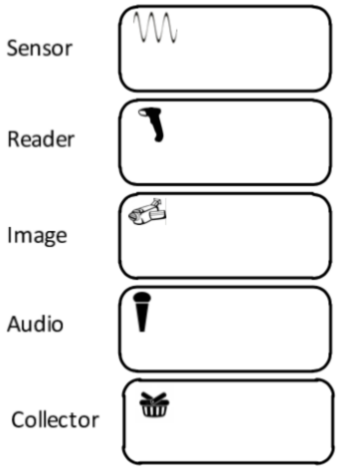


Figure 16 – uBPMN Tasks [113]

The BPMN extension for Modeling Ubiquitous Business Processes [113] details the general procedures to create and validate a BPMN extension. The artefacts produced by the authors were the graphical representation of the new proposed elements, the extended BPMN Meta-Model as well as the extended XSD/XML BPMN notation.

Figure 17 presents a simple example of a BPMN process model using the uBPMN extension.

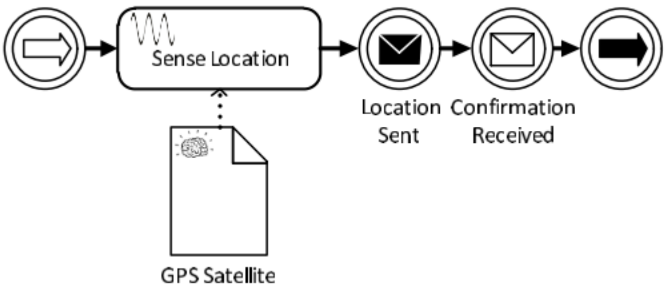


Figure 17 – uBPMN Process Example [113]

The process presented in Figure 17 is of simple complexity, introducing some of the uBPMN elements. In this process, a location request is received. The Sense Location task gets the information through the GPS Satellite. The data is sent, and confirmation of the message is received. The newly introduced elements, the Sensor Task and GPS Satellite element, allow a more detailed description and presentation of the business process.

The review in industry 4.0 allowed the identification of the concepts related to CPS and the importance of collaborative and distributed networks in the industry's future, enhancing the need to monitor, track and communicate across all the organizations involved. The review on BPM revealed the importance of business processes in nowadays organizations, strengthening the focus of the organizations in the activities related to business processes (analysis, monitoring, design) and the importance of the digital transformation across organizations to face the future of manufacturing and collaborative networks. BPM has been supporting the efficient and effective execution of an organization’s business processes. The review on IOBP allowed the identification of the several challenges involved while designing and maintaining such business processes, enhancing aspects like the transparency of information, decentralized monitoring, and others. The research and review on BPMN allowed the identification of the existing extension mechanism, with the characteristics and requirements that extensions must meet, and the structure of the BPMN extension. The study of the BPMN extension mechanism and some existing examples of already developed extensions in several areas allowed the identification of the several specific steps needed to develop a BPMN extension. It allowed to identify all the required steps and set a concrete schedule for the activities and their dependencies and requirements to be developed.

3.7 Related Work on IOBP and I4.0 Modelling

Several authors have presented proposals on the field of IOBP and I4.0 modelling. In our literature review, we identified several types of recommendations for IOBP and I4.0 modelling activities: frameworks, process modelling requirements, BPMN extensions, and reviews on existing solutions.

BPMN extensions have been proposed for I4.0 contexts. The PyBPMN extension [12] is one of the most mentioned, presenting an approach to the specification and management of the resources associated with the business processes that support cyber-physical systems. The study of [115] shows a modelling language based approach that supports the modelling of flexible and adaptive processes, mainly industrial internet-of-things scenarios. The proposal is based on the BPMN and UML modelling languages. The work of [102] presents an analysis of business process fragments for manufacturing activities in the context of I4.0. The authors review the manufacturing field concepts (e.g., operations, resources, actors), BPM, and I4.0, enhancing the most essential elements to consider while modelling manufacturing operations with BPMN. Then, the authors present several cases of modelling and analysis of manufacturing business process fragments using BPMN. The work developed by [116] presents a proposal of BPMN extension for the domain of manufacturing activities. The authors propose a set of elements to represent manufacturing operations (e.g., production operations, maintenance operations) and resources (e.g., auxiliary components, parts), followed by examples of the use of the extension. The work of [117] proposes an approach that aims to distinguish the types of resources carrying out process tasks (e.g., human, physical means, and IT resources), introducing a new composite resource made from the relationship between a user (human resource) and a task form (IT resource). The authors present a set of examples of modelling using the new proposed resources and simulation activities. The work of [8] gives an overview of the field of I4.0 business process modelling. First, the authors identify a set of requirements for modelling the I4.0 domain (e.g., IoT device, IoT task, cloud application). Then, the authors propose a set of new elements to represent the identified requirements of I4.0 (e.g., sensor task, IoT device, Human Computer Interface). The authors also present a methodology and guidelines for using the proposed notation for the modelling of business processes in the context of I4.0.

Contributions on BPMN extensions for IOBP are less common. A pioneer contribution was presented by [118] to fulfill existing problems and improvement opportunities in the field of inter-organizational systems and IOBP. Therefore, the authors propose a BPMN extension that included the adding of new concepts related to the exchange of information (e.g., messages, manual data flows, data stores), characterization of activities (e.g., automatic, manual), and actors (e.g., human, non-human). The work of [119] presents the design of a BPMN extension for collaborative business processes. The extension is mainly focused on concepts related to the execution of distributed tasks (e.g., multiparticipant tasks, private task, shared task), state of progress of activities (e.g., completed, on break, paused), and data management (e.g., shared data, private data, locked data). In addition, the authors propose the extension of the BPMN meta-model and a set of new graphical elements for collaborative business processes, illustrated with one example of the use of the extension. This work is mainly focused on general aspects of collaboration tasks and resources, not specific to any domain, such as manufacturing, business, or medicine.

Other works in IOBP focus on identifying the requirements and challenges for the design, implementation, and execution of IOBP. The result of [89] presents an overview of IOBP modelling and a proposal of a framework for IOBP. The authors identify a set of challenges to be considered while modelling IOBP (e.g., need to manage the interfaces between external and internal business processes, the decentralized execution and governance of IOBP). Regarding the modelling of IOBP, the authors present an "overview of the current business process modelling languages" and their capacity to model IOBP. To do this, the authors defined a set of modelling requirements concerning the specificities of IOBP. Next, they classified the several modelling languages and frameworks according to the fulfilment of these requirements. Finally, the authors present a proposal for a framework for the modelling, design, and implementation of IOBP. The authors also present a generic metamodel for IOBP. Furthermore, the work of [14] presents a literature review on the field of IOBP, focused on the identification of the requirements and challenges in the design and modelling of such business processes. In a first phase, the authors present a summary of the several challenges inherent to the design and modelling of IOBP (e.g., the need to establish transparency mechanisms, the need to manage each of the organizations). Then, the authors present a state-of-the-art review on several modelling languages and frameworks regarding the design of IOBP. The authors propose several modelling requirements (e.g., the representation of the several partners, specification of process interfaces, visibility of process parts) that a modelling language must fulfil to represent IOBP. The defined requirements are then used to evaluate several modelling languages, by analysing the fulfilment (or not) of the specified requirements. For those who do not fulfil the specific requirements, the authors propose concepts that may be introduced to achieve the fulfilment of such requirements.

Despite these important contributions for modelling IOBP and Industry 4.0, an integrated approach to model manufacturing in IOBP scenarios of manufacturing's digital transformation is still lacking. These previously presented solutions address the need to deal with decentralized collaboration in manufacturing activities (e.g., production of separate components, remote monitorization, decentralized decisions) and managing such processes. This section's related work can be integrated and extended, serving as the starting point for our research, explained in the following chapter. This project contributes to the new logic of BPM required by digital transformation [10].

This chapter presented the literature review on relevant concepts to set the basis for the development of the IOBP 4.0 BPMN extension. Essential topics in the fields of IOBP, I4.0, BPMN, and BPM were reviewed. In addition, the BPMN extension mechanism was studied to consider the existing approaches for the creation of BPMN extensions and existing examples. Works in the field of I4.0 and IOBP modelling were also included in the literature review.

The next chapter presents the design phase of the IOBP 4.0 BPMN extension, presenting the several stages of the process and a description of all the activities.

Chapter 4
Design of the IOBP 4.0 BPMN Extension

This chapter describes the activities executed towards the design of IOBP 4.0 BPMN extension, from the domain analysis to the creation of the graphical representation of the extension concepts. Section 4.1 depicts the overall design approach of the IOBP 4.0 BPMN extension. Section 4.2 presents the Requirements and Domain Analysis regarding the IOBP 4.0 domain, considering the previous review on the challenges and requirements of the domain. The section includes a proposal of modelling requirements and domain ontology for IOBP 4.0 and an equivalence check for the identified concepts. Next, Section 4.3 shows the CDME for IOBP 4.0, introducing the proposed extension elements to represent the IOBP 4.0 domain. Subsequently, Section 4.4 introduces the meta-model of the IOBP 4.0 extension, followed by the extension elements definition according to the BPMN standard guidelines (Section 4.5). Finally, Section 4.6 presents the proposal of graphical representation for the BPMN extension concepts.

4.1 Design Approach

The approach presented by [34] is one of the few comprehensive approaches available to guide the development of BPMN extensions. It defines a model-transformation based procedure model for the methodical development of valid BPMN extension models using UML profiles to point out several types of classes within the extension definition [35], based on the Model-Driven Architecture. The work of [18] extends the approach proposed by [34], by introducing the domain's analysis step and its conceptualization. This step involves a requirements analysis based on domain use case scenarios or literature reviews to identify the requirements of the general modelling approach. Afterward, a domain ontology should be designed to prepare the conceptual domain model and set a base for the equivalence check.

Considering the foundations provided by [34], [18], and [112], the following steps will guide the design of the IOBP 4.0 extension:

1. Produce a domain Analysis based on a literature review or use-case scenarios, creating a domain ontology, attributes list, and modelling requirements.
2. Execute and equivalence Check on the concepts identified in the Domain Analysis and the standard BPMN.
3. Conceptualize the domain by defining a CDME as a UML class diagram.
4. Transform the CDME into a valid BPMN extension model (BPMN+X) using UML stereotypes and a set of transformation rules for several model element constellations.
5. Propose a concrete syntax BPMN extension by creating a graphical representation for the BPMN extension concepts.

Steps 1 to 5 are synthetized in Figure 18, presenting the approach proposed by [34], using UML profiles, and later improved by [18].

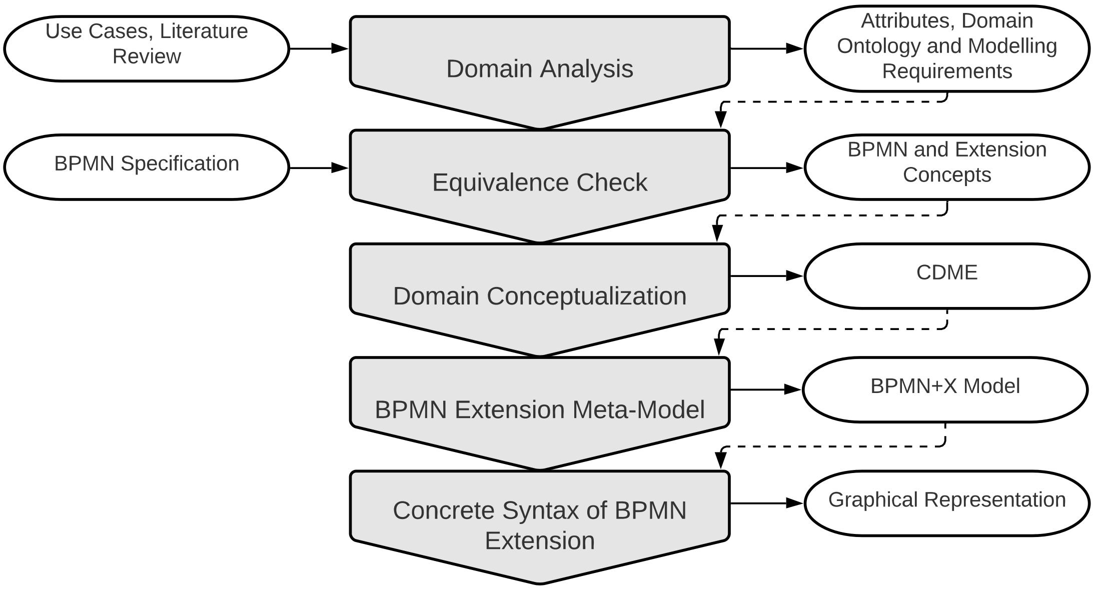


Figure 18 – Approach to Develop the IOBP BPMN Extension (based on [34] and improved by [18])

Figure 18 summarizes the steps of the DSR design of the IOBP 4.0 BPMN extension, based on the approach proposed by based on [34] and improved by [18]. It introduces the extension of the mechanism proposed by [34], by including the Domain Analysis and Equivalence Check as the first two activities (as proposed by [18])of the approach. The Domain Analysis is based on use-cases and in the literature review concepts, which will result in the identification of domain attributes, a domain ontology and modelling requirements for the IOBP 4.0 domain. The Equivalence Check is executed by comparing the identified domain concepts, attributes, and modelling requirements with the standard BPMN specification, to identify the missing IOBP 4.0 domain concepts in the standard BPMN. This step will allow the identification of the BPMN and Extension Concepts. Then, the domain is conceptualized with the creation of the CDME, based on identification as BPMN and Extension Concepts in the Equivalence Check. The next step is to transform the CDME into a valid BPMN extension model (BPMN+X) using UML stereotypes and a set of transformation rules for several model element constellations, resulting in the extension of the standard BPMN meta-model. Finally, the graphical representation (the new elements) will be produced, obtaining the concrete syntax of the BPMN extension.

4.2 Domain Analysis

The literature review, previously presented in this dissertation, established the basis for the domain analysis. With the decentralized coordination and distributed execution of the activities [20], several challenges arise regarding data access control, data sharing, confidentiality, and synchronization. Therefore, there is the need to identify the characteristics and the existing challenges to the design of IOBP 4.0, to synthetize the points that must be addressed by the IOBP 4.0 BPMN extension to overcome the current limitations while modelling IOBP 4.0. The domain analysis was made in three essential steps: the identification of attributes, the depiction of a domain ontology and the identification of modelling requirements for IOBP 4.0.

4.2.1 Attributes Identification

In a first analysis, the literature review allowed us to identify several interrelated attributes, regarding the challenges in the establishment, the characteristics, and essential elements of IOBP I4.0, based on previous works in the fields of IOBP and I4.0. The following sentences present the several identified attributes based on the literature review.

Confidentiality – Organizations may have restrictions in sharing internal information or managing customer-owned data, considering compliance requirements, industrial and/or business secrecy information, and eventual competitive advantage in some specific elements. In order to establish an IOBP I4.0, organizations must decide which elements of their internal processes may and must be shared [20], [81], [82].

Responsibility – In IOBP I4.0, shared processes require shared responsibility between the organizations for innovation, execution, and monitoring of the business processes. Organizations must take responsibility for their internal business processes and in the inter-organizational parts [20], [83], [120].

Authority – Considering the distributed nature of IOBP 4.0, global and local actors must be defined, and their decisional capacity specified in different possible scenarios. These actors and their authority (the capacity to decide in specific points of the IOBP I4.0) must be represented in terms of activity management and coordination of tasks [14], [84], [120].

Touchpoint – Given the distributed nature of IOBP 4.0, it is necessary to define when a message is required and what the impact is on all the stakeholders of the main process. For example, costumers may interact with the process at specific points, assessors touchpoints, or interaction between cyber and physical elements of the process) [102], [118].

Transparency – Considering the involvement of several different organizations and the need to share information and data, the involved organizations should embrace transparency by sharing the essential information and data transparently to keep the several partners aware of several essential aspects [81], [82].

Compliance - Regarding the distributed nature of IOBP 4.0 across several locations, multiple voluntary and enforced regulations may compete in different geographical locations and each organization (e.g., policies). The organizations must count the current regulations in the specific geographical locations in which the IOBP I4.0 is established [14], [121].

Traceability – In light of the distributed nature and the involvement of several organizations in IOBP I4.0, it is necessary to establish which of the activities, resources, data, and decisions must be traceable within the entire process lifecycle in order to keep all the organizations in the partnership informed [61].

Interface - Considering the distributed nature and the involvement of several organizations in IOBP I4.0, it is needed to establish interfaces to enable actors' intervention (e.g., digital platform) in the several shared elements (e.g., task, data) [84], [85].

Collaborative – Because of the involvement of several organizations in IOBP I4.0, we must consider that each organization has activities parallel or sequential execution that may be realized separately or in collaboration with other organizations. These considerations enhance the need to identify collaborative BPMN elements [122].

Autonomy – Considering the involvement of several organizations in IOBP I4.0, autonomous tasks and decisions (e.g., single-organization process improvement) must be identified to promote some decoupling and dependence of the organizations on the capacity and performance of others in the business process [120].

A total of ten attributes were identified in the literature review on the field of IOBP and I4.0. These attributes will be essential to complete the models by representing specific IOBP 4.0 characteristics in the BPMN base elements. Therefore, these attributes will be incorporated in the IOBP I4.0 models, allowing a more precise and complete representation of these business processes.

4.2.2 Domain Ontology

In order to gain an appropriate and deep understanding of the IOBP 4.0 context, it was necessary to conceptualize the domain by an ontology since they are appropriate means for the explication of domain knowledge and its core concepts [123], [124]. Informal ontologies are a means to that end, functioning as a terminological and conceptual basis [125], [126]. For the ontology modelling the main concepts, relationships, and properties of the domain context were structured and introduced. The goal was to establish an overview of the concepts, challenges, and requirements of I4.0 and IOBP. By using an informal notation, the several IOBP 4.0 concepts (e.g., technologies, resources, roles, activities) were introduced and connected in a brainstorming process. Each of the main concepts (in grey) was derived and explored, to connect and identify new concepts.

Figure 19 presents the domain ontology for IOBP 4.0.

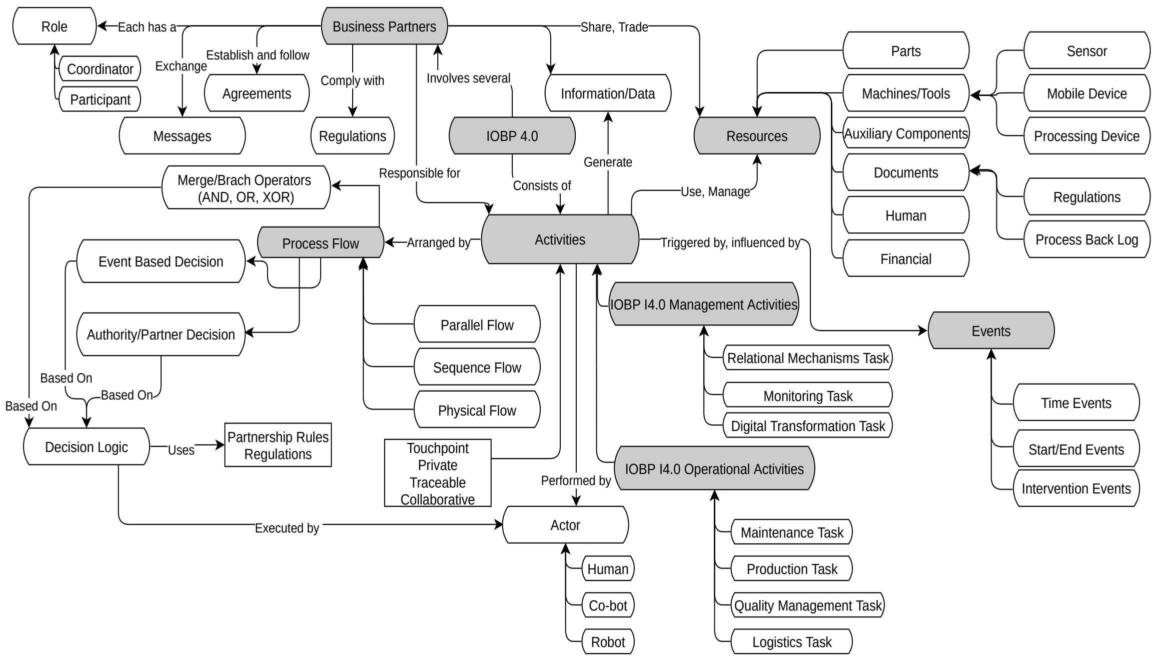


Figure 19 – Domain Ontology for IOBP 4.0

This domain's central concept is the business process involving two or more business partners (IOBP 4.0, on the top) and their individual/interrelated process activities [14].

Each business partner acts in the process (coordinates or participates) according to inter-organizational agreements established by the partners. Partners must comply with specific regulations (e.g., laws, procedures, standards, contract agreements) [87], exchange information/data (through messages and documents) [20]. In addition, they may share resources in the manufacturing network (e.g., parts, auxiliary materials) [102].

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 materials, machines, human, financial) [102]. There is a bidirectional impact between activities and events (e.g., time events, start/end events, intervention events) that coexist in business processes [20]. Activities' data may be public or private, requiring traceability [61]. The activities are executed according to a process flow (e.g., parallel flow, partner flow, physical flow), as shown on the left side of figure 19. 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) [20] executed by actors (e.g., human, co-bot, robot).

4.2.3 Modelling Requirements

The design of IOBP becomes challenging, to represent all the concepts, properties, and requirements properly. The literature review on IOBP and I4.0 concepts revealed challenges and conditions to be fulfilled while modelling IOBP. This step aims to understand the domain in detail and derive requirements to the modelling approach [18] for the domain of IOBP 4.0.

The requirements are understood as the explication of the domain concepts that need to be covered by the modelling language to represent a specific domain [18]. Regarding the field of Requirements Engineering (RE) and its application in business process modelling, it is necessary to focus mainly on the early stages of RE. If there is a group of users of the prospective modelling language (e.g., practitioners), the description of use cases can be applied to identify the requirements. If there is no specific user group, literature and state-of-the-art reviews can provide insights into requirements. In this specific project, the latter method will be followed, based on the literature review and previous works on the field of IOBP 4.0. The identified domain requirements to the modelling language should be supported by a semiformal requirements modelling approach due to the identification of concepts [18]. The domain requirements analysis was conducted to understand the domain in detail and derive the necessary requirements for the IOBP 4.0 modelling approach.

Table 9 summarizes the modelling requirements for the domain of IOBP 4.0.

Table 9 – Modelling Requirements for IOBP 4.0

Requirement	Description	Reference
R1	Provide basic concepts that allow the representation of public or private elements (e.g., tasks, data, and process parts).	[14], [20], [119]

R2	Represent tasks executed in collaboration and resources shared by the business partners (e.g., parts, components, documents).	[14], [20], [119]
R3	Represent the sharing of essential data and meaningful events between the several partners.	[14], [119]
R4	Represent the several business partners and the flow of activities executed across the partners.	[84], [85], [122]
R5	Represent the authority capacity of an organization to intervene or decide in specific moments.	[14], [120]
R6	Use terminology standardization to establish a common semantic language across several business partners.	[14]
R7	Represent the temporal dependencies and explicit time events.	[20]
R8	Represent the communication by messages/channels between the several partners and the exchanged information at those moments.	[20]
R9	Represent the tasks related to the management IOBP (transformation/innovation tasks, relational mechanisms tasks, monitoring tasks, and manufacturing tasks).	[20], [61]
R10	Represent the tasks, resources, and documents that the specified business partners remotely monitor.	[14], [119]
R11	Represent the tasks related to the manufacturing domain, specifically: production, quality management, logistics, and maintenance.	[102], [116]
R12	Represent the multiple resources used and shared by the several partners (e.g., documents, machines, parts, components).	[50], [77]
R13	Represent the several norms and compliance requirements that the several business partners must follow.	[50], [87]
R14	Represent the several machines and devices used, especially in manufacturing activities and tasks, such as sensors, production machines, or other types of devices.	[102], [116]
R15	Represent the process interfaces in the business partners, between internal and external or collaborative business process parts.	[20], [85]
R16	Represent the actors responsible for the execution of specific activities.	

The modelling requirements compiled in table 9 are essential to synthetize the aspects that a modelling language must address to represent IOBP 4.0 models properly. Based on the defined domain concepts and modelling requirements, the comparison with standard BPMN is conducted to identify the need for extension. This step is called the equivalence check and is presented in the following subsection.

4.3 Equivalence Check

The equivalence check step is conducted to evaluate whether the several identified concepts (enhanced in the modelling requirements and the domain ontology) are semantically equivalent (or not) to the existing standard BPMN elements.

The core of the IOBP4.0 BPMN extension is designed based on the domain concepts and the several corresponding requirements stated previously in the subsections. Each of the identified requirements may cover one or more domain concepts. In this step, the goal is to use these identified concepts and execute a semantic comparison/equivalence with the standard BPMN elements to identify the need or not (reasonably) for an extension in the form of new elements or properties. The element descriptions and explanations of the BPMN standard specification [100] were used. This comparison allows the identification of the required adaptions and extensions to the BPMN standard elements. In the equivalence check, the several concepts are classified into three essential equivalence categories: equivalence, conditional equivalence, and no equivalence. According to the equivalence check category, the several concepts are then classified as *BPMN Concept* or *Extension Concept*, which will feature in the CDME model. The following sentences present a description of the several equivalence categories and rules, according to the definition of [18]:

- Equivalence: It states that there is a semantically equivalent construct in the BPMN standard notation. A construct is understood as a valid combination of several elements or a single element of the BPMN standard. In this case of equivalence, no extension is necessary, and the domain concept is represented as a *BPMN Concept* in the CDME model.
- Conditional equivalence: This condition states that there is no apparent semantic matching with elements from the standard BPMN. Instead, it must be decided individually whether the semantics of a BPMN element still corresponds to the semantics of a domain-specific element. Therefore, it is necessary to give reasons for a possible mapping or explain why it is not reasonable. This analysis and discussion are necessary since the BPMN meta model specifies some elements in a vast range [100]. Depending on this analysis, the concept is either treated as an equivalent concept (*BPMN Concept*) or expanded as a non-equivalent concept (*Extension Concept*).
- No equivalence: There is no equivalence to any BPMN standard element, and there are three fundamental reasons for that. First, the entire concept is missing entirely in the notation. In this case, the domain concept is represented as *Extension Concept* in the CDME model. Second, a relation between two standard BPMN concepts is missing. Therefore, an association between the affected concepts is constructed in the CDME model. Third, owned attributes of a BPMN standard concept are missing. Then, an owned property is assigned to the element in the CDME model.

The presented categories of equivalence were used to execute the comparison between the identified modelling requirements and the standard BPMN. The equivalence check is one of the essential steps regarding the creation of a BPMN extension. This step is crucial for both an acceptable use of the BPMN and the avoidance of unnecessary extension elements [18] to cope with the simpleness and objectivity of the BPMN modelling language. An extension must use concepts and constructs from standard BPMN to keep the number of extended elements small and to exhaust the vocabulary of BPMN [18].

Table 10 presents the results of the equivalence check.

Table 10 – Equivalence Check Table for IOBP 4.0

Req	Concept	Semantics	Equivalence Check	CDME
R1	Sub-Process	Representation of Private or Public parts of the business process.	Equivalence -> Task, Activity and the use of Internal, External and Abstract Sub-Process.	BPMN Concept
R1	Activity	Representation of specific tasks that may be private or public. Other organizations can't obtain information on private tasks in the business process.	No Equivalence	Extension Concept
R2 and R4	Process	Representation of the several participants in the business process.	Equivalence -> Pools and Lanes.	BPMN Concept
R2	Activity	Representation of specific tasks that are executed in collaboration between several organizations.	No Equivalence	Extension Concept
R3 and R10	Activity	Representation of specific tasks remotely monitored by the involved organizations, due to the importance of that task.	No Equivalence	Extension Concept
R3 and R10	Events	Representation of specific events remotely monitored by the involved organizations, due to the importance of that event.	No Equivalence	Extension Concept
R4 and R15	Process Flow	Representation of the flow of the activities across the several partners in sequence.	Equivalence -> Sequence Flow and Pools/Lanes.	BPMN Concept
R5	Partner Decision	Representation of the decision of a partner in specific moment of the business process in which "path" to follow.	No Equivalence	Extension Concept

R5	Partner Intervention	Representation of the intervention of a partner in specific tasks of the business process.	No Equivalence	Extension Concept
R5	Partnership Manager	Representation of the organization that has a significant coordination role in the business process.	No Equivalence	Extension Concept
R5	Partnership Participant	Representation of the organization that participates in the business process.	No Equivalence	Extension Concept
R6	BPMN Standard	Representation of the business process in a standardized way, creating a common specification across the organizations. Use of strategic guidelines while specifying the business process.	Equivalence -> Standard BPMN and specification.	BPMN Concept + Language Specification
R7	Time Events	Temporal aspects, dependencies, and restrictions in the form of reference times, periods, or specific time values.	Equivalence -> Timer Events	BPMN Concept
R8 and R15	Messages and Message Events	Representation of information exchange or flow across the business process.	Conditional Equivalence -> Use of messages. There is a need to complement the use of messages with more information.	Extension Concept
R8	Physical Flow	Representation of the exchange of physical resources between the several partners.	No Equivalence	Extension Concept
R9	Activity	Representation of the sub-type of tasks regarding the management and execution of IOBP I4.0: digital transformation/innovation tasks, relational mechanisms tasks,	Conditional Equivalence -> Sub-types of tasks that exist in the current BPMN are not specific enough to	Extension Concept

		monitoring tasks, and manufacturing tasks.	represent the previously mentioned sub-tasks.	
R10	Documents	Representation of the retrieved monitoring data across the several partners.	Conditional Equivalence -> Existing Data Object is not specific enough to represent this sub-type of document	Extension Concept
R11	Activity	Representation of the several sub-types of tasks related to the essential activities inherent to I4.0 and manufactory: logistics/inventory, production, quality management and maintenance.	Conditional Equivalence-> Sub-types of tasks that exist in the current BPMN are not specific enough to represent the previously mentioned manufacturing sub-tasks.	Extension Concept
R12	Artefacts	Representation of the several resources used and exchanged in I4.0 and manufacturing: parts and auxiliary materials.	No Equivalence	Extension Concept
R13	Documents	Representation of regulations (e.g., norms, laws) followed by the entities.	No Equivalence	Extension Concept
R14	Artefacts	Representation of the several tools and devices used and exchanged in I4.0 and manufacturing: machines, devices, sensors.	No Equivalence	Extension Concept
R16	Actors	Representation of the actors that execute tasks or take decisions.	No Equivalence	Extension Concept

In total, 17 concepts were classified as *Extension Concept*, while five as *BPMN Concept*. As *Extension Concept* emerge aspects related to the representation of the several types of resources used in I4.0 related activities (e.g., parts, components, sensors, machines, devices), as well as the representation of the process participants' roles and the representation of the regulations that each of the participants must follow. The representation of tasks related to manufacturing activities (e.g., logistics task, quality management task) and the management of IOBP (e.g., relational mechanisms task, digital innovation task) are also featured as *Extension Concept*. The representation of the actors (e.g., human, robot, co-bot) executing tasks and taking decisions was also considered an *Extension Concept*, as well as the representation of the task visibility (e.g., private task, touchpoint task) and resource/data object visibility (e.g., a private document, shared document). As *BPMN Concept* emerges, the representation of the several business partners (supported using the BPMN pools) and the representation of time events and dependencies. The representation of the process flow (across the time and several partners) is also classified as *BPMN Concept* and the sub-process representation (e.g., private sub-process, public sub-process).

An extension must use concepts and constructs from standard BPMN to keep the number of extended elements small and to exhaust the vocabulary of BPMN [18]. Therefore, the classification of each concept as classification as *BPMN Concept* or *Extension Concept* is one of the most critical steps towards developing BPMN Extension, by defining the elements to be featured in CDME as *Extension Concepts*, resulting in the creation of the new extension elements. In the following subsection, the CDME for IOBP 4.0 is presented.

4.4 Domain Conceptualization

The Conceptual Domain Model of the Extension (CDME) represents the domain and BPMN concepts and their relationships. The CDME includes BPMN concepts and extension concepts derived from identifying extension requirements and the equivalence check stage. Based on the detailed analysis of each essential concept, the CDME model was created. The *Extension Concept* stereotype marks extension elements and BPMN elements are marked by the *BPMN Concept* stereotype. The CDME construction is based on the extension of the standard BPMN meta-model defined in the OMG's BPMN specification [105]. Figure 20 introduces the CDME of IOBP 4.0.

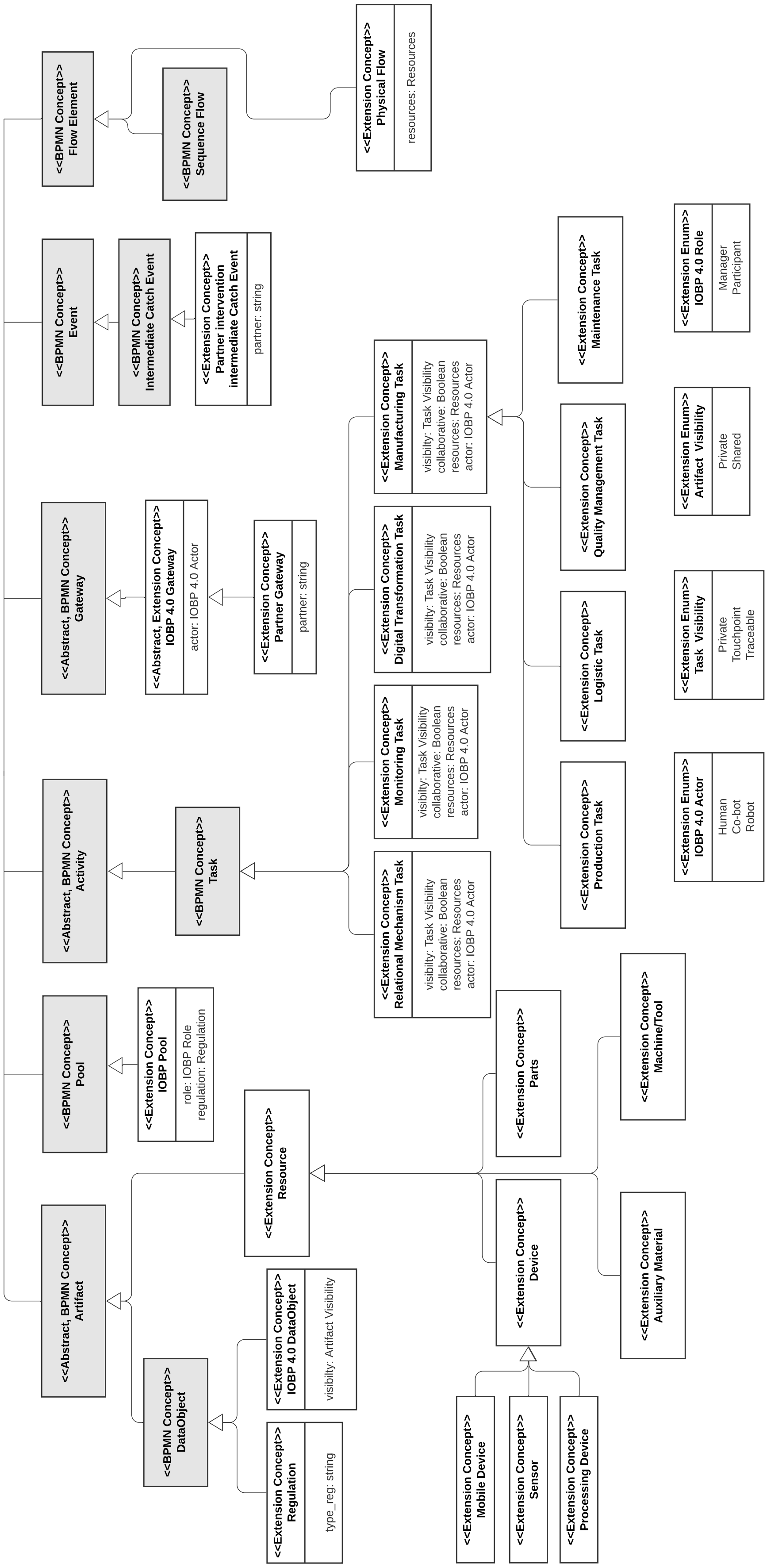


Figure 20 – CDME for IOBP 4.0

The CDME presented in figure 20 represents the domain model of IOBP 4.0. The BPMN *Artefact* concept has been extended in order to represent the four types of resources that are essential in the context of IOBP 4.0 and manufacturing activities [116]: machines/tools; parts; devices (e.g., mobile devices, sensor, processing devices); and auxiliary materials (on the left of figure 20).

The BPMN *Task* concept (in the middle of figure 20) was extended with (1) manufacturing particularities and supplemented with (2) IOBP tasks for monitoring, (3) managing relationships, and (3) digital transformation. The latter three concepts are aimed at creating synergies among process partners. Finally, manufacturing-related tasks can be quality control, inventory control, production, and maintenance [102]. Each task has a classification regarding visibility (e.g., private, touchpoint, traceable), creating the task visibility *Extension* Enum. The *Artefact Visibility* Enum was introduced to represent the visibility of artefacts (e.g., private, shared).

The BPMN *Pool* concept was extended to represent the IOBP 4.0 pool, characterizing the role of each of the process participants (e.g., manager, participant) and the regulations followed by each one (on the centre left of figure 20). The *Actor* Enum was introduced to represent the several types of actors that execute the activities (e.g., human, co-bot, robot). Resources may be shared across the different partners.

The *BPMN Data Object* was extended in order to represent the several compliance regulations that each actor must follow while executing their activities [87] (on the upper left of figure 20).

The BPMN *Gateway* concept was extended initially to introduce the actor involved in the gateway path decision. The BPMN *Gateway* was also extended by creating the "Partner Gateway", and the event concept was extended with the intermediate partner event (event raised by a partner's decision in specific moments of the business process) [19], [127].

The BPMN *Flow Element* concept was extended to represent the exchange of resources across business processes [102], creating the Physical Flow (on the upper right of figure 20). Finally, the data object concept was extended to represent the process backlog: information related to the monitorization of the business process [61] and analysis (on the upper left of figure 20).

After defining the CDME, the next step is to transform the CDME into a valid BPMN extension meta-model by applying the transformation rules presented by [34].

4.5 BPMN Meta-Model of the IOBP 4.0 Extension

Based on the model transformation rules stated by [34], we defined a valid extension meta model (BPMN+X model) by applying a set of transformation rules defined by [34]. The rules allow us to transform the CDME into a valid extension meta model (BPMN+X model). Figure 21 presents the final meta-model of the IOBP 4.0 extension.

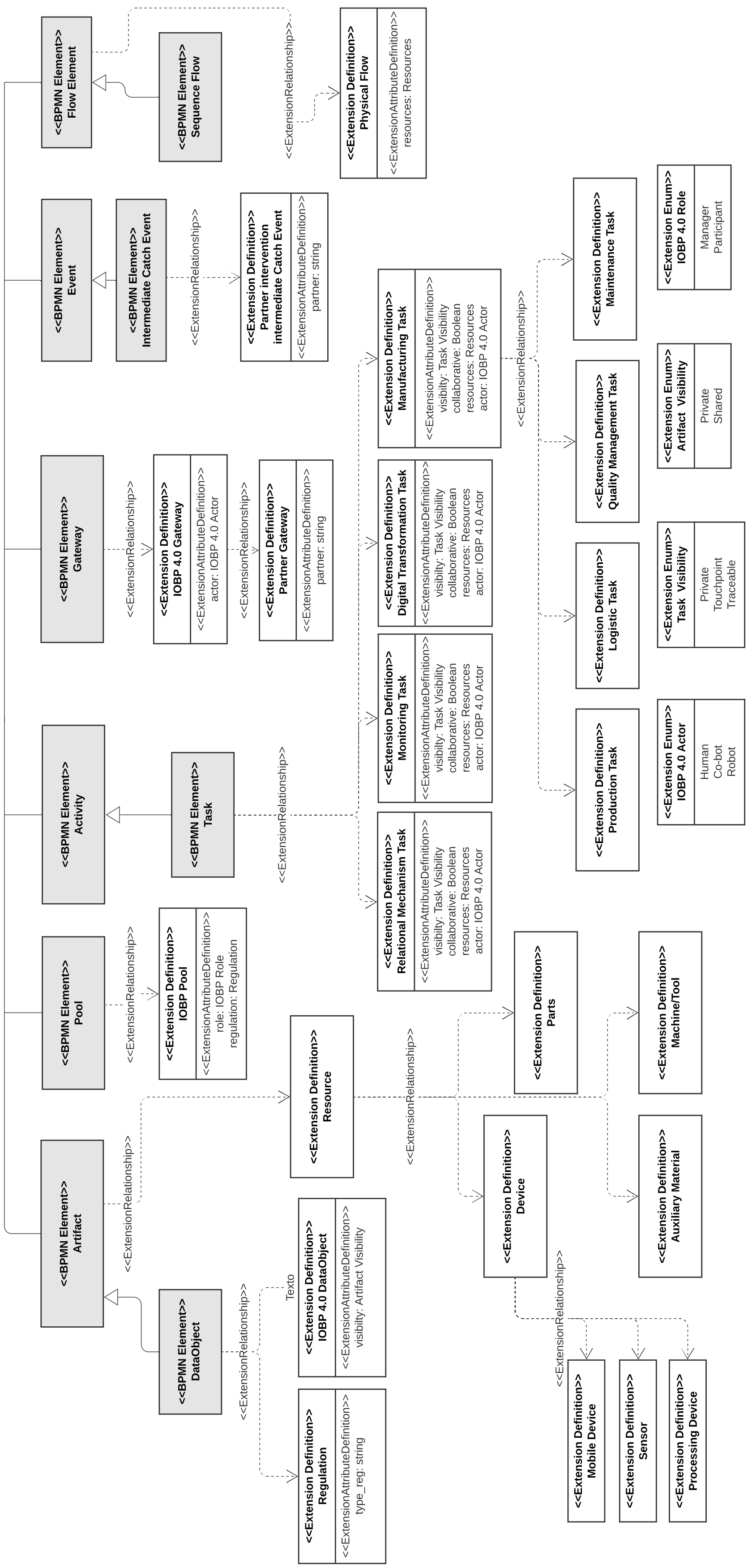


Figure 21 – BPMN+X Model for IOBP 4.0

After defining the meta-model of the extension and the CDME of IOBP 4.0, the representation and characterization of the new extension followed (Section 4.5).

4.6 Extension Elements Definition

According to the classification presented in both CDME and meta-model of the IOBP 4.0 extension, the definition, and characteristics of the several extension elements are presented in the following subsections. First, the elements are described, and then a summary table is presented, defining the extension elements according to the BPMN standard description of an extension.

4.6.1 Regulation

The regulations are aimed to represent the laws, standards, and agreements that a specific business partner must follow and respect (e.g., ISO 9001, ISO 45001) while being involved in a business process. The element extends the BPMN *Data Object* concept. Therefore, it inherits the attributes and associations from that concept. The type_reg attribute was added to clarify the type of regulation related to that element (e.g., ISO, law, agreement). Table 11 presents the Regulation extension element definition.

Table 11 – Regulation - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Regulations	
Extension Attribute Definition	
1 - type_reg: string	Defines the type of regulation that the business partner must comply with (e.g., law, standardization, norms, agreement).
Extension Attribute Value	
1 - string	The type can specify the law, standardization, or agreement that is followed by the business partner (e.g., ISO 9001, Brexit Trade Agreement)

4.6.2 IOBP 4.0 Data Object

The BPMN *Data Object* allows the representation of the data flowing through a business process that may be passed between several activities or between the partners. The IOBP 4.0 data object extends BPMN *Data Object*; therefore, it inherits the attributes and associations from that concept. The IOBP 4.0 data object considers an additional attribute representing the visibility (e.g., private, shared) of the Data Object. Table 12 presents the IOBP 4.0 data object extension element.

Table 12 – IOBP 4.0 Data Object - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
IOBP 4.0 Data Object	
Extension Attribute Definition	
1 - visibility: Artefact Visibility Enum	This attribute defines the visibility/ access to the Data Object for the business partners in the process.
Extension Attribute Value	
1 – Private/Shared	The visibility/access of the Data Object may be private or shared.

4.6.3 Resource

Resources are concerned with representing the several types of resources that might be shared between the several business partners and used in several activities. The resource element extends the BPMN Artefact concept; therefore, it inherits the attributes and associations from that concept. The goal is to consider the representation of several types of resources (e.g., parts, auxiliary materials, machines/tools, mobile devices). Therefore, an additional attribute representing the visibility (e.g., private, shared) of the Resource was added. Table 13 presents the Resource extension element.

Table 13 – Resource - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Resource (Mobile Device, Sensor, Processing Device, Auxiliary Material, Parts, Machine/Tool)	
Extension Attribute Definition	
1 – resource_visibility: Artefact Visibility Enum	This attribute defines the visibility/ access to the Resources for the business partners in the process.
Extension Attribute Value	
1 - Private/Shared	The visibility/access of the Resources may be private or shared.

The resources were extended to consider the several types of resources, from devices to 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. Sensors are currently used in tasks or incorporated in resources, enabling the retrieval of data and traceability of tasks and resources. Mobile devices (e.g., tablets, mobile phones, remote commands) are used to execute or monitor several types of activities. Auxiliary materials are used for manufacturing activities (e.g., raw materials) to obtain products. Machines/tools are used to support the execution of more complex and heavy activities (e.g., production machinery). Processing devices are used in process tasks to record information, manage documents, execute algorithms, or analyse data.

4.6.4 IOBP 4.0 Pool

The IOBP 4.0 Pool is aimed to represent the business partners that participate in the business process. The elements result from the extension of the BPMN Pool concept, inheriting the attributes and associations from that concept. It introduces the addition of a new attribute (role) representing the role of each business partner and another attribute representing the regulations that are concerned with a partner's activity (regulation). The partnership manager is the main responsible for the execution, monitoring, and management of the IOBP. The partnership participant is responsible for executing activities and reporting the agreed information to the partnership manager. Table 14 presents the IOBP 4.0 Pool extension element.

Table 14 – IOBP 4.0 Pool - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
IOBP 4.0 Pool	
Extension Attribute Definition	
1 – role: IOBP 4.0 Role Enum	This attribute defines the role of the business partner in the business partner.
2 – regulation: Regulation	This attribute defines the regulations that are followed by the business partner (e.g., law, ISO, agreement).
Extension Attribute Value	
1 – Manager/Participant	The role of business partner can be of manager or participant.
2 – Regulation	Specify the law, standardization or agreement that is followed by the business partner (e.g., ISO 9001, Brexit Trade Agreement)

4.6.5 Relational Mechanism Task

The relational mechanism task is aimed to represent the activities related to the management of inter-organizational relationships between the business partners, managing the responsibilities and capacities of the partners. The relational mechanism task extends the

BPMN Task concept, inheriting the attributes and associations from that concept and introducing a new sub-type of task. Additionally, four extension attributes are considered, as follows: (1) the task visibility for the business partners (e.g., private, touchpoint, traceable), (2) the task execution in collaboration, (3) the resources involved in the execution of the task (e.g., parts, devices) and (4) the actor responsible for the execution of the task (e.g., human, robot, co-bot). Table 15 presents the Relational Mechanism Task extension element.

Table 15 – Relational Mechanism Task - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Relational Mechanism Task	
Extension Attribute Definition	
1 – visibility: Task Visibility Enum	This attribute defines the visibility/ access of the Task for the business partners in the process.
2 – collaborative: Boolean	This attribute defines if the Task is executed in collaboration between several partners.
3 – resources: Resource	This attribute defines the set of Resources that are used in the tasks.
4 – actor: IOBP Actor	This attribute defines the actor responsible for the execution of the task.
Extension Attribute Value	
1 – Private, Shared	The visibility/access of the Resources may be private or shared.
2 – True, False	If the task is executed in collaboration, the value is true. Otherwise, the value is false.
3 – Processing Device, Mobile Device, Sensor, Machine/Tool, Part, Auxiliary Material	Resources that are used during the execution of the the task in the domain of manufacturing operations.
4 – Human/Robot/Co-bot	The task may be executed by a human, a robot or a co-bot.

4.6.6 Digital Transformation Task

The digital transformation task aims to represent the activities related to the execution of improvements using digital technologies in the business process to promote joint innovation mechanisms and keep the business process with the most reliable and efficient solutions. The digital transformation task extends the BPMN Task concept, inheriting the attributes and associations from that concept and introducing a new sub-type of task. Additionally, four extension attributes are considered, as follows: (1) the task visibility for the business partners (e.g., private, touchpoint, traceable), (2) the task execution in collaboration, (3) the resources involved in the execution of the task (e.g., parts, devices) and (4) the actor responsible for the execution of the task (e.g., human, robot, co-bot). Table 16 presents the Digital Transformation Task extension element.

Table 16 – Digital Transformation Task - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Digital Transformation Task	
Extension Attribute Definition	
1 – visibility: Task Visibility Enum	This attribute defines the visibility/ access of the Task for the business partners in the process.
2 – collaborative: Boolean	This attribute defines if the Task is executed in collaboration between several partners.
3 – resources: Resource	This attribute defines the set of Resources that are used in the tasks.
4 – actor: IOBP Actor	This attribute defines the actor responsible for the execution of the task.
Extension Attribute Value	
1 – Private, Shared	The visibility/access of the Resources may be private or shared.
2 – True, False	If the task is executed in collaboration, the value is true. Otherwise, the value is false.
3 – Processing Device, Mobile Device, Sensor, Machine/Tool, Part, Auxiliary Material	Resources that are used during the execution of the the task in the domain of manufacturing operations.
4 – Human/Robot/Co-bot	The task may be executed by a human, a robot or a co-bot.

4.6.7 Monitoring Task

The monitoring task is aimed to represent the activities related to the evaluation and monitoring of the performance of the shared elements (e.g., process execution-level agreements) regarding the existing challenges in decentralized activity management. The monitoring task extends the BPMN Task concept, inheriting the attributes and associations from that concept and introducing a new sub-type of task. Additionally, four extension attributes are considered, as follows: (1) the task visibility for the business partners (e.g., private, touchpoint, traceable), (2) the task execution in collaboration, (3) the resources involved in the execution of the task (e.g., parts, devices) and (4) the actor responsible for the execution of the task (e.g., human, robot, co-bot). Table 17 presents the monitoring task extension element.

Table 17 – Monitoring Task - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Monitoring Task	
Extension Attribute Definition	
1 – visibility: Task Visibility Enum	This attribute defines the visibility/ access of the Task for the business partners in the process.
2 – collaborative: Boolean	This attribute defines if the Task is executed in collaboration between several partners.
3 – resources: Resource	This attribute defines the set of Resources that are used in the tasks.
4 – actor: IOBP Actor	This attribute defines the actor responsible for the execution of the task.
Extension Attribute Value	
1 – Private, Shared	The visibility/access of the Resources may be private or shared.
2 – True, False	If the task is executed in collaboration, the value is true. Otherwise, the value is false.
3 – Processing Device, Mobile Device, Sensor, Machine/Tool, Part, Auxiliary Material	Resources that are used during the execution of the task in the domain of manufacturing operations.
4 – Human/Robot/Co-bot	The task may be executed by a human, a robot or a co-bot.

4.6.8 Manufacturing Task

The manufacturing task is aimed to represent the activities related to the execution of manufacturing-related activities, from production to quality control and logistics. The manufacturing task extends the BPMN Task concept, inheriting the attributes and associations from that concept and introducing a new sub-type of task. Additionally, four extension attributes are considered, as follows: (1) the task visibility for the business partners (e.g., private, touchpoint, traceable), (2) the task execution in collaboration, (3) the resources involved in the execution of the task (e.g., parts, devices) and (4) the actor responsible for the execution of the task (e.g., human, robot, co-bot). Table 18 presents the manufacturing task extension element.

Table 18 – Manufacturing Task - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Manufacturing Task	
Extension Attribute Definition	
1 – visibility: Task Visibility Enum	This attribute defines the visibility/ access of the Task for the business partners in the process.
2 – collaborative: Boolean	This attribute defines if the Task is executed in collaboration between several partners.
3 – resources: Resource	This attribute defines the set of Resources that are used in the tasks.
4 – actor: IOBP Actor	This attribute defines the actor responsible for the execution of the task.
Extension Attribute Value	
1 – Private, Shared	The visibility/access of the Resources may be private or shared.
2 – True, False	If the task is executed in collaboration, the value is true. Otherwise, the value is false.
3 – Processing Device, Mobile Device, Sensor, Machine/Tool, Part, Auxiliary Material	Resources that are used during the execution of the task in the domain of manufacturing operations.
4 – Human/Robot/Co-bot	The task may be executed by a human, a robot, or a co-bot.

Ultimately, the manufacturing task was extended to represent the four essential sub-types of activities involved in the manufacturing domain: (1) production task, (2) logistics task, (3) quality management tasks, and (4) maintenance task. The production task represents a sub-type of a manufacturing task related to the execution of production activities (e.g., assembly of parts, cleaning of components, handcraft of products, heat treatment). The quality management task represents a sub-type of a manufacturing task related to the execution of quality management activities (e.g., product testing, measuring parts, check non-conformities) to keep the products in accordance with the quality standards and regulations. The logistics task of a manufacturing task is related to the logistics activities' execution (e.g., packaging, handling, materials' storage), involving the movement, storage, or tracking of several used resources. Finally, the functions' maintenance task represents a sub-type of a manufacturing task related to the execution of equipment and tools maintenance to ensure their availability for manufacturing or execution of preventive maintenance.

4.6.9 IOBP 4.0 Gateway

The IOBP 4.0 gateway extend the standard BPMN Gateway concept, inheriting the attributes and associations from that concept. The goal is to represent the actor involved in the determination of the path to be followed in the gateway. The goal was achieved by including an additional attribute, the actor that verifies the condition and chooses the path. Table 19 presents the IOBP 4.0 gateway extension element.

Table 19 – IOBP 4.0 Gateway - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
IOBP 4.0 Gateway	
Extension Attribute Definition	
1 – actor: IOBP Actor	This attribute defines the actor responsible for the execution of the task.
Extension Attribute Value	
1 – Human, Robot, Co-bot	The task may be executed by a human, a robot, or a co-bot.

4.6.10 Partner Gateway

The partner gateway is created to represent a moment in the flow in which a specific partner decides the "path" of the activities to be executed in the following steps. The partner gateway extends the IOBP 4.0 gateway inheriting the attributes and associations from that concept. The goal is to consider an additional attribute regarding the business partner that is responsible for the decision. Table 20 presents the partner gateway extension element.

Table 20 – Partner Gateway - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Partner Gateway	
Extension Attribute Definition	
1 – partner: string	This attribute defines the business partner responsible for the decision.
Extension Attribute Value	
1 – String	Denomination of the partner with the responsibility for the decision (e.g., Partner A, Partner B).

4.6.11 Partner Intermediate Catch Event

The partner intermediate event represents a specific partner's intervention in an activity, started by an authorized partner's decision. The element results from the extension of the Intermediate Catch Event BPMN concept, inheriting the attributes and associations from that concept. The goal is to include a new attribute regarding the business partner that is responsible for the intervention. Table 21 presents the partner intermediate catch event extension element.

Table 21 – Partner Intermediate Catch Event - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Partner Intermediate Catch Event	
Extension Attribute Definition	
1 – partner: string	This attribute defines the business partner responsible for the decision.
Extension Attribute Value	
1 – String	Denomination of the partner with the responsibility for the decision (e.g., Partner A, Partner B).

4.6.12 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. The element results from the extension of the Flow Element BPMN concept, inheriting the attributes and associations from that concept. The goal is to include a new attribute regarding the resources that are transported/exchanged at that moment. Table 22 presents the physical flow extension element.

Table 22 – Physical Flow - Extension Element Definition

IOBP 4.0 Extension	
Extension Definition	
Physical Flow	
Extension Attribute Definition	
1 – resources: Resource	This attribute defines the Resources that are transported/exchanged between the partners.
Extension Attribute Value	

1 – Processing Device, Mobile Device, Sensor, Machine/Tool, Part, Auxiliary Material	The resources that are exchanged by the business partners in the domain.

4.7 IOBP 4.0 Syntax

4.7.1 Graphical Representation Design Principles

The concrete syntax of the IOBP 4.0 BPMN extension is one of the most critical steps of the extension's design since it will be the tool that the experts will use to evaluate and analyze the modelling activities and a core aspect in the BPMN modelling language. Therefore, there was the need to define a straightforward approach for the proposal of a clear and compelling BPMN extension concrete syntax (the graphical representation of the IOBP 4.0 extension elements). Furthermore, regarding the specificities and goals of the BPMN modelling language, the design process needed a set of clear design goals.

The work of [128] defines a "set of principles for designing cognitively effective visual notations: ones that are optimized for human communication and for problem solving". The work of [128], stresses the efficiency of cognitive effectiveness. According to [128], the cognitive effectiveness refers essentially to the "speed, ease, and accuracy with which a representation can be processed by the human mind". Based on this statement, one of the main design priorities of the graphical representation of the IOBP 4.0 BPMN extension was to be simple – yet expressive – so that its meaning can be communicated successfully and effectively to all the stakeholders and actors involved in the business process. There was also the need to consider the several relevant domains concerning manufacturing activities that involve business managers, operators, and productions engineers. This characteristic is essential for the design of BPMN Extension, regarding on of the main goals of BPMN, to be an intuitive and straightforward notation.

Before starting the creation and selection process of the extension designs, there is the need to establish the basis for the design concepts. The work of [128] establishes a set of principles for the construction of a visual notation, enhancing the most important aspects that must be featured in terms of design. Based on the work of [128] several of the proposed principles are used in this project in order to develop the graphical representation of the BPMN extension elements. In total, six design principles were defined, as presented below.

The first design principle is concerned with the visual representation of the newly developed extension symbols. The graphical representation is one of the aspects with a significant influence on cognitive effectiveness, as it affects the understanding of the represented concepts [129]. For the identification of suitable symbols for the graphical representation of the extension concepts, a review in the domain of manufacturing and IOBP (executed in the previously presented literature review) has been performed as well as a brainstorming session and the analysis of several documents provided by the partner companies to consider the usual type of notation presented to users furtherly. This reflection on the graphical representation is important regarding two eventual problematic situations: (1) avoid the problem of visual dialects (multiple graphical forms representing semantically equivalent concepts) and (2) aid perceptual interpretation by novice users [130]. These assumptions are based on the "*Principle of Semiotic Clarity*" [128], in which it is stated and discussed that the issues related to symbol redundancy (when multiple symbols may represent the same concept) and symbol overload (when the same symbol can represent two different concepts) [128]. Considering this, the several new extension concepts discussed for implementation should have a one-to-one correspondence between the concepts and their symbols. Finally, as per the "*Principle of Perceptual Discriminability*" [27], that is conceived as "the ease and accuracy with which graphical symbols can be differentiated from each other ", the designs are to be clearly distinguishable from each other. Therefore:

- Design Principle 1: *The appearance must be descriptive, unique, and specific for each concept* [128].

The complexity of the designs shall be kept as minimum as possible. In this context, the "complexity" refers to the amount of information that a diagram element concerns to. The goal of this principle is that the representation should transmit the correct meaning (of the concept) without overloading the user's perceptual capacity. This aspect is mentioned by [128], in the "*Principle of Semantic Transparency: Use Visual Representations Whose Appearance Suggests Their Meaning*", in which the author states that "semantic transparency is defined as the extent to which the meaning of a symbol can be inferred from its appearance" and elements "they provide cues to their meaning" [128]. This reflection on the graphical representation is important regarding two essential situations: (1) BPMN diagrams are not only designed on modelers (such as *Signavio* [108] and *Bizagi* [110]) but also drawn by hand, (2) the users may have several backgrounds but although they should be clear about the goal of each concept and (3) usually on the manufacturing models may be printed, and complex symbols might not be sensible in the printed version. Therefore:

- Design Principle 2: *The complexity of the notation elements must be minimized as possible* [128].

As previously mentioned in this dissertation, this project is focused primarily on the visualization-related aspects of the extension elements (the new proposed elements and their application in the context of IOBP 4.0). In addition, the complexity of the extensions should be minimized beyond the scope of the visual design of the elements. The relationships of the extension elements with other BPMN elements that might be technically necessary for the execution of the model may be neglected when their inclusion significantly complicates the understandability of the process model (essentially in graphical representation) for the several stakeholders. This principle is relevant by acknowledging the scope of this research project that aims to highlight the visualizing aspect of the introduced elements over their execution. Another relevant aspect was that there was no interest from the partner companies in establishing an execution environment for the BPMN extension regarding the complexity of such task and the need to prepare a complex network of elements while focusing on the potential of the representation and completeness of visual models. Therefore:

- Design Principle 3: *Execution semantics of the IOBP 4.0 BPMN extension may be neglected* [128].

The design of the newly introduced concepts should allow them to be accompanied/supported by text (or annotations). Using text or annotation play a supportive role to the symbols to upgrade their expressiveness, clarification, and completeness. As it was mentioned in Design Principle 1, the designs will be unique for each of the newly introduced concepts and distinctive from the standard ones. Thus, the text should only improve the expressiveness of concepts and not act as the main mean of distinguishing them among other concepts. In the standard BPMN, elements such as "Gateways", "Tasks" or "Flows" already allow text to be included within their design or the inclusion of annotations.

This behaviour should be preserved for all the newly introduced extension elements. Therefore:

- Design Principle 4: *Designs should allow text accompaniment* [128].

It is vital to guarantee that the new extension designs are not exclusively differentiated based on colour of the concepts "(…) *as it is sensitive to variations in visual perception (e.g., colour blindness) and screen/printer characteristics (e.g., black-and-white printers)* " [128]. There are several issues supporting this statement. The most important one is the limitation it imposes to the use of the element with respect to certain users, such as colour blind. Another practical issue may be the unavailability of basic colours for any reason (on paper or even digitally). It would be more complex to be presented or drawn on paper. Then, the use of colour to distinguish elements should be overall excluded from the design process of the new elements. Therefore:

- Design Principle 5: *The use of colours should be omitted* [128].

The IOBP 4.0 BPMN Extension should be compliant with BPMN as a valid extension. One of the key priorities should be that the standard BPMN is not altered. The new elements introduced by the extension shall elevate the understanding and representation of the performed IOBP 4.0 action without replacing the standard BPMN elements. The new designs should also be unique regarding the existing BPMN symbols. Therefore:

- Design Principle 6: *Standard BPMN representation is preserved* [128].

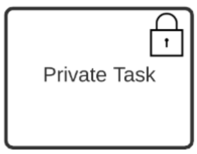
These defined design principles set some requirements to be fulfilled while representing the extension elements graphically. The following subsection presents the defined concrete syntax for the IOBP 4.0 extension elements.

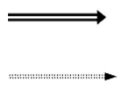
4.7.2 Graphical Representation of the IOBP 4.0 extension

The IOBP 4.0 elements were designed according to the defined design principles, aiming to comply with the goals of the standard BPMN language. In addition, the graphical representation of the extension concepts was developed using Lucidchart [25] and its icon library, aiming to support the representation of the IOBP 4.0 concepts. Table 23 presents the specific syntax of the IOBP 4.0 BPMN extension elements, followed by the graphical representation.

Table 23 – Graphical Representation of IOBP 4.0 BPMN Extension Concepts

Custom Elements	Description	Graphical Representation
Relational Mechanism Task	The relational mechanism task represents the activities related to the management of relationships between the business partners, managing the responsibilities, authority, and capacities of each partner (e.g., review role, change responsible for production).	

Custom Elements	Description	Graphical Representation
Digital Transformation Task	The digital transformation task represents the activities related to executing improvements in the business processes using digital technologies (e.g., update production line, introduce sensors in components).	
Monitoring Task	The monitoring task represents the activities related to evaluation and monitoring of the shared elements (e.g., monitor production in partner A, monitor parts transport).	
Production Task	The production task represents a sub-type of task to execute production activities (e.g., assembly, cleaning, handcraft, heat treatment).	
Quality Management Task	The quality management task represents a sub-type of task executing quality management activities (e.g., product testing, measuring parts, check non-conformities).	
Logistics Task	The logistics task represents a sub-type of task related to logistics activities' execution (e.g., packaging, handling, materials' storage).	
Maintenance Task	The maintenance task represents a sub-type of task related to equipment and tools maintenance (e.g., machine replacement, preventive maintenance).	
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.	
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.	

Custom Elements	Description	Graphical Representation
Touchpoint Task	The touchpoint task means that it is a region of interest for partners. Information about the task execution and state may be shared within the partnership.	
Collaborative Task	The collaborative task means that a specific task is executed and managed in collaboration between several business partners.	
Partner Gateway	The partner gateway represents a moment in the flow in which a specific partner decides the "path" of the activities to be executed in the following steps.	
Partner Intermediate Event	The partner intermediate event represents a specific partner's intervention in an activity, started by an authorized partner's decision.	
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.	
Process Back Log	The process log represents data objects to store information retrieved from several traceable tasks and meaningful events.	
Regulations	The regulations represent the laws and standards that a specific business partner must follow and respect (e.g., ISO 9001).	
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.	
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.	
Parts	Parts are essential elements in industry flows (e.g., parts for coating in our case company). They are used and exchanged	

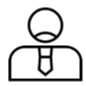
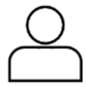
Custom Elements	Description	Graphical Representation
	between the partners and in manufacturing activities.	
Processing Devices	Processing devices are used in process tasks to record information, manage documents, execute algorithms, or analyze data.	
Partnership Manager Pool	The partnership manager is the main responsible for the execution, monitoring, and management of the IOBP.	
Partnership Participant Pool	The partnership participant is responsible for executing activities and reporting the agreed information to the partnership manager.	
Human Actor	Represents the tasks and gateways that a human actor may execute.	
Co-bot Actor	Represents the tasks and gateways that a co-bot actor may execute.	
Robot Actor	Represents the tasks and gateways that a robot actor may execute.	
Sensor	Represents sensors used in tasks or incorporated in resources, enabling the retrieval of data and traceability of tasks and resources.	
Mobile Device	Represents the mobile devices (e.g., tablet, mobile phone, remote commands) used to execute or monitor activities.	
Auxiliary Material	Represents the auxiliary materials that may be used for several activities (e.g., raw materials).	
Machine/Tool	Represents the machines/tools that are used in several activities (e.g., production machinery).	

Table 23 presents the several elements that compose the IOBP 4.0 extension. This project contributes with the addition of 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).

The new elements resulted in the creation of a customized library of the IOBP 4.0 extension concepts in the Lucidchart tool. Figure 22 presents part of the customized library in the application.

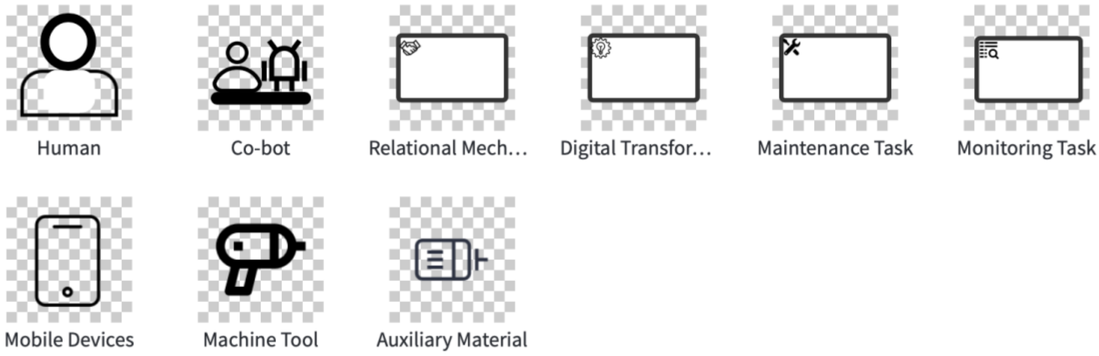


Figure 22 – Part of the IOBP 4.0 Extension Elements Library in Lucidchart

This chapter presented the several executed steps to design the IOBP 4.0 BPMN extension. The process started with the development of the domain and modelling requirements analysis, resulting in creating a domain ontology and a list of modelling requirements for IOBP 4.0. It revealed the main domain concepts, relationships, and properties of the IOBP 4.0 domain. Then, the equivalence check was executed to assess if the IOBP 4.0 concepts and modelling requirements were semantically equivalent to the standard BPMN elements. The CDME for IOBP 4.0 was then created, considering the classification of the concepts in the equivalence check phase. Using a set of transformation rules by [34], the CDME was transformed in an extension meta-model (BPMN+X model). Finally, the concrete syntax of the extension elements (graphical representation) was created.

The next chapter introduces some guidelines on how to use the proposed extension and a proposal of an approach for BPM in the case of IOBP 4.0.

Chapter 5
Guidelines for Adopting IOBP 4.0 BPMN Extension

This chapter presents guidelines to model and continuously improve IOBP 4.0 using the proposed extension. Moreover, the chapter offers a brief user manual to assist business process management practitioners. Section 5.1 describes the modelling guidelines for the use of each of the created extension elements and introduces examples of use of the extension elements. Section 5.2 suggests a continuous improvement approach for IOBP 4.0, defining four essential stages of a cycle to promote improvement.

5.1 Business Process Modelling using IOBP 4.0 BPMN Extension

The OMG's BPMN specification [105] presents guidelines for creating and interpreting business process models created with BPMN. Therefore, IOBP 4.0 guidelines follow the standard requirements defined by [105], including the new proposed elements. The goal is to adopt a top down IOBP 4.0 modelling approach for the BPMN elements. Then, choose a bottom-up description of digital transformation attributes. While the former addresses the common (shared) business objective, the latter emerges from the negotiated contribution of all partners in the network and a trade-off between individual strategies and overall collaboration value.

The IOBP 4.0 BPMN extension includes elements for describing and incorporating inter-organizational and industry 4.0 concepts in the business process models. Regarding the specificities of the proposed extension concepts and their graphical representation, a set of instructions and examples of use of the several extension elements (e.g., tasks, pools, gateways) are presented in the following subsections.

5.1.1 IOBP 4.0 Tasks

The IOBP 4.0 BPMN extension proposes two essential tasks: the operational tasks and the management tasks. Both tasks are characterized by the sub-type of task, the sharing/privacy requirements, the executing actor, and its collaborative nature.

Figure 23 introduces a general overview of the composition of an IOBP 4.0 task.

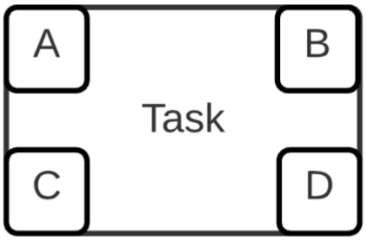


Figure 23 – IOBP 4.0 Task Composition

The example presented in figure 23 introduces the four essential areas to define an IOBP 4.0 task. Area A (upper left corner of figure 23) is used to characterize the subtype of the task, namely (1) operational (e.g., quality management task, production task) and (2) management (e.g., relational mechanism task, monitoring task). Area B (upper right corner of figure 23) is used to characterize the task in terms of its visibility to business actors (e.g., touchpoint task, private task, traceable task). Area C (lower-left corner of figure 23) is used to characterize the task in terms of the actor that executes the task (e.g., human, co-bot, robot). Finally, area D (lower right corner of figure 23) labels tasks made in collaboration (place symbol) or individually (keep clear).

Figure 24 introduces two examples of IOBP 4.0 operational activities represented using the proposed extension.

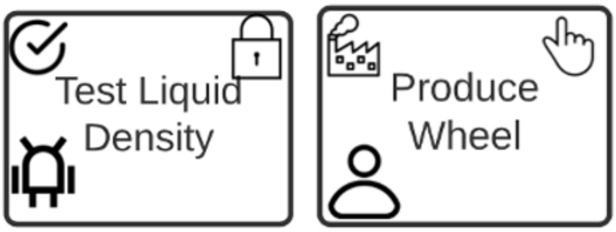


Figure 24 – IOBP 4.0 Operational Task Examples

The task on the left part of figure 24 (test liquid density) is a quality management task, executed by a robot and its private (no information can be retrieved). The task on the right part of figure 24 (produce wheel) is a production task, executed by a human and is a touchpoint (the partners may know the status of the task at a specific time). Both examples are not collaborative (Area D, on the bottom-right, is kept clear of symbols).

Figure 25 introduces two examples of IOBP 4.0 management activities represented using the proposed extension.

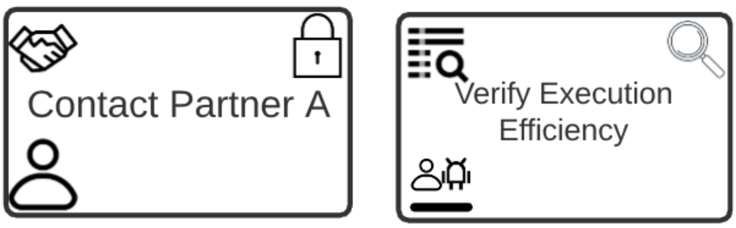


Figure 25 – IOBP 4.0 Management Task Examples

The task on the left part of figure 25 (contact partner A) is a relational mechanisms task, executed by a human actor with private visibility (no information can be retrieved). The task on the right part of figure 25 (verify execution efficiency) is a traceable monitoring task, executed by a co-bot actor.

5.1.2 IOBP 4.0 Pool

The IOBP 4.0 BPMN extension proposes a new pool to include more information on the business partners: role and applicable regulations to comply. Figure 26 introduces the general layout of an IOBP 4.0 pool.

Figure 26 – IOBP 4.0 Pool Layout

Area A (upper left corner of figure 26) represents the role of each business partner in the collaborative network (e.g., partnership manager, partnership participant). Area B (lower-left corner of figure 26) is used to identify the most relevant regulations (e.g., ISO norms, international laws, quality agreements) to which the business partner must comply.

Figure 27 presents two examples of IOBP 4.0 pools.

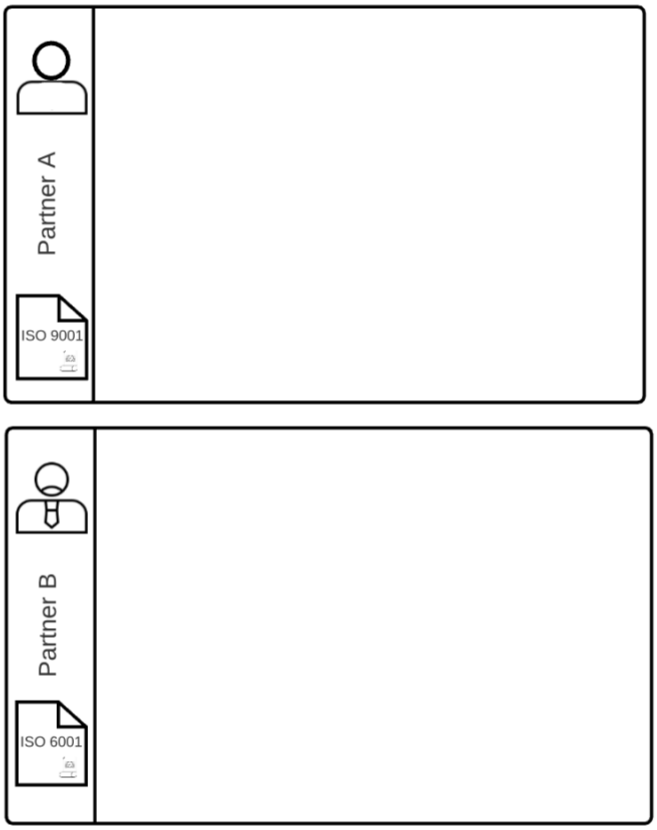


Figure 27 – IOBP 4.0 Pool Examples

Figure 27 introduces two examples of using the IOBP 4.0 BPMN extension to represent two business partners using created IOBP 4.0 pools. Partner A (in the upper part of figure 27) is a collaborative network participant and complies with the ISO 9001 standard. Partner B (in the lower part of figure 27) is the partnership manager of the collaborative network, and it complies with the ISO 6001 standard.

5.1.3 IOBP 4.0 Gateway

The IOBP 4.0 BPMN extension adds a new attribute to the traditional BPMN gateways: identification of the actor that decides the path to follow in the gateway, since any of the involved partners (not exclusively the partnership manager) may have a decision point. Moreover, it proposes a new type of gateway, namely, the partner gateway, in which a specific partner decides the "path" of the activities to be executed next at any point of the business process.

The example presented in figure 28 introduces the overall composition of an IOBP 4.0 gateway.

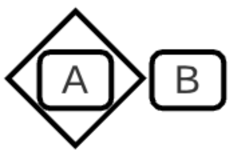


Figure 28 – IOBP 4.0 Gateway Composition

Area A (left of figure 28) is concerned with the type of gateway (e.g., exclusive, inclusive), to characterize and identify the operation that will be executed next and which factors will be considered. Area B (right of figure 28) is used to represent the actor involved in the decision (e.g., human, co-bot, robot), that will verify the defined conditions and decide the path to be followed.

Figure 29 presents an example of the use of the IOBP 4.0 partner gateway.

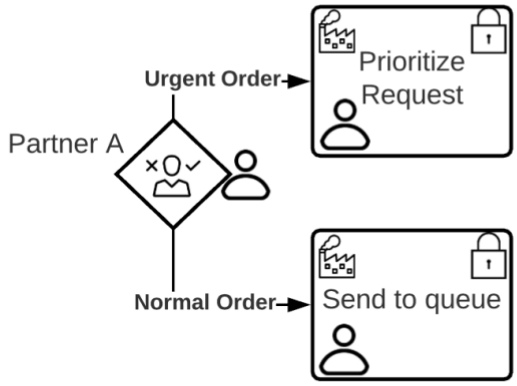


Figure 29 – IOBP 4.0 Partner Gateway Example

The example presented in figure 29 presents the partner gateway extension element followed by the execution of one of the two presented tasks, according to the decision of Partner A. In this case, a human in partner A decides if the case is an urgent order or a standard order at a specific point of the business process. The request is prioritized in an urgent order (prioritize request, a private production task executed by a human). In the case of a normal order, the request is sent to the queue (send to queue, a private production task executed by a human).

Figure 30 introduces an example of the use of an IOBP 4.0 extension gateway.

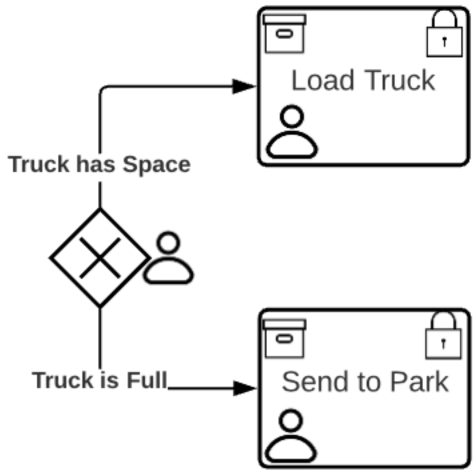


Figure 30 – IOBP 4.0 Gateway Example

The example of figure 30 introduces the use of an IOBP 4.0 partner gateway. In this case, a human must verify if the truck is full or still has space at a specific moment of the business process. If the truck has enough space, the truck is loaded. In case that the truck is full, the items are sent to the park.

5.1.4 IOBP 4.0 DataObject

The IOBP 4.0 BPMN extension proposes new data objects associated with operations represented in the tasks. Figure 31 introduces an example of the composition of the data object, regarding the characterization of its private/shared nature.

Figure 31 – IOBP 4.0 Data Object Composition

The IOBP 4.0 data object includes a single reserved Area A (upper zone of figure 31) concerned with the visibility (e.g., private, shared) of the document for the business partners. Figure 31 introduces two examples of the use of the IOBP 4.0 data object for the representation of business process information.

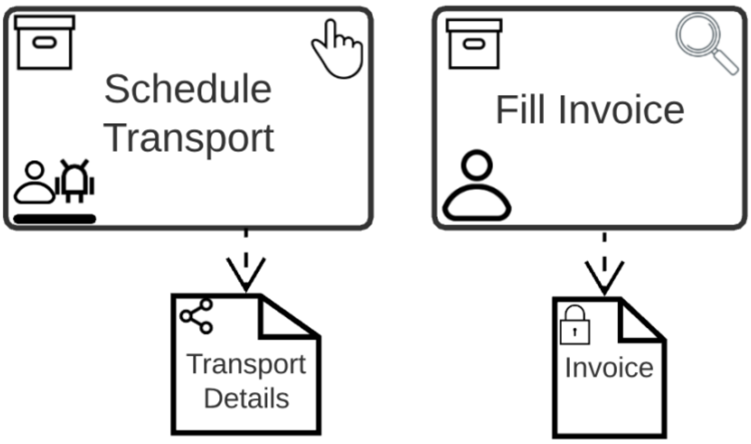


Figure 32 – IOBP 4.0 Data Object Examples

On the left side of figure 32, touchpoint logistics tasks are executed by a co-bot to schedule a transport, creating the shared transport details document. On the right side of figure 32, a traceable logistics task is executed by a human, with the objective of filling the invoice and creating a private invoice document.

5.1.5 IOBP 4.0 Resources

The IOBP 4.0 BPMN extension proposes a set of new resources to represent industrial devices and parts used in the operational activities of the IOBP 4.0 domain. Figure 33 introduces the composition of a resource and its association to a generic task definition.

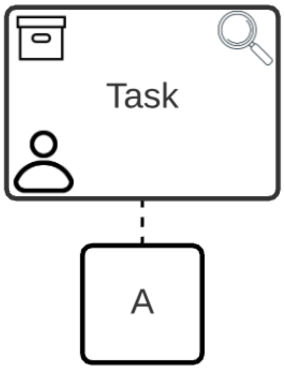


Figure 33 – IOBP 4.0 Resources Composition

Figure 33 shows an IOBP 4.0 resource associated with a task (on the top). Area A (lower zone of figure 33) is used to represent the resources (e.g., machines/tools, components, mobile devices) used in the task. The resources may also be put in other spaces around the tasks, regarding the organization of the model and the placement of other elements.

Figure 34 presents examples of the association of the extension resources to defined tasks.

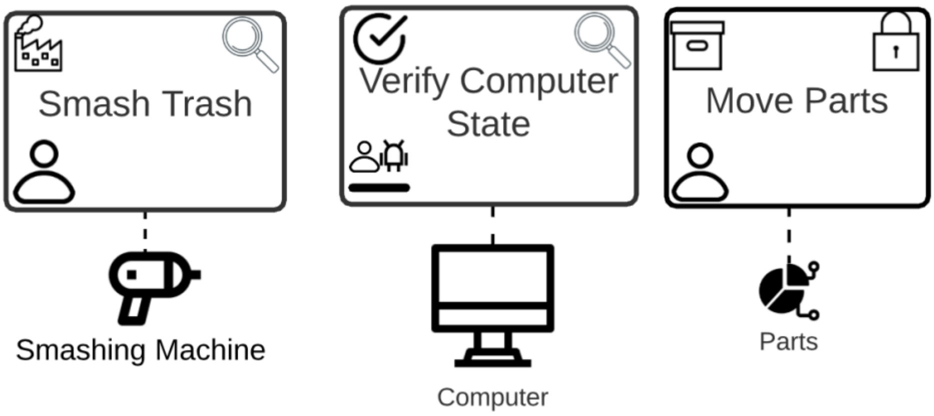


Figure 34 – IOBP 4.0 Resources Examples

The first example, on the left of figure 34, presents a traceable production task executed by a human to smash the trash using the smashing machine (resource). The centre of figure 34 presents a traceable quality management task, executed by a co-bot, to verify the computer state. Finally, in the right side of figure 34, a private logistics task is executed by a human to move the parts.

5.1.6 IOBP 4.0 Physical Flow

The IOBP 4.0 BPMN extension proposes a new flow type regarding the physical transport of resources across the partners to account for and represent. Figure 35 introduces the generic composition of the physical flow across two business partners.

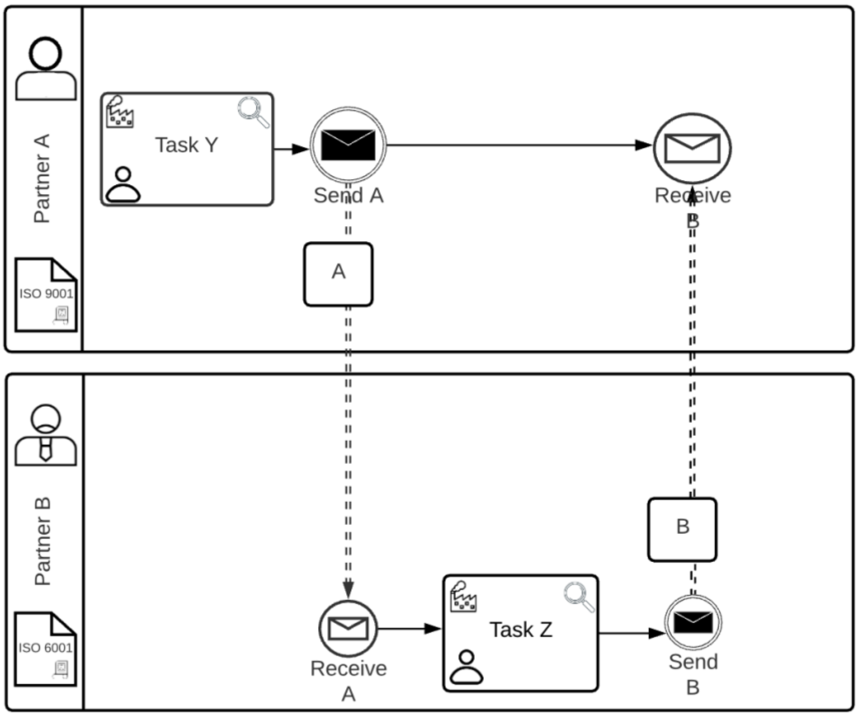


Figure 35 – IOBP 4.0 Physical Flow Composition

The example presented in figure 35 introduces the overall composition of an IOBP 4.0 physical flow associated with the movement of resources across two business partners. Area A and Area B can represent the desired resources (e.g., machines, components, devices) exchanged at a specific point by the business partners. The sending of the resources (in the physical flow) implies the sending of a message from one of the partners to the other, to communicate that the items are being sent. Figure 36 introduces an example of resources exchange between two business partners.

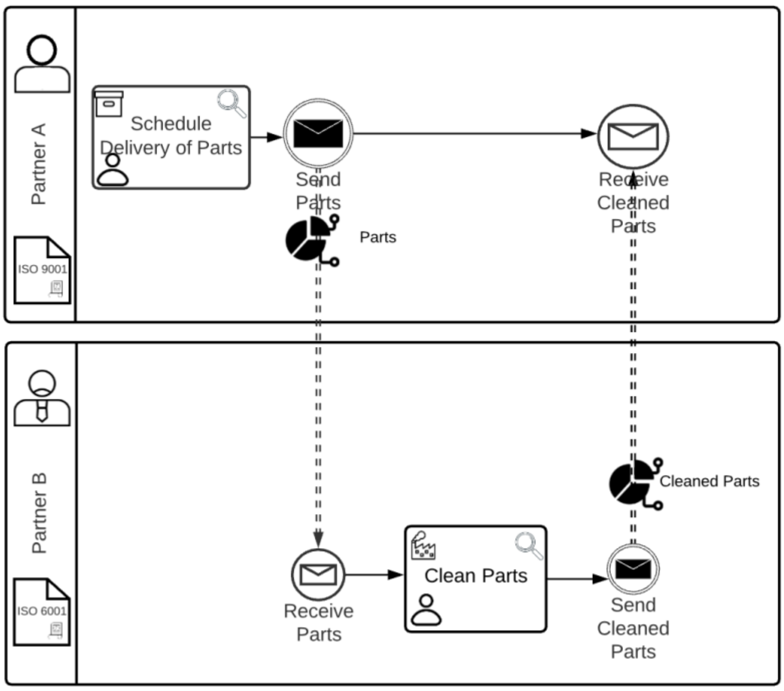


Figure 36 – IOBP 4.0 Physical Flow Example

First, partner A (represented in the upper part of figure 36) schedules the delivery of the parts (a traceable logistics task executed by a human). Then, the parts are sent to partner B (on the bottom of figure 36), which is notified of the sending of the parts. Partner B receives the parts. Then, the parts are cleaned (a traceable production task, executed by a human) and sent back to partner A.

5.1.7 IOBP 4.0 Event

The IOBP 4.0 BPMN extension introduces the partner intermediate event. The concept represents a moment in which a defined business partner can intervene during the execution of a task in another business partner. Figure 37 presents an example of its use.

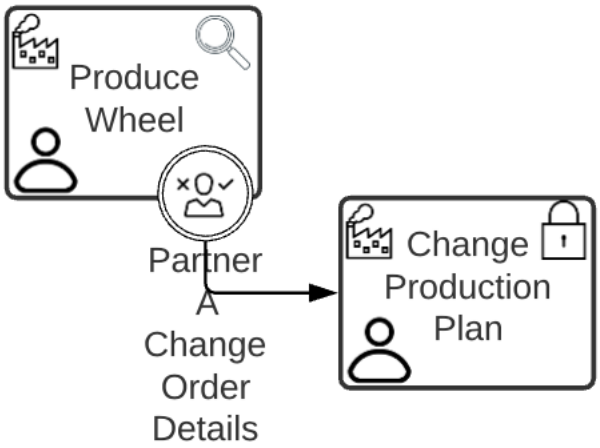


Figure 37 – IOBP 4.0 Intermediate Partner Event Example

The example of figure 37 introduces the use of the boundary partner intermediate event, that is represented at the boundary of the produce wheel task. In this case, during the production of the wheel (a traceable production task executed by a human), partner A can intervene (in case of need), to update the changes in the order details (and the flow of the business process), which then triggers the need to change the production plan (a private production task executed by a human).

5.2 A Reshaped PDCA Approach for Continuous Improvement of IOBP 4.0

Industry 4.0 is a long-term transformation. Therefore, modelling IOBP 4.0 needs to be complemented with actions to improve inter-organizational practices continuously.

The two main forces that may affect a market structure are business opportunities and technological advances [131]. The combined effect of these forces promotes and drives several value chain transformations, thus causing the emergence of new business strategies, market structures [83], and the reshaping of the collaborative network. According to their specific market and technological context, the various organizations may be affected differently by these forces. Therefore, in terms of strategic planning and decision-making, organizations need to establish guidelines and mechanisms that allow capitalizing on these situations in terms of business opportunities and technological advances [95]. This way, the network may look for opportunities to:

- Use business process models to negotiate continuous improvement initiatives among the partner organizations and establish an integrated digital transformation program.
- Continuously update IOBP 4.0 models. Industry 4.0 investments must be communicated to all interested parties, and its performance monitored over time.
- Identify priorities for shared innovation in specific parts of the process. Industry 4.0 is enabled by end-to-end digital integration of supply chains, local weak points (e.g., partners not producing as expected) may need adjustments.
- Explore business process simulation techniques to evaluate the impact of digital transformation.

The IOBP 4.0 continuous improvement gathers inspiration in the popular Plan (P) – Do (D) – Check (C) – Act (A) cycle [132], [133] and, for each step in PDCA. The context of IOBP and collaborative networks requires a set of challenges to be considered and overcome and a set of requirements in terms of synchronization, data sharing, and coordination. Besides, organizations need to constantly look for new opportunities in business and technology in today's competitive market. The reshaping of the PDCA cycle aims to apply and implement BPM mechanisms in IOBP to promote change and continuous improvement across several organizations and accomplish IOBP 4.0. The reshaped PDCA approach is defined as follows:

5.2.1 Plan (P) Phase – Shared Planning

The Plan (P) phase aims to recognize the possibility of changes, namely, setting the objectives for improvement and designing an action plan that will enable these objectives [66]. The problems are identified and carefully analysed, generate accurate solutions, and develop the plan.

IOBP 4.0 requires preparation and commitment from the different parties to scale and optimize the access to shared resources and information concerning the several interdependencies and the interconnections between the resources and the activities [95]. This way, the organization must set several objectives and targets to be achieved and measured. Organizations need to set mechanisms that may allow solving eventual problems. Each part of the process must ensure flexibility by design, revealing how it can be done (e.g., global, or local process reconfiguration or actors changes). Besides this, the organizations must seek strategies and options for implementing innovation across the business regarding technological advances and business process organization. There is also the need to consider changes in regulatory contexts that may impact the entire collaborative network, raising the need to deal with such situations. The several partners must establish strategies in terms of risk management regarding the decentralized operations and the events that may happen in different places but affect the entire collaborative network. The established mechanisms are of great importance to ensure the quality requirements of the products/services, guarantee all the compliance requirements and follow the nowadays competitive markets with the innovation in the business process. These aspects enhance the importance of Shared Planning in IOBP [6], [61], [77], [115].

5.2.2 Do (D) Phase – Shared Execution

Regarding the Do (D) phase, the developed plan to make the changes in the processes (according to the previously identified problems and proposed solution) or execute the processes is implemented in the organization in order to raise its productivity or quality and to eliminate the causes of identified problems [66].

Regarding the case of IOBP 4.0, several planned changes and business process activities must be executed by the several business partners. The business partners must ensure the mechanisms that allow the inter-organizational execution of the defined plans by using effective communication channels (through messages) and extending the shared information and details, considering the particularities of IOBP 4.0 and the used technologies. Each organization should focus on its core competencies by executing the designated process parts and providing the specified information and details with the agreed partners. It is important to have effective data retrieval mechanisms, and event registering since the obtained information in this phase will be essential for the partners and coordinators to make decisions in the present or near future. The business partners should be able to cope with the regulations in their specific contexts and execute actions that mitigate several risks. These aspects enhance the importance of Shared Execution in IOBP [20], [102], [120], [134].

5.2.3 Check (C) Phase – Shared Monitorization

Regarding the Check (C) phase, it is aimed to check and test whether (or not) the solutions introduced by a company brought adequate results, according to the expected impact of the plan, by taking measurements and comparing them with the values folded in the plan [66]. This evaluation is essential to develop a new plan in case of failure (return to phase P) or proceed to the next step in case of success.

IOBP 4.0 requires complementary monitoring processes to evaluate the performance of the shared elements and decentralized activities (e.g., process execution-level agreements), with new challenges emerging in the monitorization and auditability of decentralized operations and elements. The organizations need to set mechanisms that guarantee efficient and precise remote monitoring of the distributed activities and the most important decisions made across the organization to keep the several partners aware of relevant situations. The retrieved data will be used to compare the planned goals, objectives, measures and assess the implemented measures. This way, several partners may evaluate and analyse the data to make decisions, detect problems, and execute business processes. The several business partners must guarantee the monitorization of the several risks, collectively and individually, to guarantee that all the relevant situations are identified and appropriately mitigated. This phase also plays an essential role in assessing the possibilities and effects of introducing technological innovations or new business rules across the business process. These aspects enhance the importance of Shared Monitoring in IOBP [61], [120].

5.2.4 Act (A) Phase – Shared Digital Transformation

The Act (A) phase aims to evaluate solutions, by analysing the results and drawing the conclusions of the tested solutions. When the solutions are proven to produce the desired results, they are considered the norm and lead to standardization. Improvements using digital technologies can be implemented by each actor independently or in cooperation, becoming the norm and standardization across the process. When executing changes independently, the organization must ensure that there will be no adverse impact on the relationships and inter-organizational obligations. The organizations should embrace the changes with caution regarding the need to keep the business process stable and producing value to the customers. These aspects enhance the importance of Shared Digital Transformation in IOBP [6], [11], [51], [132], [133].

Table 24 presents the synthesis of the adapted phases of the PDCA cycle applied to the context of IOBP 4.0.

Table 24 – A shared PDCA approach to continuously improve IOBP 4.0

IOBP Lifecycle	Phase Description	References
Shared planning (P)	IOBP 4.0 requires preparation and commitment from the different parties. Companies may compete for the same resources (e.g., machines) that must be scalable and optimized. Each "part" of the process must ensure flexibility by design, revealing in this attribute how it can be done (e.g., global or local process reconfiguration or actors changes). The organization involved in collaborative improvement must specify goals to achieve (e.g., IT investments and expected results for the overall shared goal).	[6], [61], [77], [115]
Shared execution (D)	IOBP 4.0 can be described by core BPMN elements (e.g., processes, tasks, events, resources, and data objects). Messages are important but insufficient to detail (1) inter-organizational execution (e.g., who decides to cancel the process, quality criteria, performance indicators) and (2) particularities of industry 4.0 (e.g., new technologies adopted in decentralized parts of the process). Each organization should focus industry 4.0 investments on its core competencies.	[20], [127], [134], [135]
Shared monitoring (C)	IOBP 4.0 needs specific monitoring processes to evaluate the performance of shared elements (e.g., process execution-level agreements). In addition, new challenges emerge from monitoring processes in decentralized manufacturing (e.g., real-time data sharing) and protected logs for auditability purposes.	[61], [127]
Shared digital transformation (A)	IOBP 4.0 improvements using digital technologies can be implemented by each actor independently or in cooperation. Mindful actors and powerful digital technologies are inseparable.	[6], [11], [51]

In the PDCA cycle, the knowledge gained from the last stage becomes the basis for the next cycle, and current improvement is not seen as the end and does not bring satisfaction with the current situation [66]. IOBP 4.0 requires close coordination and commitment among the networking partners [20] to guarantee the stability of the collaborative network and the sustainability of the business process.

Figure 38 presents the visualization of the reshaped PDCA cycle, presenting the four proposed stages of the cycle and its sequence.

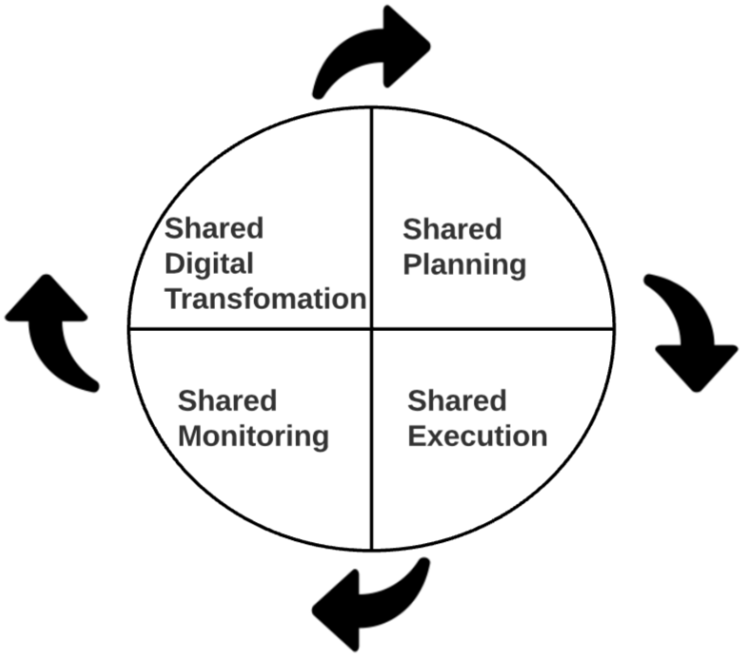


Figure 38 – Reshaped PDCA cycle for IOBP 4.0 (based on [136])

Usually, the cycle starts at the Shared Planning phase, in which the business partners set the objectives and goals for each of the partners and the collaborative network. Next, the Shared Execution phase starts, focusing on the activities performed by each partner, according to their competencies and responsibilities. Then, the Shared Monitoring phase aims to monitor the execution of the business processes and register valuable information and indicators. Finally, the Shared Digital Transformation phase is concerned with the implementation of the technological innovations (by each actor or collectively), according to the needs and evaluation results. The shared PDCA cycle is aimed at aggregating the necessity of "continuous change" in the era of digital transformation and how IOBP 4.0 could evolve since the early design stages.

This chapter presented a proposal of guidelines for the use of the IOBP 4.0 BPMN extension and the proposal of an approach for continuous improvement of IOBP 4.0. Initially, several guidelines for the modelling activities using the IOBP 4.0 BPMN extension are presented, followed by presenting several simple examples of the use of the extension. In the last part of the chapter, an approach for the continuous improvement of IOBP 4.0 is presented, based on the popular PDCA cycle [132], [133].

The next chapter demonstrates the IOBP 4.0 BPMN extension in real-world cases, introducing the modelling activities executed in the partner companies and the retrieved feedback on the potential of the proposed extension.

Chapter 6
Demonstration and Evaluation of the IOBP 4.0 BPMN Extension

This chapter presents the demonstration and evaluation of the IOBP 4.0 BPMN extension in two real-world cases. The goal was to execute several modelling activities with both the standard BPMN and the IOBP 4.0 extension to verify the capacity to model the scenarios and assess completeness and correctness when comparing both representations. It was also an opportunity to retrieve feedback from practitioners on the utility of the IOBP 4.0 BPMN extension. Section 6.1 present the chosen approach to evaluate the IOBP 4.0 BPMN extension, introducing the several steps of the evaluation and the concepts under evaluation. Section 6.2 presents the demonstration of the IOBP 4.0, introducing the modelling activities executed in the case companies and a first analysis on the results. Section 6.3 presents the evaluation results, presenting reflecting on the benefits and drawbacks of the IOBP 4.0 BPMN extension, the properties under evaluation and a reflection on the executed demonstration and evaluation process.

6.1 Evaluation Approach

The evaluation is one of the most important steps in the DSR methodology, having the goal of evaluating the created artefacts (and the process) and providing feedback for further improvement of the work. The evaluation activities may involve comparing the objectives of a solution to actual observed results from the use of the artefact in the demonstration or asses the utility of the artefacts for the users or academia. The artefact evaluation requires knowledge of relevant metrics and analysis methods regarding the comparison approaches and validation mechanisms used (from performance measures to simulations), depending on the context and domain of the problem. This phase also provides the necessary feedback to produce eventual adjustments and improvements on the proposed artefact, by going back to the design activity [29].

The Framework for Evaluation in Design Science Research (FEDS) [137] was selected for the evaluation phase of this dissertation.

6.1.1 FEDS

The FEDS framework aims to guide design science researchers in developing a strategy for evaluating the artefacts developed within a DSR project [137]. The goal is to define why, when, how, and what to evaluate in a DSR project [137]. The framework *includes a two-dimensional characterisation of DSR evaluation episodes (particular evaluations), with one dimension being the functional purpose of the evaluation (formative or summative) and the other dimension being the paradigm of the evaluation (artificial or naturalistic)* [137]. Summative and formative evaluations are mainly distinguished by their functional purpose [137]. The functional purpose of summative evaluations is to judge the extent that the outcomes match the expectations (e.g., certification, progress, effectiveness) [137]. The functional purpose of formative evaluations is to help improve the outcomes of the process under evaluation [137]. The artificial evaluation is aimed towards laboratory experiments, simulations, analysis, theoretical arguments, and mathematical proofs [137]. The naturalistic evaluation explores the performance of a solution technology in its real environment of work, typically within an organisation [137]. The FEDS evaluation design process is composed of four essential steps [137]:

1. Explain the evaluation goals: This step is concerned with the identification and characterization of the evaluation in terms of the goals that will drive the process. These goals will impact the choice of the evaluation strategy. The authors propose four essential goals to be considered: rigor, uncertainty and risk reduction, ethics, and efficiency.
2. Choose the evaluation strategy or strategies: This step is concerned with the choice of the evaluation strategy per the context of the problem and the needs and resources of the project. The author proposes four possible strategies for evaluation: Quick & Simple, Human Risk & Effectiveness, Technical Risk & Efficacy and Purely Technical Artefact. The Quick & Simple strategy conducts a relatively little formative evaluation and progresses quickly to summative and naturalistic evaluation approach, with a few evaluation episodes (or even only one episode). The Human Risk & Effectiveness evaluation strategy emphasises formative evaluations at the beginning of the process, possibly with artificial, formative evaluations, but progressing through the stages to a more naturalistic formative evaluation. The Technical Risk & Efficacy evaluation strategy emphasises artificial formative evaluations iteratively in the beginning of the process, but progressively moving towards more summative artificial evaluation episodes. The Purely Technical strategy is used when an artefact is purely technical, without the interaction of human users, or planned deployment with users is so far removed from what is developed to make naturalistic evaluation irrelevant for the process.
3. Determine the properties to evaluate: This step is concerned with the choice of the broad set of features, goals, and requirements of the artefact (design and/or instantiation) that are to be subject to the evaluation process, according to the unique context of the artefact and the domain. FEDS suggests four possible approaches, presented by other authors, for the definition of properties to consider for evaluation. The approach of [138] defines levels of granulatiry, using a cross-evaluation model to assess the system at the task completion level (e.g., task was completed, value of the task), using several measures. The work of [139] suggests a process based on the adapting context, input, process, and product, aimed at evaluating complex artefacts to be used in real context. The works of [140] proposes a set of adapting criteria as design goals (e.g., functionality, reliability, usability, efficiency, maintainability, portability), based on the ISO standard 9126. The work of [141] introduces the definition of criteria adapting both rationality and understanding, such as rationality-efficiency (e.g., quality assurance), rationality-effectiveness (e.g., cost-benefit, user satisfaction, resource utilisation).
4. Design the individual evaluation episode(s): This step is concerned with the design of the evaluation process. The goal is to define the episodes for the particular DSR project's/ programme's evaluation strategy. The design of the episodes must

consider and prioritize aspects such as the available time, the resources, and the budget. The number of episodes to be executed must also be defined.

6.1.2 Goals of the Evaluation

Considering the context of this DSR project, efficiency will be the primary goal of this evaluation. This choice considered the short time available for the evaluation activities, the goal of the extension (mainly for modelling activities) and the availability of the partner companies to participate in the project.

Efficient evaluation balances several goals (e.g., rigour, risk reduction) of the evaluation considering the available resources for the evaluation (e.g., time, resources, partners). It is important to consider the availability of the two partner companies and the activities that may be enacted (e.g., modelling of business processes, execution of business processes, feedback from users). On the other hand, the evaluation should be as precise as possible, considering the short time available to evaluate the artefact and make eventual adjustments to the extension.

6.1.3 Evaluation Strategy

Quick & Simple evaluation strategy was chosen for this project. This decision was based on the goal of having an efficient evaluation, considering the available resources (e.g., time, partner companies), the goal of the extension and the lower risk of the artefact at this stage.

The Quick & Simple evaluation strategy conducts relatively little formative evaluation and progresses quickly to summative and more naturalistic evaluation episodes [137]. The evaluation trajectory of this strategy includes relatively few evaluation episodes, which may be considered a single summative evaluation at the end of the artefact's design. Such a strategy is low cost and encourages quick project conclusion, but may not be reasonable in the face of various design risks [137].

The risks inherent to the use of the artefact are reduced since the goal of the extension is to fulfil the gap that exists in terms of modelling for the representation of IOBP 4.0. The main identified risk was the possibility of producing an incorrect or incomplete representation of the business process. With no other relevant risks being identified and according to the FEDS, we proceed to the execution of the Quick & Simple evaluation, considering the low social and technical risk and uncertainty.

6.1.4 Properties to Evaluate

After defining the evaluation strategy to be followed, it is necessary to decide the aspects that will target the evaluation. Therefore, this step is aimed to choose a set of features, goals, and requirements of the artefact that are to be subject to evaluation. The choice of the concepts to be subject to the evaluation depends on the artefact, its purpose, and the context of the evaluation. Different authors have defined and proposed a wide variety of generic goal, attribute and criteria that constitute potential evaluand properties [137].

For the case of this project, the approach proposed by [140] will be followed, defining the properties to be evaluated based on ISO standard 9126. The choice of the properties was focused in the understandability of models, regarding the importance of characterisitcs such as completeness, correctness and clarity [91].

Three properties were selected, considering that the artefact will be mainly used for modelling purposes and information sharing across the business partners and business users. Therefore, the following properties were defined:

- Completeness: Evaluate the inclusion of relevant information in the produced process models using the IOBP 4.0 BPMN extension, while representing the business processes designed and executed by the partner companies. The goal is to assess the differences between models built with the standard BPMN and the IOBP 4.0 BPMN extension, regarding the new information that can be incorporated and its impact in the models.
- Utility: Compare whether the proposed extension can improve the existing solutions for companies to represent IOBP 4.0 using their current solutions (e.g., process maps, process models). It is also a goal to understand in which companies' activities the process models created using the IOBP 4.0 BPMN extension may be used for (e.g., modelling of the business processes, formation of new collaborators companies, integration of new partners in the network).
- Comprehensibility: Assess the capacity of the process models created with the IOBP 4.0 BPMN extension to provide to the business users the information represented on the process model. It is also a goal to assess the effect of the models in terms of model complexity and saturation.

6.1.5 Evaluation Episodes

Considering the evaluation strategy and the properties to be evaluated, a single episode of the summative evaluation was considered, with the participation of two partner companies. Both companies agreed to participate in this study, by making available business process documentation regarding processes in which the companies were involved in collaborative networks, with decentralized activities and decisions. The companies also agreed to provide feedback on the developed models, in terms of the correctness of the business process models created with the extension, the activities in which the models and the extension might be included (e.g., agreements, information sharing, user formation), the comparison of the extension with the current solutions and the understanding of the process models created with the extension. Regarding the current pandemic situation, the companies requested that all the activities and meetings were executed remotely.

In the first phase, the companies would provide the business process documentation, providing information on the involved users and departments (e.g., quality manager, head of production), the involved technology (e.g., production management software, production robot), the involved business partners and the several steps and activities of the business process. The documentation was received and analysed to assess if more information or documentation is required. The documentation is then used to model the business process models using standard BPMN and IOBP 4.0 BPMN extensions. The business process models were then sent to the partner companies to retrieve feedback on the BPMN extension and the properties under evaluation. The feedback received from the industries experts is therefore analysed, to identify not only the points for future improvement, but also to enhance positive aspects on the use of the IOBP 4.0 BPMN extension.

The insights gathered at the evaluation are included in Section 6.3, after demonstrating how IOBP 4.0 BPMN extension was adopted in real settings (Section 6.2).

6.2 Demonstration

6.2.1 Escudo Iberia Case

Escudo Iberia's mission is to research and develop solutions for the coating of rotary and static industry apparatuses. According to the type of product, composites, and context of use, the company executes coatings in components. Currently, the company's operations require outsourcing, and they are investing in a new coating robot and artificial intelligence models to forecast product failures under operation. Being ISO 9001 certified, the company found the proposed approach interesting to model processes aligned with I4.0 investments in decentralized contexts. To proceed with the adoption of IOBP 4.0 extension, the company provided process related documentation, more precisely, the process mapping document from the production management. This documentation allowed us to model the processes using both standard BPMN notation and the IOBP 4.0 extension.

6.2.2 The Coating Business Process

The process is concerned with the execution of the coatings in the components used in process industries (e.g., energy, oil, and paper). Escudo Iberia cannot execute certain types of coatings (e.g., thermal spraying coatings, laser coatings, polymeric coatings), requiring the outsourcing of these operations to partner companies. Figure 39 presents the coating process model using the traditional BPMN.

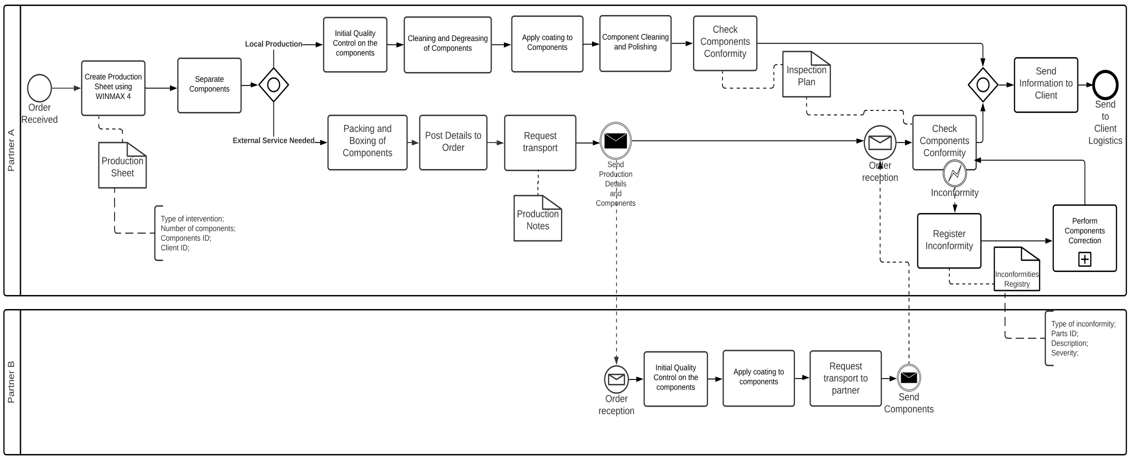


Figure 39 – Coating Process Model using BPMN

Partner A (Escudo Iberia) triggers the business process's execution (event order received), creates the production sheet using WINMAX 4 software, and separates internal and/or external production components according to the required operations. In the latter situation, the components need to be sent to partner B. Partner A performs preliminary quality control, followed by cleaning and degreasing the components. Afterwards, the components follow the (1) coating, (2) cleaning, and (3) polishing. The outsourced components are packed, and the order details are attached before shipment to partner B.

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.

Figure 40 shows the same process modelled with the proposed IOBP 4.0 extension. Appendix D presents the expanded visualization of the business process models included in this section.

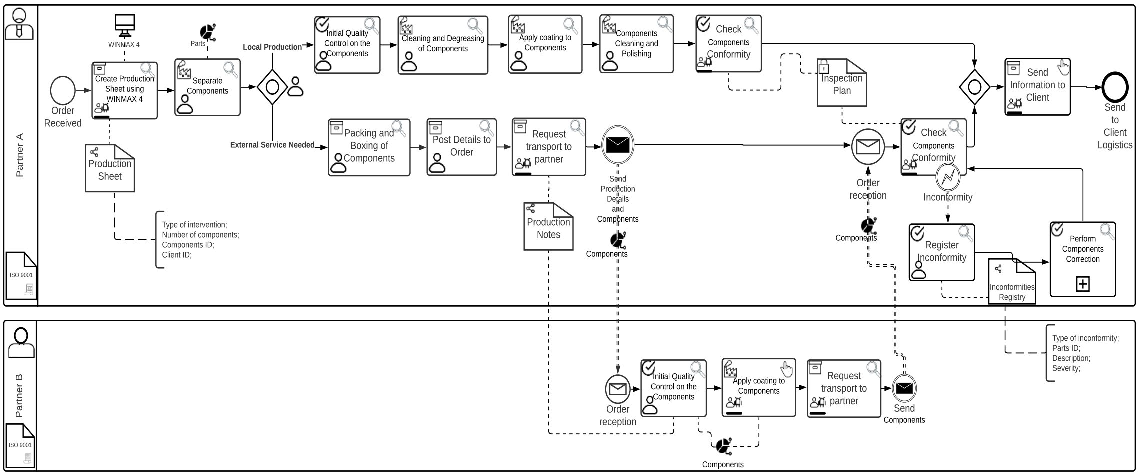


Figure 40 – Coating Process Model using IOBP 4.0 BPMN Extension

The use of the IOBP 4.0 extension allows the inclusion of more details in the models. New layers of information are visible in the extended model of figure 40, which cannot be represented with the standard BPMN notation used in figure 39. 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 (e.g., apply coatings to components) automate tasks while other are executed by human actors (e.g., post details to order).

6.2.3 Request Transport Process

This business process is concerned with the request of transport service from partner A to either partner B or the client. The transport company is responsible for the planning and retrieving of packages in the company's facilities, which are then transported to the final destination. Figure 41 presents the request transport process model using BPMN. Appendix E presents the expanded visualization.

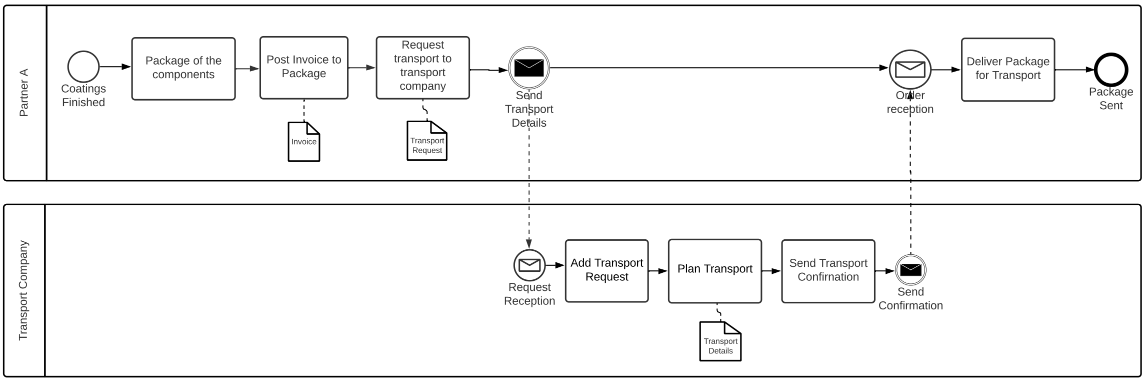


Figure 41 – Require Transport Process Model using BPMN.

Partner A (Escudo Iberia) triggers the business process's execution (coatings finished in the production unit). First, the components are packaged, and the invoice is posted to the package. Then, Partner A submits a transport request to the transport company, sending all the transport details.

The Transport Company receives the transport request, adding it to the queue. Then, the transport is planned according to the requested and the transport details are produced. After planning the transport, the transport confirmation is sent to partner A, which delivers the package sent to the customer on the planned date.

Figure 42 (expanded visualization available in Appendix E) shows the same process modelled with the proposed IOBP 4.0 extension.

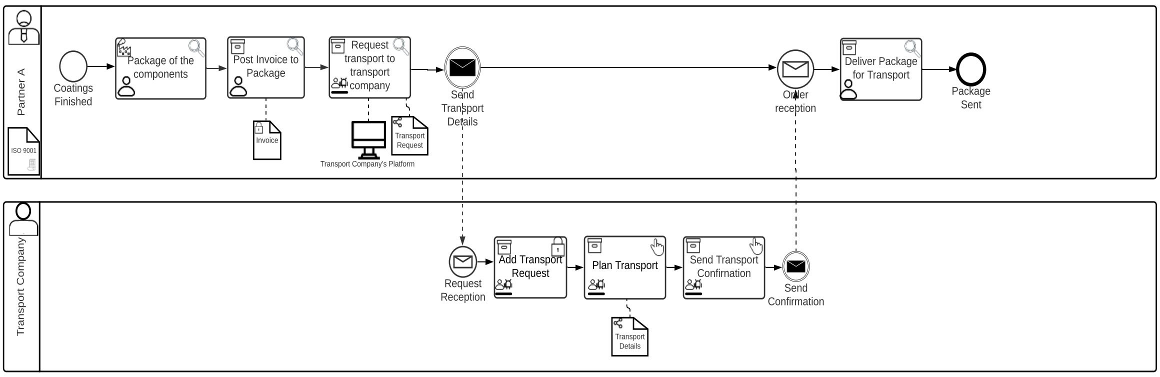


Figure 42 – Require Transport Process Model using IOBP 4.0 BPMN Extension

As in the coating process model, the IOBP 4.0 extension allows the inclusion of more information and details in the models. New concepts are visible in the extended model of figure 42, which cannot be represented with the standard BPMN notation used in figure 41. The process model built with the extension is more rigorous about process participants' roles (pools): partner A is the business process coordinator and is IS0-9001 certified (new elements in the pools). Digital elements are also identified in different parts of the business process (e.g., the transport company’s platform is used to submit the transport request). Partner A can verify the status of the requests made to the transport company (e.g., plan transport, send transport confirmation). Several documents are shared between the partners (e.g., transport request, transport details), while others are kept private (e.g., invoice). Most of the performed tasks are classified as logistics tasks (e.g., plan transport, the package of the components, post invoice to package). Robots may partially automate tasks (e.g., add transport request, send transport confirmation) while others are performed by human actors (e.g., package of the components, post invoice to package).

6.2.4 Altri Case

Altri is a leading Portuguese eucalyptus pulp producer and one of the most efficient European producers. Besides the production of pulp, the company also operates in forest management and biomass power production. Currently, the company's produces about 20% of the needed eucalyptus to produce the pulp, buying the most part (80%) from other providers. The company is ISO 9001 certified, having found the IOBP 4.0 approach interesting to model processes aligned with the current I4.0 investments. To proceed with the execution of the modelling activities, the company provided process related documentation. Similarly to the previous case company, this documentation allowed us to model the processes using both standard BPMN notation and the IOBP 4.0 extension.

6.2.5 The Biomass Business Process

The business process is concerned with biomass management, starting from acquiring it from the suppliers to the treatment and producing bioelectric energy. Biomass is a left over from wood cutting activities, that can be used to produce electric energy. The biomass is used as fuel for the combustion, which then produces the high-pressure gases to move the turbines. Biomass is cheap and the process to produces renewable energy has low pollution ratio, without the emission of carbon dioxide. Currently, Altri not only consumes biomass internally for bioelectric energy production, but also sells biomass to other companies. Figure 43 (please see Appendix F for an expanded version) presents the biomass process model using BPMN.

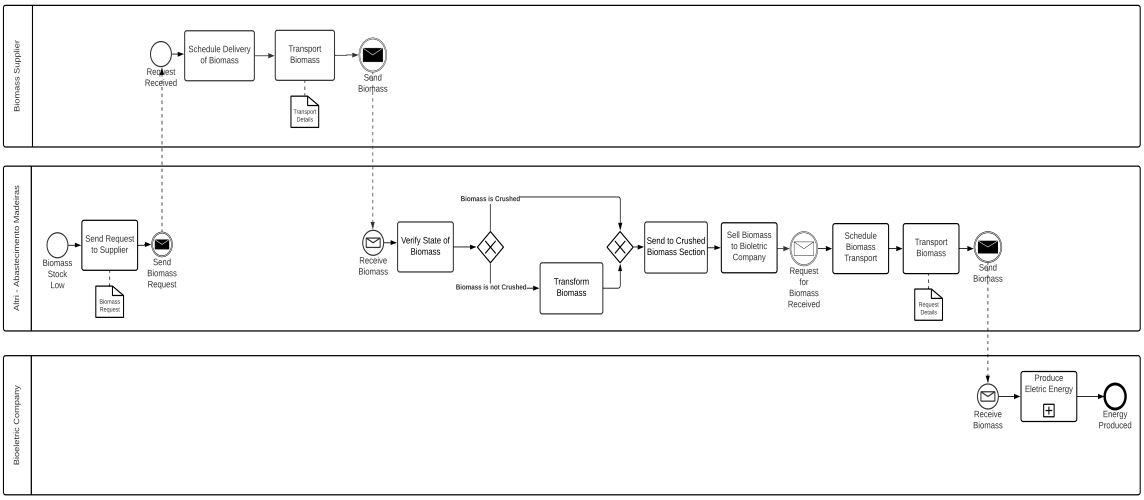


Figure 43 – Biomass Process Model using BPMN.

The process is triggered when Altri – Abastecimento Madeiras needs to acquire biomass from a third party. First, a request is sent from Altri to the Biomass Supplier. The Biomass Supplier receives the request and schedules the delivery of the biomass to Altri – Abastecimento Madeiras. The Biomass is then transported from the Biomass Supplier to Altri – Abastecimento Madeiras, along with details on the transport and the biomass. Altri – Abastecimento Madeiras receives the biomass and then check its condition. If the biomass is crushed, it is sent directly to the crushed biomass sections. Otherwise, the biomass must be transformed to be in proper conditions for the production of electricity. The biomass is then set for sale to bioelectric companies. When a request for biomass is received at Altri, the transport and details are scheduled. The biomass is then transported to the biomass company's facilities, along with the details of the transport and biomass. The bioelectric company receives the biomass, which is then used to produce bioelectric power.

Figure 44 (larger version in Appendix F) shows the same process modelled with the proposed IOBP 4.0 extension.

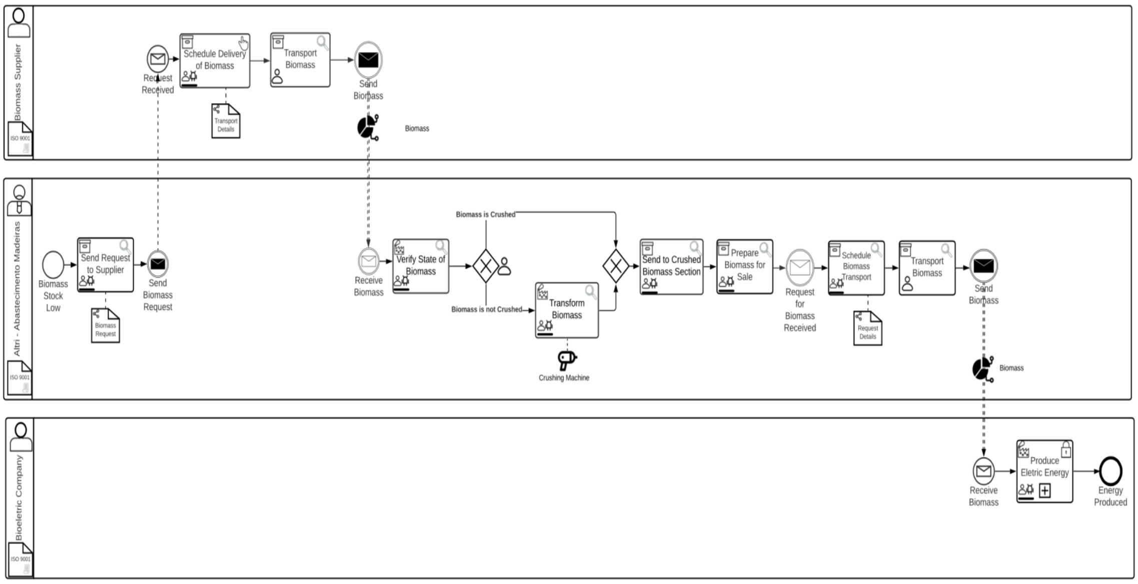


Figure 44 – Biomass Process Model using IOBP 4.0 BPMN Extension

The use of the BPMN extension allows more details on the digital elements and information sharing. New elements become visible in the model produced with the IOBP 4.0 BPMN extension in figure 44, which cannot be represented using the standard BPMN notation in figure 43 (e.g.,). The process model built while using the extension is more accurate in representation of the roles of the process participants: Altri is the business process coordinator and is ISO-9001 certified, while the other two are process participants also certified by ISO-9001. New digital elements are also integrated into the model produced with the extension (e.g., the crushing machine used to transform the biomass). Altri can monitor the transport of the biomass from the supplier to their own facilities and access information on the scheduled delivery of the biomass. Altri also retrieves and analyses data from their tasks (e.g., verifying biomass, transforming biomass, sending to crushed biomass section). Several documents are shared between the business partners (e.g., request details, transport details). Most of the tasks performed are classified as logistics tasks (e.g., transport biomass) and production tasks (e.g., verifying biomass, transforming biomass). Robots partially automate some of the tasks (e.g., transform biomass, schedule delivery of biomass) while others are performed by human actors (e.g., transport biomass).

6.3 Evaluation

The IOBP 4.0 BPMN extension provides an answer to the need to represent inter-organizational business processes in increasingly digitalized manufacturing contexts. The feedback retrieved from the industry's experts and the modelling of the real-case scenarios allowed the collecation of relevant information for the evaluation process.

6.3.1 Utility

First, the proposed IOBP 4.0 BPMN extension can replace the traditional modelling approach for IOBP 4.0, based on the use of separated models to represent the activities executed by each partner. The business process models produced using the extension can represent a unique and unified vision of the collaborative network and the activities executed by each partner. The unified version of the business process contributes to the enhanced perception of the decentralized activities and decisions, the flow of information between the business partners and the shared resources.

Second, the models produced with the extension can be used to integrate new business partners in the collaborative network, by introducing additional information on the roles of each business partner, the performed operations, shared resources and regulations requirements.

Third, 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) across the several business partners of the collaborative network.

Fourth, the IOBP 4.0 business process model can be used as a tool for joint innovation efforts, enabling the identification of (internal/external) improvement opportunities by any of the involved organizations in terms of technology or procedures. Lastly, the process models can be adopted in internal audits, increasing transparency of each participant's responsibilities, type of activities, internal/external interactions, and technology investments.

In a future perspective, the business process models produced with the extension may be used for the integration of information in contractual agreements between the several business partners. The business process models can also be incorporated in BPMS, to promote several stages of the BPM cycle, mainly for real-time business activity monitoring (BAM) tasks, business process simulation, detection of errors and process improvement.

The proposed extension contributes to the closer alignment of the several business partners involved in a collaborative network.

6.3.2 Completeness

Model completeness is one of the most immediate advantages of using the IOBP 4.0 BPMN extension. First, the proposed BPMN extension introduces representative elements of the private/shared data (e.g., a private inspection plan, a shared production planning document) and activities (e.g., the production of a component is private/secret, the transport of goods in traceable by the business partners).

Second, the new elements, aligned with the core BPMN standard, can represent the key manufacturing stages: the production tasks (e.g., apply the coating to components, crush the biomass), the logistics tasks (e.g., schedule delivery of biomass, transport biomass), the quality management tasks (e.g., check components conformity) and the maintenance tasks (e.g., execute a periodic review on production machine one).

Third, the technology strategy of I4.0 actors becomes visible (e.g., conformity check of the components is executed by humans and robots, humans execute packaging of the components).

Fourth, the technological elements used for the I4.0 activities are explicit in the models (e.g., the transport request is made using the online transport company's platform, the crushing of the biomass is done with the crushing machine).

Fifth, the IOBP 4.0 BPMN extension had the capacity of modelling business processes in different fields of industry, more precisely in forest management and coatings. Sixth, the business process models produced with the extension produced the essential information featured in the process documentation provided by the partner companies.

The models produced using the proposed extension included essential details that were not featured while using the standard BPMN language.

6.3.3 Comprehensibility

The IOBP 4.0 BPMN extension has shown the extent to transmit the correct information with the new created syntax for the end users, having the capacity to represent the different sub-types of manufacturing activities (e.g., manufacturing task, quality management task), the digital elements (e.g., machines, processing devices), the sharing of information and the private elements. The produced graphical elements are in line with the standard BPMN. The produced notation introduced a straightforward and intuitive interpretation of the several extension concepts in the IOBP 4.0 models. The created guidelines (presented in Chapter 5) can support both design and interpretation of business process models produced with the IOBP 4.0 BPMN extension.

Therefore, the proposed extension contributes to the enhanced perception of IOBP 4.0.

6.3.4 Weak Points

The evaluation episodes in the real-world case companies also revealed some of the weaknesses of the proposed IOBP 4.0 BPMN extension.

First, the additional information in the business process models created with the IOBP 4.0 BPMN extension increases the complexity and may reduce readability when compared with the standard BPMN. The intensive use of the extension elements may lead to the over saturation of the business process models. The presented guidelines (in Chapter 5) can play a role while dealing with these problems, by explaining the use of the several concepts and how to apply them. 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. Another issue is the representation of regulations: only the most important may be represented. Additionally, comments or text annotations can be used to inform on additional regulation requirements that are not represented. Second, the current version of the extension does not identify the state of process transformation (e.g., Industry 4.0 evolution). For example, showing if the specific technology (e.g., IoT infrastructure, mobile application, machine learning model, sensor) used in activity X is already deployed or under development. I4.0 adoption is dynamic, so it would be important 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), to identify points for the implementation of new techonologies at specific points of the business process (e.g., automate a task with new a robot).

6.3.5 Points for Future Improvement

After reflecting on the evaluation process and the obtained results, two possible avenues for improvement were identified to overcome some of the identified limitations of the proposal.

The first proposal is inspired by enterprise architecture and the Archimate language [139] to explore the possibilities of creating separated process models views, according to the specific user's domain and type of information that he needs to be presented. A digital transformation view could be considered, which would focus on the representation of digital technologies and structures that composed the business process, allowing the analysis of the business process in terms of technological elements towards the execution of business process improvement activities. On the other hand, an inter-organizational view could be also developed. This view would focus mainly on aspects related to the relationships and agreements between the business partners, presenting points of information sharing (e.g., activities execution monitorization, the occurrence of events), resources sharing (e.g., documents shared, machinery shared) and points of decentralized decision. This possibility could be tested by creating a BPMN modelling tool that allowed the creation of process model views, which also included the possibility of overlapping (to have a complete process's visualization) and separating the several process views. The creation of business process views can reduce the complexity of a unique view and even allow the inclusion of more information in the business process models.

As a second proposal, emerges the inclusion in the models of the I4.0 maturity level, that could be represented by a number (e.g., maturity stage ranging from 1-Explorer to 4-Expert) in each element of IOBP 4.0. The classification of the elements with the maturity level can play an essential role in executing business process improvement activities, based on the classification of each element points for improvement and implementation of new technologies. Several maturity models could be studied and experimented with to improve IOBP 4.0 (e.g. [142]).

6.3.6 Reflection on the Evaluation Process

The evaluation process integrated two partner companies that were essential for evaluating the BPMN extension in real cases.

On the one hand, the evaluation process allowed us to model different business processes in different sectors of activity, one in the coatings field and the other in the forest management field, highlighting the capacity of the BPMN. The partnership with the companies also allowed the retrieval of feedback from the industry's experts regarding the properties under evaluation, the potential of the extension for the industry, and the identification of points for improvement. The evaluation process allowed to understand the context of the industry and to proceed to several minor adjustments to the extension. The involvement of a company such as Altri, listed in PSI-20, highlights the potential of the developed artefact for large companies adopting Industry 4.0.

On the other hand, some weaknesses are also identified in the evaluation process. First, the evaluation process considered a single evaluation episode, which may reduce its effectiveness. The evaluation process considered companies working in different contexts and collaborative networks, focusing only on the view of one of the partners instead of considering the point of view from the several partners of the collaborative network. The industry's experts received the models produced with the IOBP 4.0 BPMN extension, providing feedback on the models.

This chapter presented the demonstration and evaluation stage of the DSR for the development of the IOBP 4.0 BPMN extension. The chapter started with the introduction of the approach and strategy for the evaluation of the IOBP 4.0 BPMN extension. The evaluation episode and the properties to be evaluated were defined at this point. Then, the demonstration steps were explained, regarding the presentation of the case companies, introdcuing the modelling of several business processes using both standard BPMN and the IOBP 4.0 BPMN extension, to proceed with the comparison of the representation. An analysis of the evaluation results follows, presenting a reflection on the several properties under evaluation based on the feedback received from the industry's experts. The chapter ended with a reflection on the positive and weak points of the extension, followed by an analysis of possibilities for future improvement.

The next chapter presents the final considerations on this dissertation, presenting a reflection on the entire process, on the limitations of the project and points for future work.

Chapter 7
Final Considerations

7.1 Conclusion

This master's dissertation creates, tests, and evaluates a BPMN extension to model inter-organizational business processes in the context of I4.0. This project was divided into two essential stages, the first semester and the second semester. The contact with the case companies allowed us to access business process documentation and the feedback from their experts. The information retrieved from the companies was essential for developing the extension and the evaluation of the extension. The results of this project include (1) a domain ontology for IOBP 4.0, (2) a requirement modelling analysis for the representation of IOBP 4.0, (3) a CDME for IOBP 4.0, (4) the graphical representation of the IOBP 4.0 extension concepts, (5) a demonstration of the use of the proposed extension in real-cases, and (6) an evaluation of the proposed extension.

The first semester focused on planning the project, defining the research methodology, risk analysis, literature review, and the development of initial artefacts for the design of the IOBP 4.0 BMN extension. The first phase of this project started with the establishment of a working plan, defining the project guidelines, the overall planning for each of the semesters and risk analysis. The defined methodology to develop this project was Design Science Research since it is a problem-solving paradigm that relies on kernel theories to produce innovative artefacts [28]. The key concepts were reviewed and studied during the literature review process, focusing on concepts related to BPM, IOBP, business process modelling, BPMN, BPMN extension mechanism, and existing approaches to develop BPMN extensions. After the literature review, the requirements and domain analysis started to identify the several attributes and particularities of IOBP 4.0, essential to complete the BPMN models. The first semester resulted in the production of some initial drafts, resulting in (1) a shared PDCA approach to IOBP 4.0, (2) attributes particular to IOBP 4.0, and (3) the initial artefacts of a BPMN extension. The first semester addressed the first part of the DSR, with the writing of the intermediate report, focusing on the literature review, objectives definition, and problem analysis.

The second semester focused on the design and evaluation of the IOBP 4.0 BPMN extension. The first steps were aimed on the reviews of the dissertation's jury by proceeding to some corrections and changes on the previous work. The development of the IOBP 4.0 extension continued by creating a domain ontology on IOBP 4.0. The domain analysis was concluded by conducting a modelling requirements analysis on the IOBP 4.0 domain, resulting in the identification of 16 modelling requirements. Then, an equivalence check step followed, aimed to identify if the several identified IOBP 4.0 concepts were semantically equivalent to the existing BPMN elements, to derive the needed extension BPMN elements. The extension elements were then represented by extending the standard BPMN meta model and producing the CDME. Then, according to a set of predefined design principles, the graphical representation of the new elements were created. After creating the extension concepts, a testing and evaluation phase followed. The first case was developed with a technical coatings provider, in which a IOBP was modelled, and feedback from experts was retrieved. A second case followed in ALTRI, retrieving feedback from the experts and modelling a business process involving the biomass cycle to produce bioelectric energy. During the testing and evaluation phases, several adjustments were executed to the proposed extension. Parallelly to the development of the extension, the dissertation was written. The risk management proceeded during the second semester with the monitoring of the identified risks.

The IOBP 4.0 BPMN extension can be helpful for standards-certified companies adopting a process approach to management, like ISO 9001, to disclose their processes and third-party collaborations, with a more complete and concise representation of the several interactions and activities.

Considering the importance and novelty of the proposal, two scientific papers were written. The first paper with the title "*A BPMN Extension to Model Inter-Organizational Processes in Industry 4.0*" which is attached to this dissertation (Appendix C). The paper was submitted to the 29th International Conference on Information Systems Development, being accepted for presentation in the conference. The second paper with the title "*Business Process Improvement in Industry 4.0: An Interorganizational Perspective*" (Appendix C) was submitted to a conference and is still under review.

7.2 Study limitations

Despite accomplishing all the defined objectives for this dissertation, some limitations must be stated.

First, the artefacts produced in this dissertation project are essential to model IOBP 4.0 in a complete way. However, it was not possible to produce sufficient evidence about the proposed approach's benefits to model IOBP 4.0 for the entire collaborative network.

Second, the companies that participated in this project are not representative of the entire industry sector since the participating organizations work in the field of pulp production and technical coatings. Other fields could be considered, such as business, finances or automotive.

Third, the main target of this project was manufacturing-related IOBP 4.0. However, the model can be extended or adapted to IOBP executed in other relevant sectors and different digital transformation strategies (e.g., health 4.0, finances).

Fourth, the domain concepts and attributes were identified based on a literature review and process documentation analysis in two companies. It would have been interesting to conduct industrial surveys to understand the most relevant layers that could also be added and other elements that may be missing.

Fifth, the evaluation process focused only on the vision and information of one of the partners participating in the collaborative network. It would have been interesting to study the process documentation from two or more companies involved in the same collaborative network.

Sixth, the proposed PDCA cycle for the IOBP 4.0 process improvement was only conceptually defined, with no evaluation or demonstration activities being executed to validate it due to time limitations.

Despite the identified limitations, the knowledge obtained during the execution of this project, the analysis of companies' activities, the contacts with industry experts, and scientific writing was an extremely positive and rewarding experience.

7.3 Future Research

Several opportunities for improvement can be identified, namelly:

- First, inspired in enterprise architecture field and the Archimate language [143], it would be possible to separate the business process model in views, with each adapted for each stakeholder, according to their area of expertise and needs. Testing the visualization of the complete process or only a part of its layers is an exciting opportunity for future work.
- Second, the I4.0 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, with the adaption a matutiry model supporting the representation.
- Third, the main focus of this project was on manufacturing-related IOBP 4.0. Concepts such as the sharing of information and resources, decentralized decisions and decentralized authority are inherent to the several inter-organizational domains.
- Fourth, the adaption of the proposed extension to other domains in which collaborative networks are gaining importance (e.g., health 4.0, finances) could be an interesting opportunity for future work.
- Fifth, the proposed PDCA cycle for business process improvement in IOBP 4.0 could be tested in real-cases with companies involved in the same collaborative network and looking to promote joint innovation mechanisms. The IOBP 4.0 BPMN extension could also be tested with business partner involved in the same collaborative network, to assess the utility of the extension for the entire network.

I4.0 is proving to be a great challenge for companies that need to adapt and reshape their business processes to seize the emerging opportunities. The proposed IOBP 4.0 BPMN extension can assist companies in exploring the potential of collaborative networks, aiming to produce more complete business process models, and assisting companies in the execution, monitorization and improvement of IOBP 4.0.

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Appendixes

Appendix A – Modelling Tools Comparison

Visio

Visio [39] is a tool produced by Microsoft, with the goal of creating and managing diagrams and vector graphics models. Visio is a tool that allows the creation of models, based in standard existing libraries. The tool allows the creation of customized libraries of elements to be featured in the models. After analysing and testing the application, the following aspects were considered relevant:

- The application is of simple and intuitive use, requiring registration or login with Microsoft account, followed by the set up.
- The application presents a complete set of modelling languages (e.g., UML, BPMN 2.0, AWS Diagrams) and standards complete application, with several example pre-existing models.
- The application is available in two essential plans: Plan 1 is the online version of the application and Plan 2 allows the use of a downloadable version.
- The produced files are compatible with other modelling tools (e.g., SmartDraw, LucidChart).
- The application allows the integration of the models in Office applications (e.g., Power Point, Word, Excel).
- The application includes 2GB of cloud storage for created models.
- The application includes collaboration functionalities, allowing several users to work simultaneously and share the models easily.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The BPMN 2.0 library is only available in the desktop version of Visio (Visio Plan 2), compatible only with Microsoft Windows.
- The application allows the creation of customized libraries of elements to be featured in the models, by creating customized elements.
- The application includes an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG, JPEG).
- There is no free version available. The paid version has a cost of 15 euros per month per user.
- There is no educational license available.

IBM BlueWorks

IBM Blueworks Live is a cloud-based software that provides a dedicated, collaborative anywhere environment to build and improve business processes through process mapping, created by IBM [40]. This tool allows teams to work together through an intuitive and easily accessible web interface to document and analyse processes. After analysing and testing the application, the following aspect were considered relevant:

- The application is of simple and intuitive use, requiring an initial registration and set up.
- The application uses a specific modelling language, based on the BPMN 2.0 standard.
- The application is only available in online mode.
- The produced files are not compatible with other modelling tools.
- The application does not allow the integration of the models in Office applications.

- The application includes 100MB of cloud storage for created models.
- The application includes collaboration functionalities, allowing several users to work simultaneously and share the models easily.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The BPMN 2.0 complete library is not available in this application.
- The application does not allow the creation of custom elements.
- The application does not include an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG).
- There is no free version available. The paid version has a cost of 44 euros per month.
- There is the possibility to obtain an educational license.

Draw.io/Confluence

Diagrams.net is free online diagram software that allow the creation of several types of models and charts [26]. It is relatively recent tool, that does not require any kind of download. The use of this tool does not require the creation of an account, being easily accessed by users online. After analysing and testing the application, the following aspect were considered relevant:

- The application is of simple and intuitive use, with no registration needed and immediate use and accessibility.
- The application presents a complete set of modelling languages (e.g., UML, BPMN 2.0, AWS Diagrams) and standards complete application.
- The application is available in two essential formats: the online mode and the offline mode.
- The produced files are not compatible with other modelling tools.
- The application does not allow the integration of the models in Office applications.
- The application does not include any storage. However, the application allows the creation of repositories in external cloud services (e.g., Google Drive, OneDrive, Dropbox) or in local storage (e.g., computer).
- The application includes collaboration functionalities, allowing several users to work simultaneously and share the models easily.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The application presents the complete set of elements of BPMN 2.0.
- The application allows the creation of customized libraries of elements to be featured in the models, by creating customized elements.
- The application does not include an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG, JPEG).
- The application is totally free of costs.

LucidChart

Lucidchart is a web-based platform that allows users to create and collaborate on drawing, revising and sharing diagrams [106]. This application is totally established in cloud, allowing an easy access and use almost anywhere, by requiring no installation or download. After analysing and testing the application, the following aspect were considered relevant:

- The application is of simple and intuitive use, requiring an initial registration and set up.
- The application presents a complete set of modelling languages (e.g., UML, BPMN 2.0, AWS Diagrams) and standards complete application, with several example pre-existing models.
- The application is available in online mode. The downloadable version is still in Beta phase, with some of the features still not available.
- The produced files are compatible with other modelling tools (e.g., SmartDraw, Visio).
- The application allows the integration of the models in Office applications (e.g., Word, Power Point).
- The application includes 1GB of cloud storage. The application also allows the creation of repositories in external cloud services (e.g., Google Drive, OneDrive, Dropbox).
- The application includes collaboration functionalities, allowing several users to work simultaneously and share the models easily.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The application presents the complete set of elements of BPMN 2.0.
- The application allows the creation of customized libraries of elements to be featured in the models, by creating customized elements.
- The application includes an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG, JPEG).
- There is no free version available. The paid version has a cost of 8,95€ euros per month per user.
- There is the possibility to get a free educational license.

Smart Draw

SmartDraw is a diagram tool used to make flowcharts, organization charts, mind maps, project charts, and other business visuals [41]. This application is established in cloud, allowing an easy access and use, by requiring no installation or download. After analysing and testing the application, the following aspect were considered relevant:

- The application is of simple and intuitive use, requiring an initial registration and set up.
- The application presents a complete set of modelling languages (e.g., UML, BPMN 2.0, AWS Diagrams) and standards complete application, with several example pre-existing models.

- The application is available in two essential versions: an online (cloud) edition and a downloadable edition for desktop.
- The produced files are compatible with other modelling tools (e.g., Lucidchart, Visio).
- The application allows the integration of the models in Office applications (e.g., Word, Power Point).
- The application includes 100MB of cloud storage. The application also allows the creation of repositories in external cloud services (e.g., Google Drive, OneDrive, Dropbox).
- The application lacks in terms of collaboration functionalities, allowing only the sharing of the models.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The application presents the complete set of elements of BPMN 2.0.
- The application allows the creation of customized libraries of elements to be featured in the models, by creating customized elements.
- The application does not include an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG, JPEG).
- There is no free version available. The paid version has a cost of 99€ euros per year per user.
- There is no educational license available.

Modelio

Modelio is an open-source tool developed by Modeliosoft that supports the UML and BPMN standards [42]. The application presents a very simple user interface and a complete set of elements and directory management. After analysing and testing the application, the following aspect were considered relevant:

- The application is of simple and intuitive use, requiring an initial registration and set up.
- The application presents a limited set of modelling languages, limited to UML and BPMN 2.0.
- This application is only available in an offline version, requiring the download and install of the application.
- The produced files are compatible with other modelling tools (e.g., Lucidchart, Visio).
- The application does not allow the integration of the models in Office applications.
- The application does not include any cloud storage since it is only available in offline mode.
- The application doesn't allow any kind of collaboration functionalities.
- Considering the context of this project, the use of the BPMN 2.0 library is one of the essential aspects. The application presents the complete set of elements of BPMN 2.0.
- The application does not allow the creation of customized libraries of elements.
- The application does not include an icon library.
- The produced elements are exportable in several formats (e.g., PDF, PNG, JPEG).
- The application is totally free of costs.

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

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

First Name Middle Name Last Name
Full Institution/Organization/Company Name
City/Town, Country *email.address@domain.com*

First Name Middle Name Last Name
Full Institution/Organization/Company Name
City/Town, Country *email.address@domain.com*

First Name Middle Name Last Name
Full Institution/Organization/Company Name
City/Town, Country *email.address@domain.com*

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 for continuous business process improvement in manufacturing networks.

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

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, 3D printing, augmented reality, or artificial intelligence techniques to improve production flows [27]. 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, by creating a technological infrastructure to decentralize production, providing visibility to product flows since the early stages of sourcing raw materials to product use. On the other hand, by requiring more "*effectiveness of communication between actors and favoring data collection and sharing*" [25]. 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].

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, inter-organizational business processes, BPMN extensions, and other related work. We detail the research approach in Section 3, and the results follow in Section 4. Subsequently, we evaluate the adoption of IOBP 4.0 in a real-world setting. The paper closes by stating conclusions, the main limitations, and future work opportunities.

Background

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 flows of data and activities [27].

More complex business processes in Industry 4.0 are mobilizing academia to propose process modeling approaches [28]. 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 [25] while keeping the process compliant and traceable.

Inter-Organizational Business Processes

Inter-Organizational Business Processes (IOBP) are interrelated and sequential activities shared and executed by two or more trading entities to achieve a business objective that is of value to the partners [5]. The implementation and execution of IOBP requires 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 [31].

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 the production of 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 [29];
- Monitoring decentralized activities and decisions in IOBP requires the deployment of 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 in a more effective and complete way.

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 (BPMN) 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 [32]. Moreover, BPMN is one of the few process modeling languages that allows the development of extensions, adding domain-specific concepts while ensuring BPMN core elements' validity [24]. 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 [24], 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 [32] suggests a methodology to create BPMN extensions. However, only a few developed BPMN extensions are designed in conformance with OMG's standard [34]. 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 cannot represent all the details of 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. Therefore, BPMN extensions emerge as a promising solution [34].

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 [33]. The study conducted by [35] proposes a BPMN extension for the domain of manufacturing. These authors create a set of elements for representing manufacturing operations and resources, followed by the presentation of 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 important contributions for modeling IOBP and Industry 4.0, an integrated approach to model manufacturing in IOBP scenarios of manufacturing's digital transformation is still lacking. This section's related work can be integrated and extended, serving as the starting point for our research, explained in the next section.

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*" [26].

Our DSR cycle had a problem-centered initiation [26], 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 demonstration of its utility [17]. The design phase follows the approach proposed by [32] using UML profiles, later improved by [8] with the analysis of the domain and its conceptualization [8]. 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.

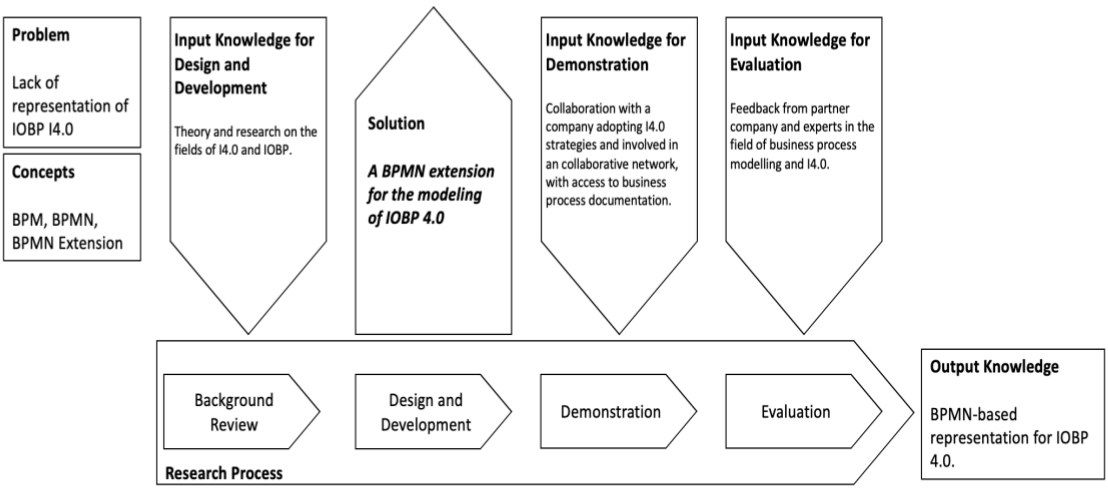


Fig. 1. DSR Grid for IOBP 4.0 (adapted from [11] and [26]).

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. 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.

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.

Domain Ontology

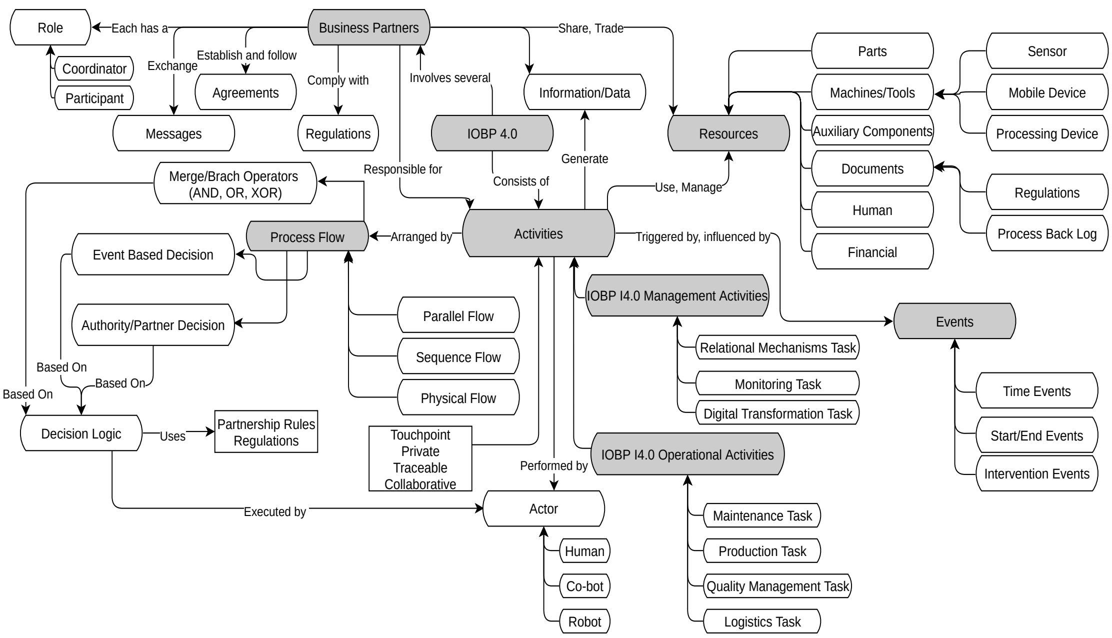


Fig. 2. Domain Ontology of IOBP 4.0.

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

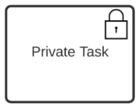
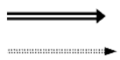
Each business partner acts in the process (coordinates or participates) according to inter-organizational agreements. Partners must comply with specific regulations (e.g., laws, procedures, standards, contract agreements) [29], exchange information/data (through messages and documents) [7], and may share 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 a sequence, following a 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).

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, measuring parts, 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 and state may be shared within the partnership.	
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 the flow 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.	

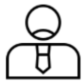
BPMN Concept	Domain	Custom Elements	Description	Graphical Representation
Data Object	**IOBP and Cyber-Physical**	**Process Back Log**	The process log represents data objects to store information retrieved from several traceable tasks and meaningful events.	
Data Object	**Manufacturing**	**Regulations**	The regulations represent the laws and standards that a specific business partner must follow and the standards that must be respected (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 [37] 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.

Demonstration

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

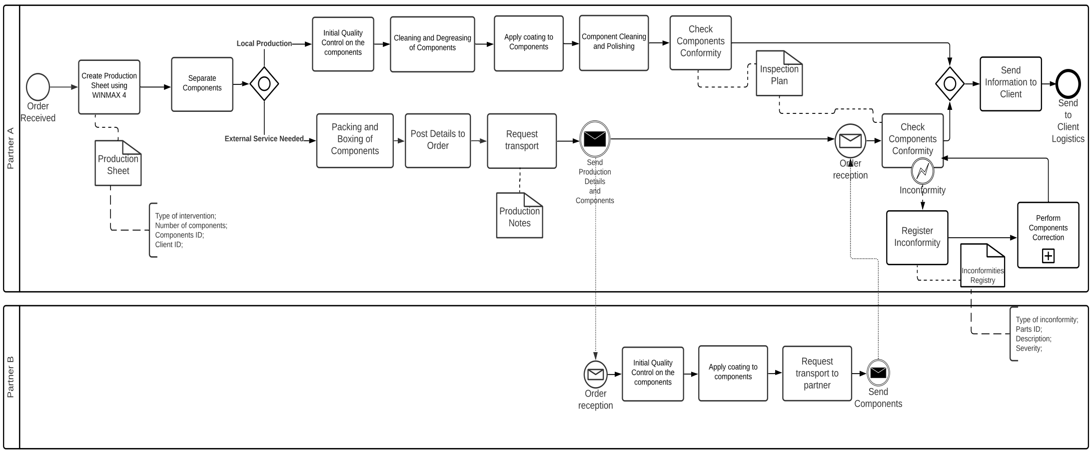


Fig. 3. Coating Process Model using BPMN.

The case 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 WINMAX 4 software, and separates components for internal and/or external production. In the latter situation, 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 to partner B.

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.

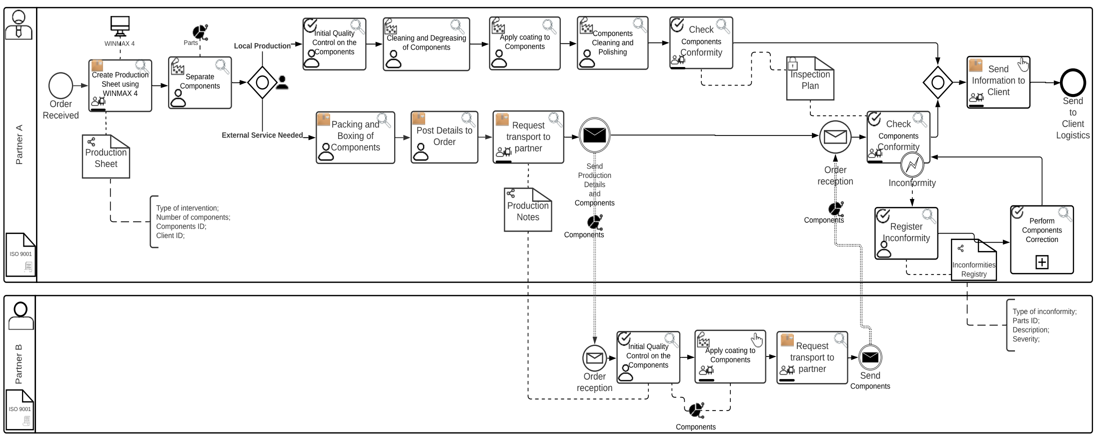


Fig. 4. Coating Process Model using IOBP 4.0 extension.

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 the Appendix.

Section 6 discusses the evaluation of the developed IOBP 4.0 extension.

Evaluation

The proposed BPMN extension provides an answer to the need to represent inter-organizational business processes in increasingly digitalized manufacturing contexts.

Model completeness is one of the most immediate advantages of IOBP 4.0. 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 pertaining to 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 identifying (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, type of activities, internal/external interactions, and technology investments. Therefore, IOBP 4.0 contributes to an enhanced perception of each partner's contribution.

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 important 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 [36], it would be possible to separate the process model in views (e.g., digital transformation view for showing only the technology and maturity, omitting the IOBP-related data, IOBP view hiding the technology layer). Testing the complete process's visualization or only a part of its layers is an interesting opportunity for future work. 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. [30]).

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. It will also be important to assess the social implications of using IOBP 4.0 for different partners.

IOBP 4.0 can be useful 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 for 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.

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Appendix: Examples of IOBP 4.0 Use Cases

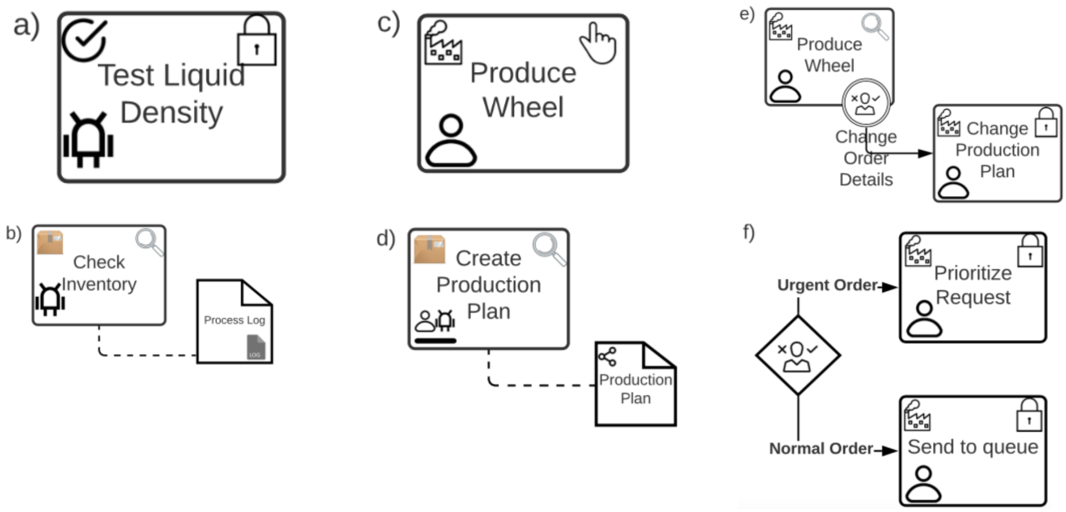

Fig. 5. Examples of IOBP 4.0 Use Cases.

The use case a) included in Fig. 5 (on the top-left) 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 orders 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.

Appendix C - Business Process Improvement in Industry 4.0: An Interorganizational Perspective

Business Process Improvement in Industry 4.0: An Interorganizational Perspective

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Abstract. Industry 4.0 calls for end-to-end digital integration of supply chains and a new boundary-spanning logic of process design. The shift is from shared operation to shared transformation. Design science research was chosen to (1) propose an approach for interorganizational business processes improvement in decentralized contexts of Industry 4.0 (IOBP 4.0) and (2) draft a BPMN extension mechanism for IOBP 4.0. The results are relevant to guide the fourth industrial revolution with increasingly shared and digitalized business processes. For theory, our work contributes to the emerging BPM logic of digital transformation: support for coordinated touchpoints, flexible infrastructure, and empowered participants. For practice, we propose a continuous improvement approach for IOBP 4.0 that ensures manufacturing visibility in collaboration networks. Managing the punctuated equilibrium of boundary spanning business processes will be a priority for this decade.

Keywords: Interorganizational Business Process, Industry 4.0, Business Process Improvement, BPMN Extension.

Introduction

Business process management (BPM) has enabled organizations to move beyond functional boundaries. Much has changed since the pioneer contributions of BPM, but the boundaryless nature of business processes is more evident than ever. Furthermore, in the digital transformation era of industry (alias Industry 4.0 or I4.0), cooperation, communication, and integration within and between organizations become priorities. Therefore, process models representing "how work is done" must support downstream planning of operations, upstream assessment, and decentralized continuous improvement.

Industry 4.0 is leveraged by multiple technologies such as the Internet of Things (IoT), cyber-physical systems, cloud computing, mobile systems, or artificial intelligence shaping the smart factory infrastructure. The overall aim is to integrate and digitalize distributed business processes and redesign supply chains. For example, a company may be manufacturing final products with 3D printers, while, at the same time, their partners produce accessories and raw materials needed to satisfy the customer's order. It is now clear that a new agenda is necessary to promote synergies between BPM and digital innovation in the industry [1, 2].

The collaborative nature of Industry 4.0 highlights the need to manage interorganizational business processes (IOBP) [3]. The study presented by [4] is an example of this trend. The authors present an approach to merge different process models collaborating in the production of artifacts. However, the resulting process models are often incomplete (e.g., some parts may be private) and challenging to share in organizations that need to compete in collaborative production networks. BPMN (OMG's Business Process Model and Notation - BPMN 2.0) is one of the primary standards in process modeling, including elements like tasks, events, and data objects [5]. However, BPMN cannot represent all the details of interorganizational practices [3], making BPMN extensions a promising solution to extend the vocabulary of the notation [6].

Contacts with industry managers revealed that rudimentary practices are still the norm, with process models (1) created independently by each organization in the supply chain, (2) supported by separate documentation (e.g., procedures and requirement lists), and (3) lacking a boundaryless approach to the design, improvement, and audit of IOBP. Moreover, despite the ISO 9001 requirements to adopt a process approach [7], the traditional focus of quality audits tends to be the internal documentation, missing crucial details in distributed environments. This paper aims to address this gap by proposing (1) an approach to continuously improve interorganizational business processes in companies adopting Industry 4.0 and (2) the foundations for a BPMN extension to capture the complexity of IOBP 4.0.

The remainder of this paper is structured as follows. Section 2 presents background literature on Industry 4.0 and business processes. Next, the research approach is introduced. The results of the DSR cycle follow. Afterward, the discussion enumerates design guidelines for IOBP 4.0 design and continuous improvement. Finally, Section 6 presents the conclusions, limitations, and an outlook for the future.

Background

Decentralized Manufacturing Networks and Interorganizational Business Processes in the Industry 4.0 Era

Shifting from single-site to multi-site manufacturing comes with the need for decentralized decisions and more complex flows of data and activities. Collaborative networks also call for autonomous teams of humans and machines equipped with advanced computing power. Therefore, new process modeling languages and methods are necessary for the Industry 4.0 era [8]. However, when "parts" of manufacturing processes are enacted in different locations/settings, it is necessary to deal with moments of disruption (e.g., when a new system implemented) and stability [9], exploiting manufacturing capabilities not restricted to a single organization.

Modeling and improvement in BPM are two sides of a single coin, and popular quality standards like ISO 9001:2015 suggest a process approach to management. Following this standard, companies can adopt the PDCA cycle [7] and, for each step in Plan (P) – Do (D) – Check (C) – Act (A), continuously improve their business processes. BPM is "*the art and science of overseeing how work is performed in an organization to ensure consistent outcomes and to take advantage of improvement opportunities*" [10]. However, "*shifting from strategic interactions (driven by reduction of transaction costs) to transformational interaction (driven by collaborative transorganizational development) appears to be difficult to achieve in practice in a network setting*"[11].

Process, infrastructure, and people are fundamental building blocks of BPM culture [12] and quality culture. First, organizations should focus on the lifecycle of process identification (1), discovery (2), analysis (3), redesign (4), implementation (5), monitoring, and controlling (6), in which the process models assume a crucial role [10]. Second, BPM promotes the alignment between the business process goals and the organizational infrastructure, mainly through technology. Third, actors are expected to follow the processes as documented and modeled [1]. Nevertheless, the complexity of BPM in the digital transformation era needs to balance the traditional stability and predictability of work practices with the emerging uncertainty and dynamic nature of change [2, 9]. Moreover, the emerging cyber-physical infrastructure must maximize process exploitation and leverage exploration capabilities to foster continuous improvement in decentralized contexts of manufacturing.

Recent research points to the necessity to move beyond the organization borders in modeling process details, incorporating process deviations and the constraints/opportunities for sociotechnical change [13] while keeping the process compliant and traceable. Representing social, technical, and transformational elements in process models is one of the challenges for research in this area.

Interorganizational business processes are interrelated activities shared and executed by two or more entities to achieve a business objective that is of value to the partners [14]. Globalization and technological advances increase the need for collaboration within supply chains [15]. Therefore, entities involved in IOBP 4.0 development need to establish a trustful relationship supported by technical, behavioral, legal, and strategic mechanisms [16].

However, balancing the needs of real-time control and compliance with decentralized decision-making and flexibility can be challenging [17]. As stated by [18], this type of collaboration arrangement offers "*significant opportunities at strategic level, as well as significant challenges at tactical level, in order to properly combine flexible and effective inter-organization collaborations with traditional internally managed processes*". Examples include the need for transparency between internal business processes and the "external part" [19], precise coordination and management of process interdependencies [3], and a clear definition of responsibilities across the different companies and activities in the IOBP 4.0 flow [20]. In addition, companies must address the semantic gap caused by diverse internal process language/specifications [21] and the autonomy that each organization requires to implement their strategies at a different pace. Therefore, mechanisms to reduce the degree of coupling between the internal and external interfaces must be put in place [22].

The investments required by partnering across organizations in the digital transformation era require agility and joint innovation mechanisms to support continuous improvement [14]. However, when business process management is geographically dispersed [23] and transversal to different power structures, it is crucial to deploy innovative policies to allow traceability metrics for each activity [24].

Despite the essential contributions recently proposed to synthesize IOBP in a unified visualization [4], we could not find an approach in the literature to assist the entire lifecycle of IOBP 4.0 transformations at both design-time (modeling) and run-time (operation).

Business Process Modelling and Extensions for Industry 4.0

The main goal of BPMN is to support BPM activities with an intuitive and straightforward notation comprehensible by different domain experts. BPMN can be used to represent complex processes, for example, in manufacturing [25]. Another advantage is that BPMN has a well-defined language meta-model that facilitates model exchangeability and tool integration [6]. Moreover, the BPMN meta-model contains a specification of elements for the structured definition of language extensions [6], which is particularly useful for adapting to new contexts.

Diagrams can be shared across organizations and partners using an XML-based interchange format. Therefore, our research follows current BPMN standards and gathers inspiration in:

- BPMN extensions for industry: PyBPMN extension [26] for cyber-physical systems is the most cited. Additional studies in this area include modeling industrial internet-of-things scenarios [27], business process fragments for manufacturing [28], requirements of process synchronization [25] and ubiquitous business process modeling [29]. Nevertheless, "*business process modelling remains unproven for all the processes encountered in manufacturing enterprises*" [28].
- BPMN extensions for interorganizational contexts: Some studies focus on time-aware business process modeling. For example, processes must "*adhere to a wide range of temporal requirements which rise from legal, regulatory, and managerial rules*" [30]. Notably, the first contribution with an approach for IOBP model design was presented by [31], using messages and pools for each organization. [32] presents a comprehensive BPMN extension for collaborative business processes, focusing on concepts related to the execution of collaborative tasks, privacy, confidentiality, state of execution of tasks, data management, and activity monitoring. The authors propose a set of new elements and illustrate them with examples.

It is now possible to extend these important contributions to the field of manufacturing and Industry 4.0 adoption. Therefore, our paper follows the new logic of BPM required by digital transformation [1, 2]. The following section describes the research approach towards IOBP4.0: interorganizational business processes for Industry 4.0 that balances compliance and change by design, adhering to the needs of multiple manufacturing organizations sharing a common production aim.

Research Approach

Design science research (DSR) is a problem-solving paradigm that relies on kernel theories to produce innovative artifacts [33]. The authors of [33] suggest an iterative process starting with the problem identification and motivation, define objectives of a solution, design and development, demonstration, evaluation, and communication [33]. Complementarily, the FEDS framework [34] was proposed to evaluate DSR projects, which considers the possibility of a "quick & simple" summative evaluation.

The DSR cycle reported in this paper includes a review of synergies between Industry 4.0 and IOBP − summarized in Section 2. First, we obtained 80 hits in Google Scholar using the keyword combination "BPMN extension" AND ("industry 4.0" OR "digital transformation"), excluding patents and citations. However, only ten results were found in the same database using "BPMN extension" AND ("inter-organizational business process" OR "interorganizational business process". Then, we searched for recent papers focusing on Industry 4.0 foundations and digital transformation in BPM to understand the trends in these fields of knowledge.

The methodology to create DSR artifacts (steps of design and development according to [33]) was adapted from [35], using UML profiles, and later improved by [36], with the analysis of the domain and its conceptualization [6]. First, we conceptualized what continuous improvement means in the context of interorganizational business processes. Second, we identified key attributes in the literature to represent IOBP 4.0 and support (decentralized) digital transformation of business processes. Third, we created a Conceptual Domain Model of the Extension (CDME) as a UML class diagram. Finally, we conducted a summative evaluation [34] of the results with two companies adopting Industry 4.0.

Company CC1 is a major European paper pulp production company, and CC2 is a small technical metal coatings provider. CC1 had an ongoing digital transformation project for the forest management process (integrating companies in production, logistics, inspection, transformation). CC2 created a new product line partially executed by external partners (investing in a new coating robot and artificial intelligence models to forecast product failures under operation). Both companies are ISO 9001-certified and interested in continuously improving their processes in collaborative environments.

Section 4 details the artifacts created during our DSR endeavor.

Modeling and Improving IOBP 4.0

The team created three foundational artifacts for the design and improvement of IOBP 4.0. We were first aggregating the necessity of "change" in the digital transformation era and gathered inspiration in the PDCA cycle to describe how interorganizational business processes improve throughout the lifecycle (Table 1).

Lifecycle	Description	Ref.
Shared planning (P)	IOBP 4.0 requires preparation and commitment from the different parties. Companies may compete for the same resources (e.g., machines) that must be scalable and optimized. Each "part" of the process must ensure flexibility by design, revealing in this attribute how it can be done (e.g., global, or local process reconfiguration or actors changes). The organization involved in collaborative improvement must specify goals to achieve (e.g., IT investments and expected results for the overall shared goal).	[1, 14, 24, 27]
Shared execution (D)	IOBP 4.0 can be described by core BPMN elements (e.g., processes, tasks, events, resources, and data objects). Messages are important but insufficient to detail (1) interorganizational execution (e.g., who decides to cancel the process, quality criteria, performance indicators) and (2) particularities of Industry 4.0 (e.g., new technologies adopted in decentralized parts of the process). Each organization should focus Industry 4.0 investments on their core competencies.	[15, 25, 30, 37]
Shared monitoring (C)	IOBP 4.0 needs specific monitoring processes to evaluate the performance of shared elements (e.g., process execution-level agreements). In addition, new challenges emerge from monitoring processes in decentralized manufacturing (e.g., real-time data sharing) and protected logs for auditability purposes.	[24, 37]
Shared digital transformation (A)	IOBP 4.0 improvements using digital technologies can be implemented by each actor independently or in cooperation. Thus, mindful actors and powerful digital technologies are inseparable.	[1, 2, 9]

Table 1. Continuous improvement of IOBP 4.0: A PDCA approach.

After describing the lifecycle of IOBP 4.0 improvement, we extracted attributes to create the IOBP 4.0 extension from the literature (Table 2).

Attribute	Description	Ref.
Confidentiality	Organizations may have restrictions on sharing internal information or managing customer-owned data. As a result, decisions may occur under incomplete information.	[15, 19, 32, 38]
Responsibility	Shared processes require shared responsibility for innovation, execution, and monitoring.	[15, 20, 37]
Authority	Global and local actors must be defined, and their decisional capacity specified in different possible scenarios.	[3, 37]
Touchpoint	It is necessary to define when a message is required and the impact on all the stakeholders of the main process (e.g., customers may interact with the process at specific points, assessors' touchpoints, or interaction between cyber and physical elements of the process).	[28, 31]
Transparency	Partner organizations should embrace transparency.	[19, 38]
Compliance	Multiple regulations (voluntary and enforced) may compete in different geographical locations.	[3, 23]
Traceability	Activities, resources, data, and decisions must be traceable within the entire process lifecycle.	[24]
Interface	Shared elements (e.g., task, data) must have an interface to enable actors' intervention (e.g., app).	[22, 32]
Collaborative	Collaborative BPMN elements must be identified. Parallel or sequential execution may be separate or in collaboration.	[32, 39]

Attribute	Description	Ref.
Autonomy	Autonomous tasks and decisions (e.g., single-organization process improvement) must be identified.	[37]
Digital Infrastructure	Digitalized activities require technological devices to retrieve data (e.g., sensors), interact (mobile devices) and produce value with data.	[8, 26]
Digital Transformation Phase	BPMN elements (e.g., task, gateway) have specific transformation stages (planned, development, deployed).	[1, 2, 11]
Target Innovation	BPMN elements can be classified in terms of innovation status (state-of-the-art, outdated, actual, stable).	[1, 2, 11]

Table 2. Key Attributes of IOBP 4.0.

Finally, we produced the CDME for IOBP 4.0. Four types of resources are essential in the context of Industry 4.0 [40]: machines/tools parts; devices; and auxiliary components. In addition, the task concept was extended with (1) manufacturing particularities and supplemented with (2) IOBP tasks for monitoring, (3) managing relationships, and (3) digital transformation. The latter three concepts aim to create synergies among process partners, while manufacturing-related tasks can be quality control, inventory control, production, and maintenance [28].

Fig.1 presents the proposed CDME.

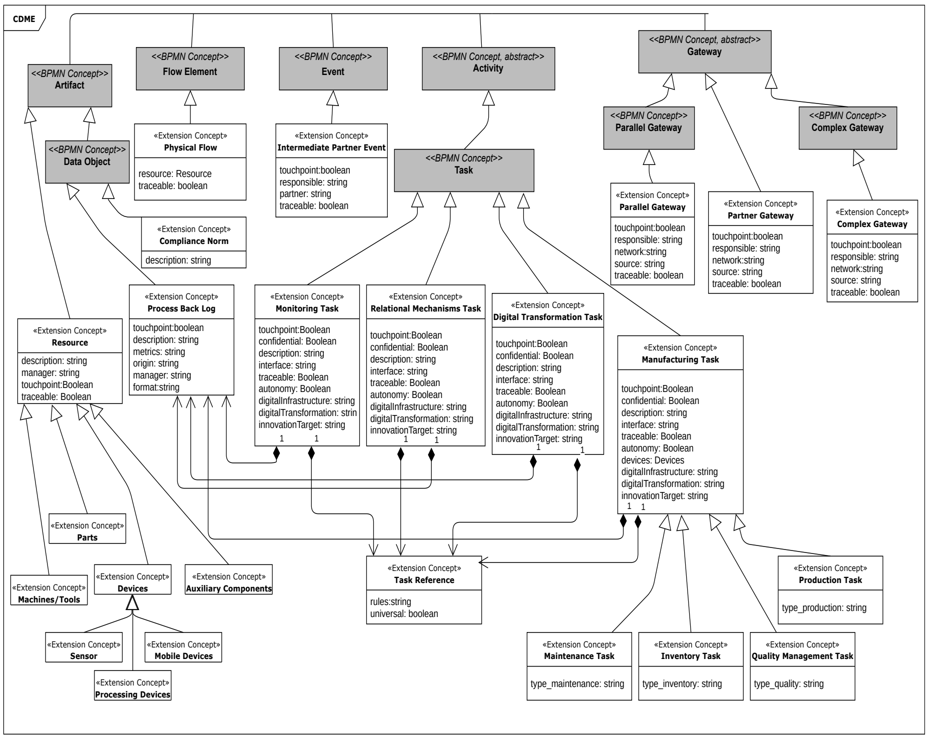

Fig. 1. CDME for IOBP 4.0.

Resources (on the left of Fig.1) may be shared across the different partners. The data object was extended to represent the several compliance regulations that each actor must follow while executing their activities [23]. The "Partner Gateway" extends the gateway concept, and the event concept was extended with the intermediate partner event (event raised by a partner's decision in specific moments of the IOBP) [3, 37]. The flow element extension represents the exchange of resources across business processes [28]. Finally, the data object concept was extended to represent the process backlog: information related to the monitorization of the business process [24] and analysis. The following section discusses the main findings of this DSR cycle and suggested guidelines for the continuous improvement of IOBP 4.0.

Discussion

Process activities need to be monitored and controlled across the collaboration network involved in Industry 4.0 investments. For example, some activities may need to comply with specific regulations (affecting one or multiple partners). The manufacturing stages may also require transport/sharing resources, represented by the physical flow. At the same time, partners' (independent/agreed) decisions raise the necessity to include the partner gateway and the partner event. Moreover, Industry 4.0 adds new challenges to traditional interorganizational process management because companies are changing their digital infrastructure in cycles of stabilization (exploitation) and destabilization (digital exploration), affecting each partner's BPMN element in particular ways.

PDCA cycle was considered suitable by the project participants familiar with ISO 9001, suggesting simple steps for continuous improvement in distributed environments. However, Table 1 also reveals issues when operating in collaborative networks. For example, governance, risk, and compliance (GRC) are more complex and involve interdependencies between partners [31], which is challenging to represent in traditional BPMN models. Nevertheless, we agree with [23] that GRC management is an opportunity to improve business processes, achieve genuine cost savings, and improve their competitive positions.

Due to the complex and dynamic nature of organizations, markets, and technologies in Industry 4.0, more complete models are necessary to represent work practices and the stage of digital transformation to design new systems or improve the operation of existing ones. According to the domain experts contacted during our DSR, a standard notation can assist the global process actors to manage activities and coordination of tasks (e.g., similarly to how Gantt-charts are usually adopted in project management to share information between partners). Furthermore, those models can be included in a common repository, shared by all actors, and integrate into their contractual agreements. Thus, the models can be helpful for the "top-down" communication of the global process owner and to collaboratively design, change, and promote innovation and improvement in boundary-spanning processes of Industry 4.0. However, despite the popularity of BPMN (as happens in ISO 9001 certified industries), we cannot confirm the acceptance by the industry at this stage.

The artifacts developed in this cycle and the discussion with practitioners allowed us to derive the following design principles for IOBP 4.0:

- Adopt a top down IOBP 4.0 modeling approach for BPMN elements. Then, choose a bottom-up description of digital transformation attributes. While the former address the common (shared) business objective, the latter emerges from the negotiated contribution of all partners in the network and a trade-off between individual strategies and overall collaboration value;
- Use business process models to negotiate continuous improvement initiatives among the partner organizations and establish an integrated digital transformation program;
- Continuously update IOBP 4.0 models. Industry 4.0 investments must be communicated to all interested parties, and its performance monitored over time;
- Identify priorities for shared innovation in specific parts of the process. Industry 4.0 is enabled by end-to-end digital integration of supply chains, local weak points (e.g., partners not producing as expected) may need adjustments;
- Explore business process simulation techniques to evaluate the impact of digital transformation.

Conclusion

This paper presents the results of a design science research project aiming to create (1) a shared PDCA approach to continuously improve interorganizational business processes in Industry 4.0 contexts and (2) the grounds for a BPMN extension for IOBP 4.0. Five main design guidelines are suggested to create IOBP 4.0 models that portray how industries collaborate and support shared continuous improvement planning, execution, and evaluation.

There are also limitations that need to be stated and opportunities for the next DSR cycle. First, although we have identified a lifecycle for the digital transformation of IOBP 4.0 and an extension, we have used a specific combination of keywords in our literature review. Other attributes may be included via search improvements and insights from the practitioners. Second, the artifacts produced in this cycle are essential to change the traditional (separate) process models. However, we do not yet have evidence of its benefits in the entire collaboration network. Our contribution includes the proposal of design guidelines for the creation/transformation of boundary-spanning IOBP 4.0, balancing the needs of digital transformation, which is essential, but also challenging when we evaluate change "over time" [2]. Third, the companies that agreed to participate in our work sharing their models are not representative of the entire industry. Other companies adopting Industry 4.0 can be added to the study. Fourth, the focus of this cycle was on manufacturing-related IOBP 4.0, but the model can be extended to other interorganizational business processes, for example, purchasing, marketing, or services. Finally, further evaluation will need an external ISO 9001 process audit. This limitation was already considered in preparation for the next cycle. We have included ISO 9001-certified companies adopting industry 4.0 with processes that need to be shared by at least another organization with an independent decision hierarchy.

The next DSR cycles will focus on developing the graphical representation for the extension and evaluating the organizational (e.g., synergies in identifying process improvements) and social (e.g., the usability of the IOBP 4.0 models) implications of its adoption by the case companies.

Acknowledgments

<Removed for paper review>

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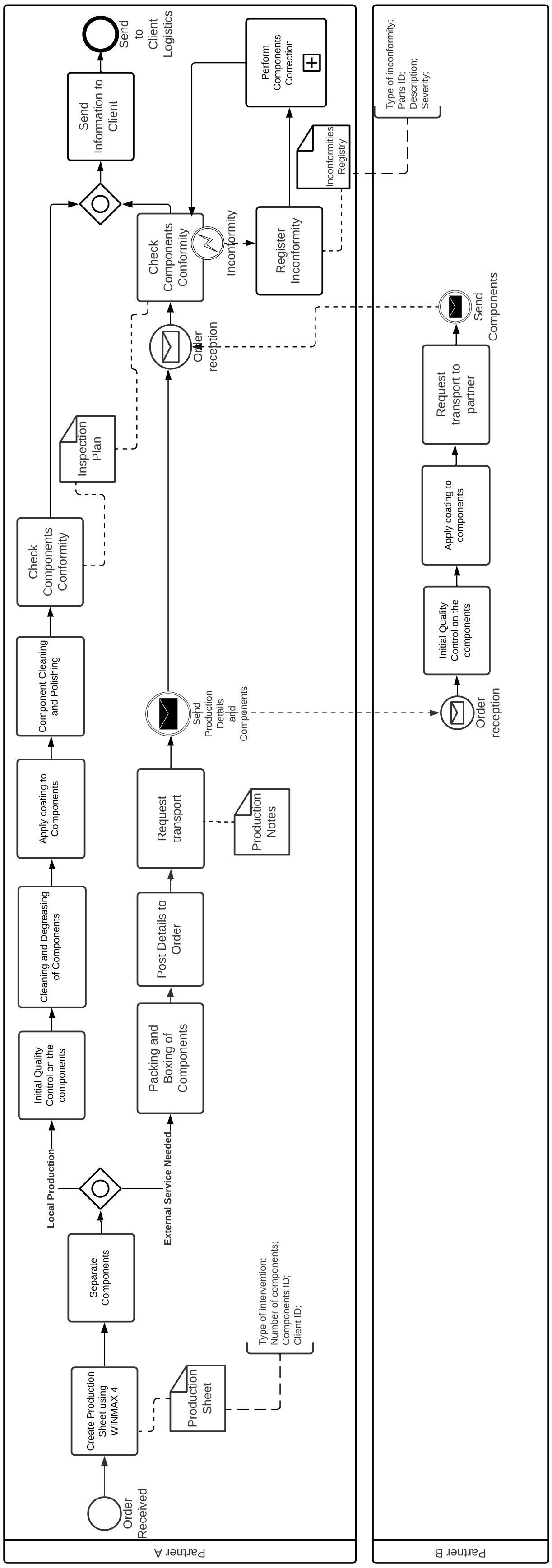
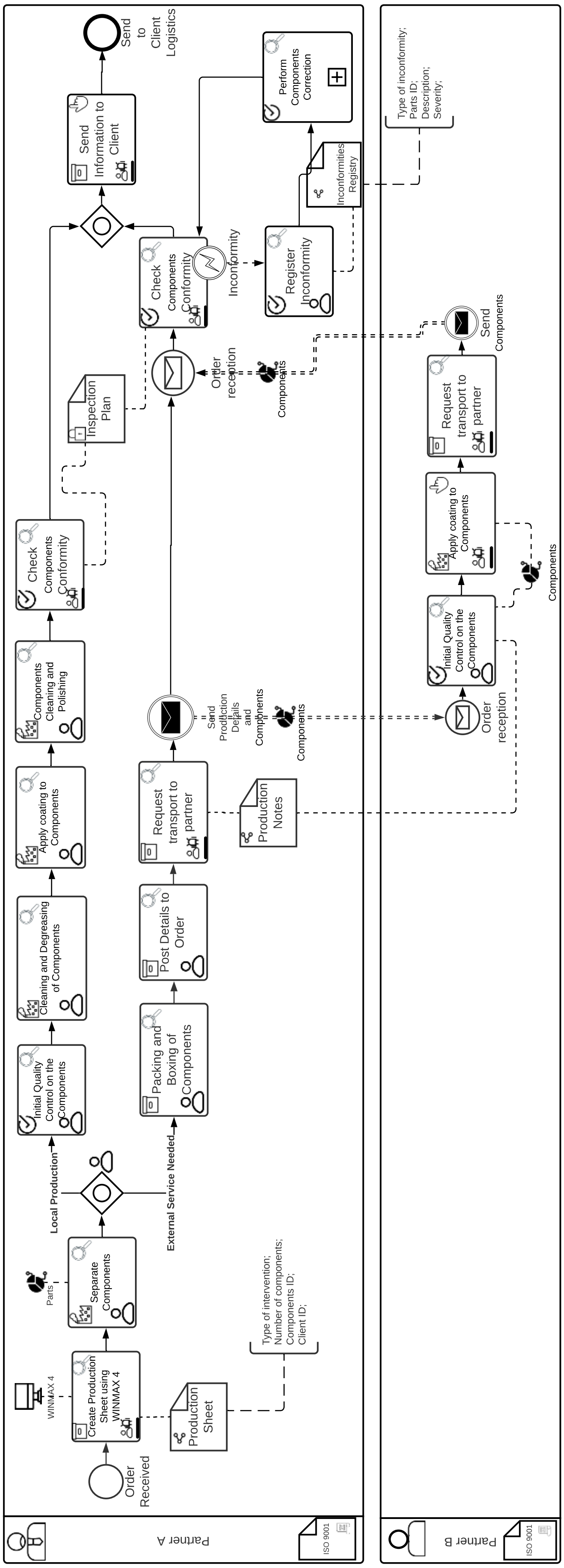
Appendix D – Coatings Business Process

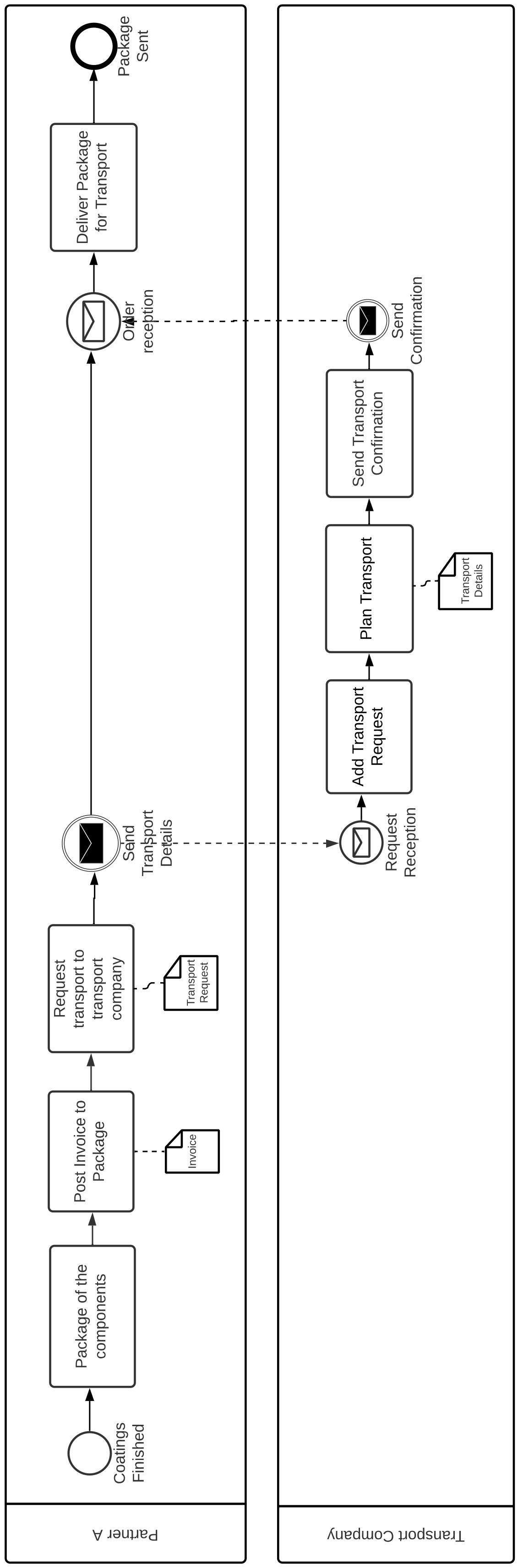


Coating Business Process Model using BPMN

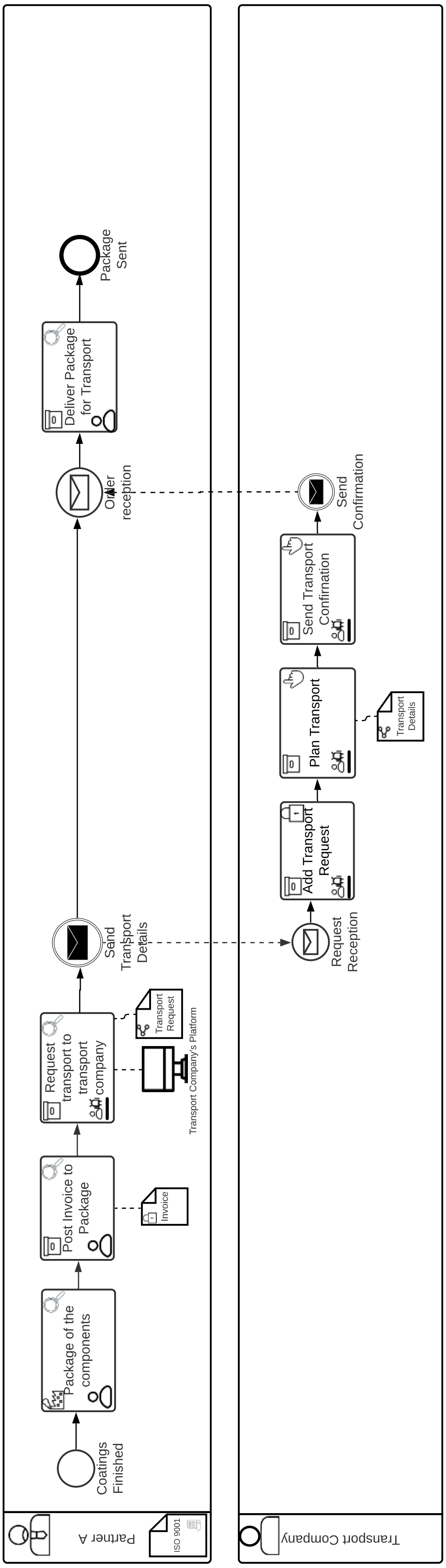


Coating Business Process Model using IOBP 4.0 BPMN Extension

Appendix E – Request Transport Business Process

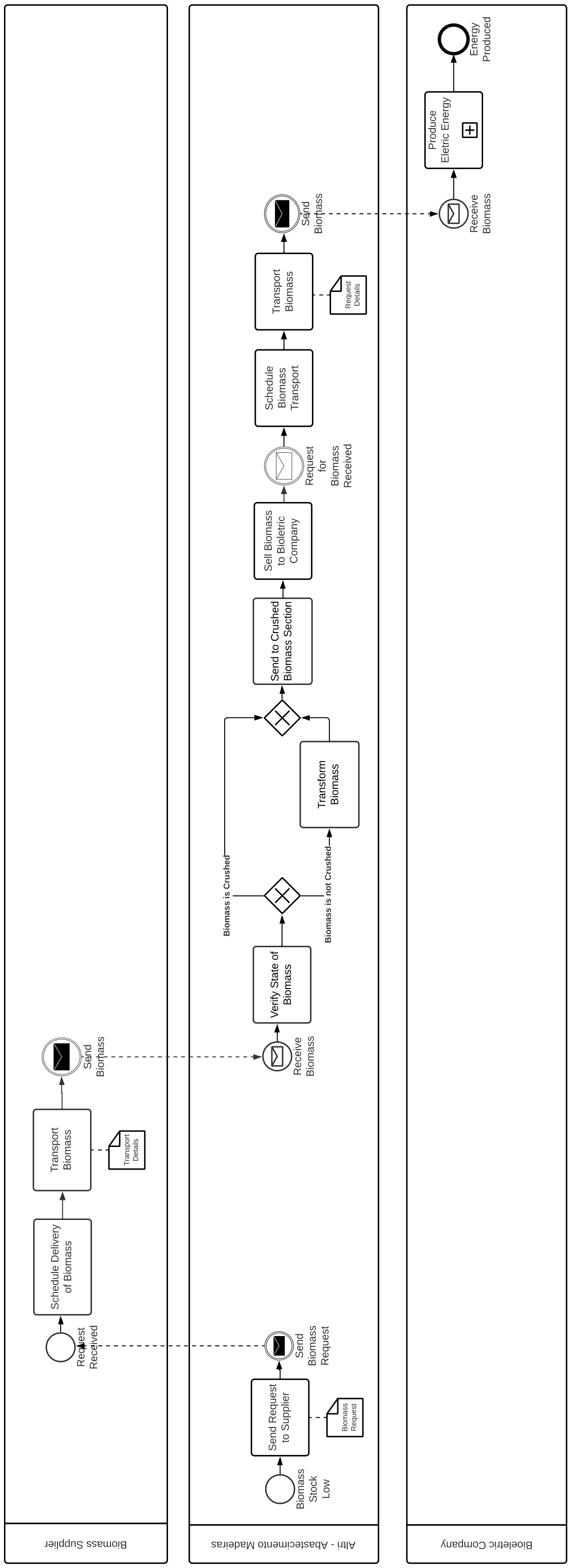


Require Transport Business Process using BPMN

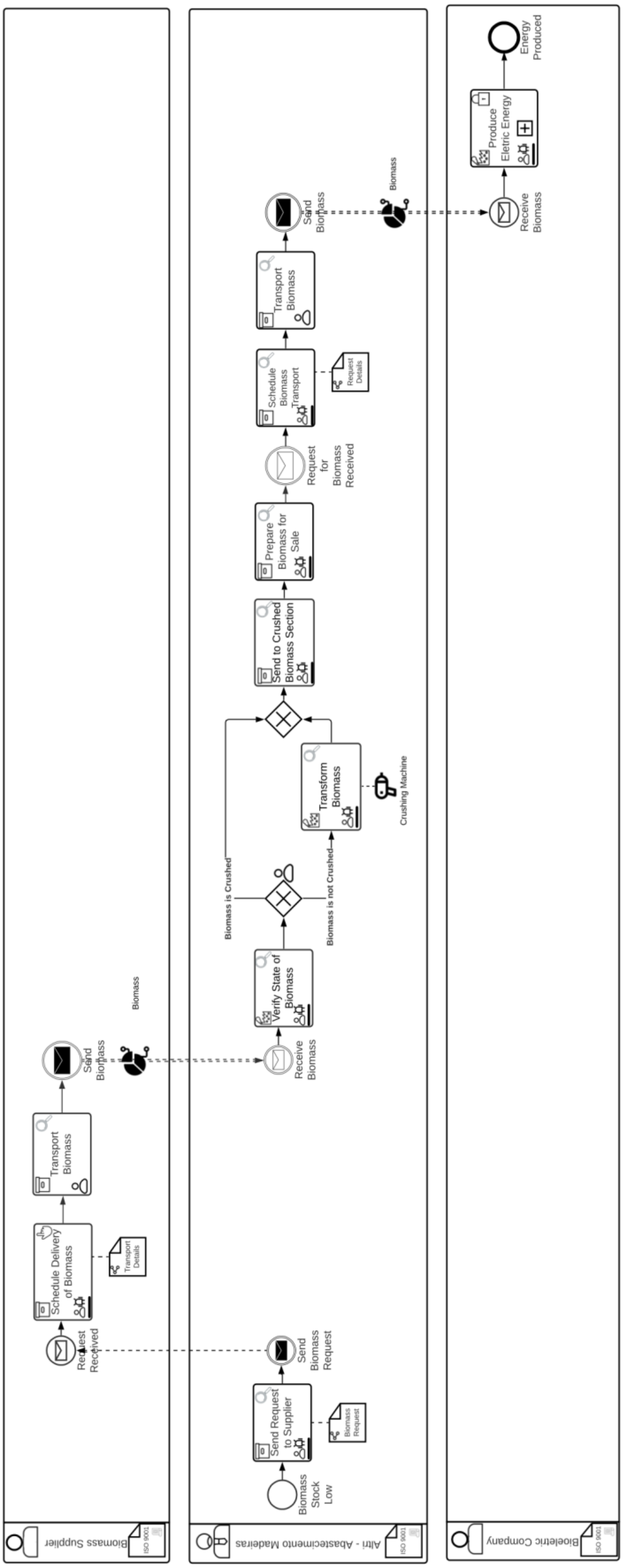


Require Transport Business Process using IOBP 4.0 BPMN extension

Appendix F – Biomass Business Process



Biomass Business Process using BPMN



Biomass Business Process using IOBP 4.0 BPMN extension