MASTER

Extending BPMN for modeling manufacturing processes

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Extending BPMN for modeling manufacturing processes

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Abstract

In the realm of manufacturing, an evolutionary journey has begun towards the fourth industrial revolution, Industry 4.0, characterized by smart manufacturing. The idea of smart manufacturing is to create a network whose components have enhanced capabilities that can interact with each other in real time. In this environment, discussion has commenced over the use of Business Process Management for the merge of the different emerging technologies. With BPMN becoming the standard for modeling the behavior of business processes, its fit to the manufacturing domain needs to be examined.

This research addresses this issue by identifying the necessary manufacturing concepts that cannot be modeled explicitly with standard BPMN and proposes a valid extension to the notation, called MPMN. The proposed extension elements were defined with the extension mechanism provided by the BPMN notation to ensure their validity to the notation; their identified attributes and model associations with other BPMN elements were explicitly defined and a metamodel completes each extension concept definition. In addition, conceptual designs were introduced for each extension concept.

A visualization tool accompanies this research for the modeling of the MPMN extension. Realistic manufacturing processes were modeled with the visualization tool to evaluate the MPMN extension, compared against the same manufacturing processes modeled with standard BPMN. An expert evaluation of the MPMN extension was finally performed to assess the contribution of the proposed solution to the manufacturing domain.

Keywords: Industry 4.0, Smart Manufacturing, Smart Factories, Business Process Management, BPMN, Extension, MPMN, process modelling, visualization, metamodel
Preface

This thesis concludes my Master studies in Eindhoven University of Technology. When I arrived to the Netherlands three years ago, bright eyed and brimming with motivation, I had no idea of the challenges I would face. Thankfully, a kind Dutch person soon taught me of the meaning of the word ‘gezellig’ and I instantly decided to let it express my Dutch life.

My favorite Dutch word—in full disclosure, I only know a dozen—certainly expresses the last six months that I have been working on my graduation project. This is, first and foremost, due to the amazing people who supervised my research. I would like to thank the lovely Irene Vanderfeesten, for being my first supervisor and supporting me throughout this journey. Your guidance, given with kindness and motivating excitement, has given me great strength and inspiration. I could not have had a better mentor, thank you.

Secondly, the man himself, Jonnro Erasmus, who has guided me from the very beginning and was present in every step of the way, thank you for everything. You have not only given me guidance but friendship as well, sorry for being louder than most. I will make it up to you with the greatest gift given to mankind, chocolate.

Finally, my fellow Greek comrade, Kostas Traganos, thank you for all—and I mean, ALL—your comments and feedback. Your dedication in helping me improving my work has been one of the biggest challenges—and possibly incredulous laughs—of my project. I hope I managed to make you proud with this masterpiece.

To my TU/e ‘family’, Ege, Rick, Caro, Jason and Sander, thank you for your friendship and more importantly, the drinking sessions. Lots of wine was—unintentionally—spilled in the past few months, all of it was worth it. To the few of you who thought it was a good idea to go on that ride in the theme park, I want you to know that I am alive, but not thanks to you.

And to my dear friends who have been right next to me in the past three years, making my life in the Netherlands a true joy with their presence, Antonis, Vicky, Dimitris, Piona, Rodrigo, Nikola, Laura and Petriek, you guys are the absolute best. I love you.

Last but not least, my family, the people who mean absolutely everything to me, I would not be here without your support. To my father, mother, sister and—as of this year—my adorable baby niece, σας αγαπώ.

Maria Aspridou
Eindhoven,
September 2017.
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Introduction

In recent years, Industry 4.0 has come to the forefront of discussed industrial business concepts. The stages of industrial development began with the First Industrial Revolution, in the 19th Century, where production shifted from farming to factories (using water and steam power). The Second, running from the 1850s to World War I, used electric power to create mass production and the Third, up to the late 1970s, launched the digitization where electronics and IT were included in the production processes taking over a great portion of the tasks. Through the advancements in technology over the past decade, Industry 4.0 was introduced. In this phase, information flows between different platforms, people, objects and business processes to create a “smart production”; robotics connect remotely to computer systems equipped with machine learning algorithms that can learn and control them with minimal input from human operators [16]. The idea of smart production and Smart Factories is to create a network whose components have enhanced capabilities that can interact with each other—and with humans—in real time and most decisions are decentralized—planning and scheduling will remain centralized in the near to medium future. Technological concepts such as the Internet of Things (IoT), Embedded Systems (ES) and Cloud Computing (CC) are key enablers of Industry 4.0.

In this environment of accelerating rates of change, manufacturing companies wish to improve their performance, but they are faced with several challenges; Redundancy in systems and processes, lack of transparency and flexibility in their processes, along with high complexity in the value chain. To achieve automation while adopting new technologies, manufacturing companies should aim for flexibility [35]. Flexibility allows companies to cope with the uncertainty of changing environments through its dynamic capabilities, while production automation is secured to ensure productivity increase and efficiency in innovation. Flexibility in production may also help companies transform their processes from the departed high volume - low variability production to the emerged low volume - customization one. The automation of activities for a certain function is accomplished through process automation.

Business processes can be determined for most company activities. A business process is defined [32] as such:

\[\text{A business process is the combination of a set of activities within an enterprise with a structure describing their logical order and dependence whose objective is to produce a desired result.}\]

Business processes enable the achievement of corporate objectives and often start by a trigger, which initiates a set of predefined workflow steps. Business Process Management (BPM) aids to improve enterprise performance by achieving greater efficiency, clarifying job responsibilities and

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reducing human error. There are several process modelling techniques; Business Process Model and Notation (BPMN), UML ¹ diagrams (Use Case, Activity, Sequence, etc.), flowcharts, data flow diagrams, IDEF for function modeling ², and more.

Business Process Management (BPM) is a discipline involving any combination of modeling, automation, execution, control, measurement and optimization of business activity flows, in support of enterprise goals, spanning systems, employees, customers and partners within and beyond the enterprise boundaries.[36]

The graphical representation of the process description provides the most efficient way in communicating the proposed solution. While both BPMN and UML are open standards maintained by the OMG group, UML is an object-oriented technique and therefore the process-oriented approach of BPMN makes it more suitable to model a business process domain [41].

The primary goal of BPMN is to provide a notation that is readily understandable by business users, ranging from the business analysts who sketch the initial drafts of the processes to the technical developers responsible for actually implementing them, and finally to the business staff deploying and monitoring such processes[28]

The standardized language contains definitions on the symbols for the process elements, their meaning and their combinations. The output of the modelling process should be a map of the organizational processes or a section of them (see figure 1.1).

![Business process diagram expressed in BPMN](image)

Figure 1.1: Business process diagram expressed in BPMN [36]

The BPMN standard has been used successfully in various domains [21], such as healthcare, finance, or insurance. Its greatest advantage is that it has a well-defined syntax [28] that most business analysts are familiar with, making collaboration easier. Recently, BPMN has been proposed for modeling manufacturing processes [44, 45]. Manufacturing companies use various methods, such as Value stream mapping (VSM), IDEF models or Supervisory control and data acquisition (SCADA) [2, 3, 43], to view their processes from several viewpoints and at various abstraction levels. BPMN’s potential for modeling manufacturing processes has yet to be explored sufficiently and systematically; this research aims to contribute in addressing the issue.

¹Unified Modeling Language
²Integrated Definition
CHAPTER 1. INTRODUCTION

The research will initially address the benefits BPM can bring to the manufacturing domain and recognize which are the most important specific functions of the domain. Thereafter a link between the essential manufacturing functions and their modelling with BPMN will be made. As this research will focus mainly on the visualization aspect of the necessary new additions, it aims to ensure their validity to BPMN; This will be achieved by addressing the necessary additions to the BPMN metamodel for the graphical extensions of BPMN that will better visualize manufacturing activities. This extension of BPMN for manufacturing processes will be referred to as MPMN™ (Manufacturing Process Modelling Notation) from this point onward.

1.1 Problem Definition

Identifying the extent of the project context is an important step in analyzing the necessary components of the research; starting from the specific problem identification leading to the contribution of this research to its context.

While the market changes and demands grow higher, manufacturers face high expectations to ensure control and clear understanding of all processes and their interconnections in all operational units (see section 2). With the use of BPM, manufacturing organizations may analyze and design their processes around their people, assets and raw materials; when processes are formulated accurately, they can support the organization in the ever-changing competitive environment. Although several model processing standards exist, BPMN has attracted the most attention due to its expressiveness and flexibility in defining workflows and its capability in automated execution of the processes. BPMN has gained respect as the de-facto standard for business process modeling and thus its successor, BPMN 2.0, has the power and the advantage to be supported by a great number of software tools [11, 21].

Section 2.2 provides some insight on the benefits of BPMN for the manufacturing domain. However, BPMN’s potential for the domain has not yet been fully explored and there is limited literature on the topic [26, 30, 44, 45]. Modelling manufacturing processes with BPMN, while feasible, may lead to non optimal process models since specific characteristics of the domain (such as the allocation of tasks to agents existing only in the manufacturing domain) can not be expressed distinctly. Therefore there is a need to extend BPMN with custom concepts in order to represent specific characteristics and meet the requirements of the domain. Adapting the BPMN language is aided by the fact that the language itself provides an extension mechanism in its metamodel to secure the validity of the BPMN core [5, 28] (see section 2.3 for further information on the extensibility of BPMN).

Thus, the problem statement of this research can be defined as:

<table>
<thead>
<tr>
<th>Problem Statement</th>
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<tbody>
<tr>
<td>Standard BPMN language, while interdisciplinary respected as the dominant notation for expressing business processes, lacks options to visualize manufacturing processes explicitly. Therefore there is a need to extend the language in order to make it more compatible to the manufacturing domain.</td>
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CHAPTER 1. INTRODUCTION

1.2 Approach

This research follows the classic problem-solving cycle [1, 38], which is based on the fundamentals of design science [17] and has a predefined set of steps to reach a solution relating to a problem. The process of solving a research problem starts with the proper and structured definition of the problem. Once the problem is understood, the cycle proceeds to the analysis phase; there, the problem and its context are analyzed to understand its causes. The following phase is the design of a solution, where the important issues are considered and the design of the solution is realized. Next, the implementation of the solution (or else, intervention) can be performed. In this phase, the proposed solution is implemented on the basis of the actions conceived in the design phase. Finally, in the evaluation phase the effects of the solution are assessed. The last phase may lead to the definition of a new problem, in which case the cycle may start again.

Figure 1.2: The problem solving cycle, adapted from [38]

1.3 Research Objective

The goal of this research project can be divided into two phases. In the first phase, on the academic front, the main objective is to identify which are the core manufacturing functions that create the necessity for a BPMN extension. This requires detailed research on all the functions within the manufacturing domain and clear mapping to the standard BPMN elements. On the second phase, the practical aspect, the goal is to develop the extension MPMN with all necessary extended elements explicitly defined (through visualization, syntax and semantics – execution is considered out of scope due to time constraints). A qualitative analysis will be performed at the end of the research to verify that the objective is met; domain experts will be requested to evaluate the MPMN extension in contrast to standard BPMN for modeling manufacturing activities.
1.4 Research Questions

In order to achieve the research objective, it is important to acquire relevant knowledge within the project scope. The most efficient way to gain the necessary insight is through the formation of research questions. Therefore, the main requirement for the definition of the research questions is that they yield the required knowledge for achieving the research objective.

Figure 1.2 shows the approach (adapted from [38]) that will be taken in undertaking the challenge of this research which can be seen as divided in five phases. The research questions will be addressed in the Analysis, the Design, the Implementation and the Evaluation phases, since they are the drive behind the performed activities in the aforementioned phases.

The research objective, as specified in the previous section, implies the question of, "How can BPMN be extended to satisfy the manufacturing domain?". As this is seen as a general question driving this research, it is necessary to split it into the following questions to properly address the research problem. Thus the research questions are defined as followed:

<table>
<thead>
<tr>
<th>Research Question 1</th>
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<tr>
<td>Which are the essential functions of the manufacturing domain and how can they be mapped to BPMN?</td>
</tr>
</tbody>
</table>

The first research question is addressed in the Analysis phase. The intention for this question is to i) identify the key functions of the manufacturing domain, and ii) map them to BPMN elements. It is within the spectrum of this question that the academic gap is recognized; where standard BPMN cannot visualize manufacturing elements explicitly. In order to properly respond to these questions there is a need to perform a literature review to acquire the essential academic knowledge, as well as to contact several field experts to gain their insight on missing functions, along with the ranking of the identified ones. Finally, personal observations will bind the acquired knowledge to justify a proper response.

<table>
<thead>
<tr>
<th>Research Question 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>How can standard BPMN be extended for the manufacturing process characteristics that cannot be visualized with standard constructs?</td>
</tr>
</tbody>
</table>

The second research question is addressed in the Design and Implementation phases. It guides the actions needed to respond to the academic gap and highlights the need for a formal definition of the proposed extension. The question commends for clarification on i) the extended elements, ii) their visualization, and iii) a proper manual with clear instructions on their use.

As stated before, BPMN provides an extension mechanism through its metamodel that enables the definition of domain-specific concepts [5, 28]. This mechanism guarantees the validity of the BPMN core but it lacks proper instructions for the development of the extensions and therefore only few BPMN extensions make use of it [6]. Stroppi et al address this problem by defining
a methodical procedure model of valid BPMN extensions based on conceptual domain models [34]. However, since this approach is more engineering driven, Braun et al [7] extend it in order to aid the identification of the need for the extension and the conceptualization of the domain. Figure 1.3 shows the procedure model for the development of the BPMN extension as proposed by [7]. The Analysis and the Design phases follow the aforementioned procedure.

Figure 1.3: Procedure model for the development of BPMN extensions [7]

<table>
<thead>
<tr>
<th>Research Question 3</th>
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<tr>
<td>Is the proposed extension perceived as beneficial to the modelling of manufacturing processes?</td>
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</table>

The last research question is addressed in the Evaluation phase. The aim is to perform a fair evaluation on the proposed solution to the research problem. The evaluation will be performed through interviews with field experts, after modeling real manufacturing processes. This will act as a qualitative analysis to assess the benefit of the extension to the field. Experts can identify the advantage (or disadvantage), or any important missing functions (and thus potential improvements) of the new method. The modeling of real manufacturing processes aims to assure that the solution achieves the research objective effectively. The research intends to produce an extension that successfully models manufacturing activities in a more realistic and comprehensive way, thus making this the value of the proposed solution to the domain literature.

1.5 Research framework

Research frameworks represent the internal logic of a research project and aid the comprehension of the structure of the research. Figure 1.4 is a schematic visual representation of the necessary steps to achieve the research objective showing the interconnection of the different phases of this research.
Figure 1.4: Visual representation of the research framework
The steps shown in figure 1.4 follow a sequential flow, starting with the identified problem (BPMN inept for manufacturing processes) and ending with improving the visual suitability through the proposed extension. Orange blocks refer to the research questions, purple blocks are information items from the Knowledge Base, blue blocks refer to the extension constructs, red blocks refer to theoretical constructs and finally green blocks refer to the various steps of this research. The ‘technique’ refers to the produced tool that will realize the extension elements and makes use of the previous three blocks within the 'MPMN' group.

With the construction of the schematic presentation it is feasible to summarize Verschuren’s [39] step-by-step approach for constructing the research framework:

1. Characterize briefly the **objective** of the research project:
   Identify and Implement MPMN (section 1.3).

2. Determine the **objects** (parts of reality) of the research project:
   Manufacturing Domain & BPMN (section 1.3).

3. Establish the **nature** of the research perspective:
   Design-oriented Research (section 1.2).

4. Determine the **sources** of the research perspective:
   Scientific literature & Experts’ interviews (section 1.4).

5. Make a **schematic presentation** of the research framework:
   Figure 1.4 (section 1.5).

### 1.6 TU/e and HORSE

This research project is realized as an internal project in the Eindhoven University of Technology (TU/e). It is closely related to the HORSE project which aims to develop technologies for Smart Factories. The TU/e team focuses on the exaptation of the BPM technology for the manufacturing domain.

The HORSE project, funded by the European Horizon 2020, is a R&D project aiming to bring innovation to the manufacturing industry by developing new technologies for Smart Factories. It proposes new flexible models that promote the collaboration of humans, robots, AGVs and machinery to realize industrial tasks in an efficient and safe manner.

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3The HORSE project: http://www.horse-project.eu/The-project

4The extension or refinement of existing design knowledge so that it can be used in some new application area[15].
1.7 Thesis Outline

The structure of this report follows a logical narrative. At the end of the introduction the identified problem driving this research is defined and the methodology that the research will follow in order to provide a solution is discussed; The research questions and the framework were presented here. Chapter 2 discusses the background information and the required related context for the research project. The manufacturing domain is introduced and its defining aspects are discussed. Following that information, discussion on the benefits of BPM for the manufacturing domain are recognized and BPMN and its extension mechanism are explained. Next, chapter 3 focuses on the Analysis Phase. The domain is conceptualized and its key functions are mapped to BPMN so that the necessary extension elements would be identified. The requirements and the abstract syntax of the extension are within the scope of this chapter.

Following, chapter 4 engages on the Design Phase for the construction of the concrete syntax of the extension. The design decisions and the visual designs of the proposed extensions are discussed and selected there. The next two chapters, 5 and 6 deal with the Implementation and Evaluation Phases respectively. The former one shows the construction of the visual extension and its grammar rules whereas the latter showcases the use of the extension in real manufacturing processes and discusses the received feedback from domain experts. Finally, chapter 7 discusses the contribution of the proposal and its limitations.

The steps shown in figure 1.4 can provide a guideline since every block can be linked to specific sections in this research. Table 1.1 shows the aforementioned links.

<table>
<thead>
<tr>
<th>Framework Block</th>
<th>Section</th>
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<tbody>
<tr>
<td>BPMN inept for Manufacturing Domain</td>
<td>Section 1.1</td>
</tr>
<tr>
<td>BPMN justification for Manufacturing processes</td>
<td>Section 2.2</td>
</tr>
<tr>
<td>Identify Deficiencies</td>
<td>Section 3.2</td>
</tr>
<tr>
<td>Requirements Analysis</td>
<td>Section 3.2.2</td>
</tr>
<tr>
<td>Identify Extensions</td>
<td>Section 4.1</td>
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<tr>
<td>Symbols</td>
<td>Section 4.4</td>
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<td>Semantics</td>
<td>Section 4.5</td>
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<tr>
<td>Syntax</td>
<td>Section 5.1.7</td>
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<tr>
<td>Technique</td>
<td>Section 6.1</td>
</tr>
<tr>
<td>Implementation</td>
<td>Section 5.1</td>
</tr>
<tr>
<td>Evaluation</td>
<td>Section 6.2</td>
</tr>
</tbody>
</table>

Table 1.1: Links between blocks in figure 1.4 and report sections.
Theoretical Background

This chapter provides the theoretical background for this research in order to communicate basic knowledge of the manufacturing domain and BPM to the readers. Initially the chapter introduces the manufacturing domain as to paint the main picture of how production lines operate and then proceeds to more specific information on the different control levels in automated interfaces between the enterprise and the control systems. Thereon, section 2.2 aims to connect the manufacturing domain to BPM by recognizing several benefits the latter can bring to the former. Finally, the chapter ventures on the pragmatical aspect of the merge between the two by reflecting on domain research that has pursued to do so in the past and point out the technical feasibility of such an endeavor.

2.1 The manufacturing domain

The first and most influential study of manufacturing technology was conducted by Joan Woodward, a British industrial sociologist [42]. She developed a scale (figure 2.1) and organized the firms according to the technical complexity of the manufacturing process.

Figure 2.1: Woodward’s classification on system of production
The three groups are described as,

1. **Small Batch and Unit Production**: all technologies that produce one or several products simultaneously such as art work and construction projects.

2. **Large Batch and Mass Production**: technologies in assembly line operations, such as automobile and consumer electronics plants that produce standardized, identical products based on routines and standard procedures.

3. **Process Production**: technologies at ongoing, non-discreet, capital intensive production processes that require minimal manual involvement such as chemical plants and oil refineries. Successful companies here reflect organic structures and more levels of management.

Woodward discovered that span of control, formalized procedures and centralization are high for mass production and low for other technologies (i.e. unit and process production). The number of skilled workers and the use of verbal versus written communication also depend upon manufacturing technology; it is high in unit and process production and low in mass production. She also described the technical complexity of a manufacturing process as the degree of its mechanisation, where unit technology is the least complex and the process production is the most complex one. It was observed that unit and process technologies required non-routine behaviour while mass production was better served by mechanical structures characterized by routines and procedures (see figure 2.2).

![Figure 2.2: Technologies relation to Woodward’s items](image)

The manufacturing process involves several machines (or actions) positioned in a specific order to transform a product into the desired output. Traditional production lines were constructed so that they would follow large runs; Make-to-Stock (MTS), where the production and the inventory are specified by the manufacturer and the finished product is ready for immediate shipment. However, the increasingly volatile markets shift the trend towards Make-to-Demand (MTD – where current and changing demand patterns determine the production) and Make-to-Order (MTO – where nothing is produced until there is a customer order) lines. Figure 2.3 shows [Extending BPMN for modeling manufacturing processes](image)
the different buffer points between MTO and MTS strategies; MTD may use any combination of the other strategies that are needed to meet customer demand as it is a flexible strategy that responds to the customer’s order, yet can achieve delivery speed close to that of MTS [33].

Today’s increased global competition means shorter product life cycles and knowledgeable consumers. As mass production is replaced by customization, manufacturing processes need to change: The challenge is to avoid a stop-start production line due to highly specialized and expensive equipment that requires to be configured for different products at short notice. The solution comes from Smart Factories as they provide dynamic reconfiguration [14].

Manufacturing standards grant guidance to designers, engineers and other specialists on how to conduct disciplined activities within their domains, while facilitating communication between stakeholders across domain borders and life cycle phases. The ANSI/ISA-95\textsuperscript{1} standard describes the manufacturing process as a result of an interaction of several subsystems that create a hierarchy where each key layer corresponds to an individual level of control (figure 2.4).

The levels of control are described as such:

- **Level 4 – Business logistics systems**
  Managing the business-related activities of the manufacturing operation.
  (ERP, establishes the basic plant production schedule, material use, shipping and inventory)
  Time frame: months, weeks, days, shifts.

- **Level 3 – Manufacturing operations systems**
  Managing production workflow to produce the desired products.
  (Batch management, MES systems, laboratory, maintenance and plant performance management systems, data historians and related middleware)
  Time frame: days, shifts, hours, minutes, seconds.

- **Level 2 – Control systems**
  Supervising, monitoring and controlling the production process.
  (Real-time controls, human-machine interface, supervisory and data acquisition)
  Time frame: minutes, seconds.

\textsuperscript{1}International Society of Automation
CHAPTER 2. THEORETICAL BACKGROUND

• **Level 1 – Intelligent devices**
  Sensing and manipulating the production process.
  (sensors, analyzers, actuators and related instrumentation)
  Time frame: minutes, seconds, milliseconds.

• **Level 0 – The physical process**
  Defines the physical production processes.
  Time frame: minutes, seconds, milliseconds.

Figure 2.4: ISA-95 functional hierarchy of enterprise control

The ISA-95 standard has gained wider acceptance for specifying a complete functional model to integrate the business and manufacturing layers. Technologies that enhance BPM practices, such as BPMS\(^2\) and ERP\(^3\), stand strongly on level 4 since they cater to different business processes or organizational functions. The MPMN extension for modelling manufacturing processes can therefore be viewed as traversing functional units and standing across levels 3 and 4 in the ISA-95 standard (see figure 2.4).

### 2.2 Benefits of BPM for the manufacturing domain

As mentioned before, manufacturers are facing a quickly evolving marketplace. BPM, as a cross-functional approach that improves efficiency in organization processes, leads businesses to be more competitive by improving their performance through analysis, proper design, execution and control. Initially, manufacturing processes should be defined by analyzing how work is performed and break it into individual actions for creating a pattern; these repeatable steps will then become the process steps of the manufacturing processes.

\(^2\)Business Process Management System

\(^3\)Enterprise Resource Planning

Extending BPMN for modeling manufacturing processes
BPM has achieved numerous benefits for organizations, many of which can be linked to the manufacturing domain. First and foremost, enforcing standard processes will help in optimizing the entire manufacturing process with a more efficient utilization of the resources, great end-to-end coordination, reduction of errors and overall improvement on safety. Tasks that do not add any value, like scheduling or task allocation can be automated and thus process waste (such as wasted time, inventory and resources) can be reduced as well.

Process modeling creates a comprehensive visualization of the performed work which enables the identification of strengths, weaknesses and (time) sensitive conditions in order to improve and optimize the process and by extend, the performance and the efficiency of the process. As BPM allows real-time visibility, the monitoring of process KPIs \(^4\) becomes feasible; thus a corrective action may take place before the process (or item) is completed. This end-to-end process control makes the processes adaptable and can predict –or even avert– bottlenecks. The BPM customization is achieved through configuration which ensures long-term support of the models [8].

The aforementioned benefits of BPM for the manufacturing domain reflect several requirements for smart factories. Smart factories are expected to be highly adaptable in order to respond in real time so that they can be competitive; re-configurable running processes can attain low downtime, while product customization through real life data can influence production decisions to achieve flexibility. Furthermore, smart factories are expected to be modular (with reusable components); BPM can visualize this and more so it enables the tracing of material throughout and beyond the production chain. Finally, as smart factories should be connected to the upper management levels of the enterprise, this forms a clear indication that BPM, that can create a connection between the production process and the company’s business processes, may be a great fit for the manufacturing domain.

2.3 BPMN extension mechanism

In order to allow the representation of domain-specific aspects, BPMN provides an extension mechanism to its metamodel which enables the reuse of the modeling language. Conforming to BPMN in such a way allows other domains to take advantage of the benefits of the notation (such as the standardization) while ensuring model core validity.

The BPMN extension mechanism (see figure 2.5) consists of four additional elements:

1. **Extension** – Binds the extension to the BPMN model definition
2. **Extension Definition** – Naming the new attributes to be used by BPMN elements.
3. **Extension Attribute Definition** – Defining distinct attributes.
4. **Extension Attribute Value** – Defining specific attribute values.

The *Extension* element helps in importing each extension (with its attributes) to a BPMN model definition. The *Extension Definition* is merely an additional attribute that can be referenced by a Base Element multiple times and consists of various *Extension Attribute Definitions*, whose values are defined in the *Extension Attribute Value* class.

\(^4\)Key Performance Indicators
Despite the existence of the extension mechanism, development of BPMN extensions are usually unguided since there is no well-defined process model for their formulation. Braun and Esswein [6] provide an overview of 30 domain-specific BPMN extensions. Through their classification (which only the 16.7% of the extensions are defined by the BPMN extension mechanism), it becomes evident that there is lack of maturity in BPMN extension research. As mentioned in the section 1.1 there is even less research done on extending BPMN in order to fit the manufacturing domain.

Figure 2.5: BPMN metamodel relating to the extension mechanism [28]

While the extension mechanism has its limitations [5], this research will try to define the proposed extension while conforming to the BPMN standard (section 4.5).
Manufacturing Domain Analysis

As stated before (section 1.4), the Analysis phase is linked to the first research question.

RQ1: Which are the essential functions of the manufacturing domain and how can they be mapped to BPMN?

The remaining of this chapter will address this issue by splitting it into two sub-questions. Initially the manufacturing domain will be analyzed and its key functions will be individualized and later those functions will be linked to BPMN elements. Through this mapping, the nonconformity of standard BPMN to the manufacturing domain will be detected and thus the extension concepts will be identified.

3.1 Key Manufacturing Functions

Conceptualizing the domain entails the unambiguous description of the concepts within the manufacturing domain. In order to answer the first research question, it is important to first look into the manufacturing domain as a whole and understand how it operates.

RQ1.1: Which are the key functions of the manufacturing domain?

As a first step, an upper ontology for the manufacturing domain should be presented in order to describe the domain as a whole. Figure 3.1 represents the concepts of the manufacturing domain that are relevant to this research. The present ontology is based on the MASON ontology, proposed by Lemaignan et al. [23]. The original MASON ontology with the relevant concepts for this research are represented in figure A.3 in appendix A.2. The present ontology shown in figure 3.1 builds on the original one and extends it for the purposes on this research.

As per MASON, the presented ontology is built upon three head concepts; entities, operations and resources which roughly correspond to Martin’s [25] product, process and resource. Entities are helper concepts that specify the product; for this research only the base concept of Raw Material is presented since other entities such as Cost, are considered out of scope. Operations cover the processes linked to manufacturing; this concept will be further discussed below (see figure 3.2). Finally, Resources refer to the various components that take part in manufacturing activities.

As per MASON, we assume that all resources are required for an operation (in contrast with just the ‘tools’) and thus the relevant relationship is adjusted accordingly. Breaking down the individual Resources concepts, Material Resources refer to the objects that take part in the creation of the final product, whereas Geographical Resources refer to the
CHAPTER 3. MANUFACTURING DOMAIN ANALYSIS

spaces that partake in the processes, such as workshops, plants, building zones, etc. For the MPMN ontology, an adjustment has been made in order to include the Robot agent; a critical deviation from the business processes to the manufacturing ones.

Robotics is a field that is growing and evolving at an exponential rate. In manufacturing, robots may work alongside humans without endangering them and helping with a wide range activities in the process. While currently industrial robots are most common in auto plants, they are starting to handle jobs that require more agility. As Automated agents’ role in manufacturing is growing, their presence should be acknowledged and differentiated. In the presented ontology, as mentioned before, the original Human Resource is replaced by Agent Resource, which in turn includes both Humans and Robots for this reason. Finally, a clear distinction should be made between agents (who will perform an activity, ie. to whom a task can be allocated to) and machines (that take part as a resource to an activity). Therefore, Agent Resources are introduced in place of the Human, which is then split into Human and Robot. Agent resources refer to the handlers responsible for performing an activity and form the most dynamic part of the production system.

As mentioned earlier, Manufacturing Operations should be further discussed. There are two main subcategories that emerge through the literature; The manufacturing processes that involve the conversion of raw materials\(^1\) into finished products with specific characteristics [10] and materials handling that concerns all industrial activities that do not add to the value of the product [29] but are essential for the proper run of the factory.

Looking through the literature for a well defined manufacturing process classification, in order to understand and identify the various ways to manufacture different products, two available taxonomies are highlighted; The Todd [37] and the CO2PE! (based on the German DIN8580 standard) [13, 18] taxonomies. Both classification systems base their categorization on the nature

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\(^1\)By ‘raw materials’ we refer to all intermediate stages of a product before it reaches its final state.
of the operation being performed on the raw material (see Appendix A.1). Todd’s classification is used in the United States and Europe as a valuable tool in identifying processes and their capabilities and it will be the one referenced in the construction of the final classification of manufacturing processes for this research project (green block in figure 3.2).

Although well defined classifications can be found for the manufacturing processes that focus on creating or adding value to the product, materials handling does not have a universally accepted definition. For this research project the materials handling subcategory is based on the definition that was originally adopted by the American Materials Handling Society; "Materials handling is the art and science involving the moving, packaging and storing of substances in any form." [4]. The moving of raw materials from the sources to the plant is referenced as transportation of materials [29]. In addition to the aforementioned processes, inspection operations are commonly referenced as a typical process found in manufacturing facilities [12, 24, 40] and therefore it is also considered. Thus, the final classification of Materials Handling within this research entails the activities of Inspection, Transportation, Packaging and Storing (red block in figure 3.2).

Figure 3.2 shows the constructed classification of Manufacturing Operations as perceived within the scope of this research project; The individual manufacturing functions are shown within dash-lined circles. 'Mass conserving' has been divided in two classes given that the state of the raw material is different; solid vs liquid (see Appendix A.1 for further information). The classification in figure 3.2 is linked to figure 3.1 as it is a more detailed view of the ‘Manufacturing Operations’ block; they are shown in different figures to preserve their readability. The decision on the level of detail for this research is discussed in the next section.

Figure 3.2: Classification of the operations in the manufacturing domain
3.2 Mapping of key manufacturing functions to BPMN

Following the domain analysis, the equivalence check has to be performed.

RQ1.2: How can the key functions be mapped to BPMN?

The previous section identified the key manufacturing functions. The classification of Manufacturing Operations in figure 3.2 provides ten concepts; six from Manufacturing Processes and four from Materials Handling. In addition, 'Entities' and 'Resources' from the ontology in figure 3.1 provide six more concepts; Raw Materials, Machine and Tool from Material Resources, Geographical Resources and Human and Robot from Agent Resources. Finally, two more concepts are considered, the Hybrid agent and Material Access; the reasoning behind these additions are discussed below.

Table 3.1 shows the equivalence check as it was proposed in [7]. In the last column, extension elements are marked as ‘Extension Concept’, whereas BPMN elements are marked as ‘BPMN Concept’. In case the concept is not equivalent to a BPMN concept but an extension has been proposed in the literature the element is marked with an ‘?’ (since they will be disregarded in this research); This was decided in order to eliminate repetition and respect relevant work in the domain. However, given that literature found on BPMN for the manufacturing domain is very limited, this applies only for the concepts of ‘Machines’ and ‘Tools’ [44] and ‘Raw Material’ [45] proposed by Zor, et al.

3.2.1 Mapping Principles

In order to perform a fair mapping of the manufacturing functions to BPMN, several assumptions and decisions should be addressed. First, as mentioned earlier, the level of detail in Manufacturing Processes has to be discussed. In the classification shown in figure 3.2 the six main sub-categories are shown (these can be split further down to more detailed tasks – appendix A.1). However when considering the MPMN concepts these divisions are not taken into account. The reasoning supporting this decision is twofold. Firstly, the various activity tasks in BPMN represent an atomic action within a process flow and the end-user or the applications that will perform the task when it is executed. In other words, the question behind the modeling decision is who will execute the task or how this task will be executed and not what the task does. Secondly, experts (table B.1) were questioned (informally) in order to get practical insight on this decision. The received feedback confirmed and supported this decision. Defining different tasks for every manufacturing processing activity (even on the level of six) was seen as redundant.

The second assumption is with regard to the use of the User Task. A User Task is executed by a person via an application’s user interface (as in BPMS2). If a task is not performed within the context of a “process-aware” application, Manual or Abstract Tasks are being used. When mapping human tasks in MPMN we assume that User Tasks are equivalent even though the described task might not be performed via an application. The reasoning behind this decision is that when a process instance reaches a User Task, an entry is created in the performer’s work list – unlike the Manual Task which is performed independently of the process engine; it is possible to define several variables as input or output for the task and for the execution of the task itself. This implied interaction between the user and the system is considered important for the Human Task and therefore they are linked to the User Task instead.

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2Business Process Management System
<table>
<thead>
<tr>
<th>Concept</th>
<th>Semantics</th>
<th>Equivalence Check</th>
<th>BPMN Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processes</td>
<td>Manufacturing activities that convert raw material into finishing products.</td>
<td><strong>Equivalence</strong> → <strong>User Task</strong></td>
<td></td>
</tr>
<tr>
<td>Mass reducing</td>
<td>Material removal.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td>Joining</td>
<td>Two or more components are joined to create a new entity.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td>Consolidation</td>
<td>Material is heated to make into liquid and then formed into desired shape.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td>Deformation</td>
<td>Transformation of solid materials from one shape into another.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td>Heat treating</td>
<td>Property enhancing.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td>Finishing</td>
<td>Surface treatment.</td>
<td><strong>No equivalence.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Materials Handling</strong></td>
<td>Manufacturing activities that do not add value to the finishing product.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspecting</td>
<td>Critical appraisal of the materials/product.</td>
<td><strong>Equivalence</strong> → <strong>User Task</strong></td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td>Processes employed to contain, handle and protect the product(s).</td>
<td><strong>Equivalence</strong> → <strong>(User / Service) Task</strong></td>
<td><strong>BPMN Concept</strong></td>
</tr>
<tr>
<td>Storing (Buffer)</td>
<td>Placement of goods or materials, usually with the intention of retrieving them at a later time. Maintenance of supplies to keep operations running smoothly.</td>
<td><strong>No equivalence</strong></td>
<td><strong>Extension Concept</strong></td>
</tr>
<tr>
<td>Transporting</td>
<td>The moving of materials/products from one place to another.</td>
<td><strong>Conditional equivalence</strong> → <strong>Sequence Flow</strong>&lt;br&gt;The process flow is shown with no indication of physical objects flowing through.</td>
<td><strong>Extension Concept</strong></td>
</tr>
<tr>
<td><strong>Agent</strong></td>
<td>Responsibility for performing a task.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>A human who can/will perform a task.</td>
<td><strong>Equivalence</strong> → <strong>User Task</strong></td>
<td><strong>BPMN Concept</strong></td>
</tr>
<tr>
<td>Robot</td>
<td>A robot who can/will perform a task.</td>
<td><strong>Conditional equivalence</strong> → <strong>User Task</strong>&lt;br&gt;Visualization of the task is misleading but the execution could mirror the one of the User Task.</td>
<td><strong>Extension Concept</strong></td>
</tr>
<tr>
<td>Hybrid</td>
<td>Task can be performed by <strong>both or either</strong> a human and a robot.</td>
<td><strong>No equivalence</strong></td>
<td><strong>Extension Concept</strong></td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td>The set of all resources linked to a manufacturing process.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine</td>
<td>Necessary equipment for the completion of a task.</td>
<td><strong>No equivalence</strong></td>
<td></td>
</tr>
<tr>
<td>Tools</td>
<td>An implement for performing or facilitating operations.</td>
<td><strong>No equivalence</strong></td>
<td></td>
</tr>
<tr>
<td>Geographical: Inventory</td>
<td>An itemized catalog or list of tangible goods or property, or the intangible attributes or qualities.</td>
<td><strong>Conditional equivalence</strong> → <strong>Data Store.</strong>&lt;br&gt;When considering the data reference of the physical goods/tools.</td>
<td><strong>BPMN Concept</strong></td>
</tr>
<tr>
<td><strong>Entity:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw Material</td>
<td>Any state of the material before it reaches form of the final product.</td>
<td><strong>No equivalence</strong></td>
<td></td>
</tr>
<tr>
<td>Material Access</td>
<td>Queued transfer of material between processes (with max capacity)</td>
<td><strong>No equivalence</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: Equivalence Check
CHAPTER 3. MANUFACTURING DOMAIN ANALYSIS

The Hybrid agent and Material Access are included in table 3.1 as emerging concepts due to Human and Robot agents and the Storage ones respectively. In manufacturing, it is possible for a Human and a Robot to work together for the execution of a task. There are also cases where task is able to be completed by either a human or a robot. The Hybrid Agent has emerged through these cases.

Material Access is included in table 3.1 as an emerging concept due to the one of Storage. The concepts of ‘Storage’ and ‘Material Access’ have a clear connection to each other; Storage refers to the physical placement of goods (the final product and its several intermediate steps) while Material Access refers to the means of placing or retrieving the material (LIFO\(^3\), FIFO\(^4\), etc.). Therefore we assume that material access is an internal aspect of the storage. With respect to the storage, it is considered an important aspect of manufacturing activities; the notion of ‘buffering’ refers to the temporary placement of material that can not be further processed immediately. In this research we refer to storage as the physical location where raw material are placed temporarily.

3.2.2 Requirements on modeling manufacturing processes

The Equivalence check in table 3.1 highlights the extension concepts that need to be developed in this research; Storage, Transportation, Robot and Hybrid agents. In order to proceed to the next research phase –the Design of the aforementioned extension concepts– the consolidation of requirements are necessary to direct the creation process of the MPMN extension. These requirements present the need for the individual extension concepts that will form the MPMN extension. As stated earlier, this research considers the execution of the extension MPMN out of its scope and thus the following requirements clearly direct the Design phase towards putting emphasis on the visualization aspect of the four extension elements.

**Requirement R1:** A BPMN extension for the manufacturing domain should provide suitable concepts for the representation of agents specific to the manufacturing domain.

- **Requirement R1.1:** A concept of an agent should be provided for activities that should be performed by a Robot.

- **Requirement R1.2:** A concept of an agent should be provided for activities that should be performed by either or both a Robot and a Human (Hybrid).

**Requirement R2:** A BPMN extension for the manufacturing domain should provide the necessary element to enable the visualization of transitory storing (buffer) that occurs during a manufacturing process and involves physical objects.

**Requirement R3:** A BPMN extension for the manufacturing domain should provide an appropriate element for the visualization of the transportation of physical objects. There should be clear distinction from the other BPMN elements with similar objectives (flows).

\(^{3}\)Last In, First Out  
\(^{4}\)First In, First Out
Design of MPMN

This chapter focuses on the Design Phase of the problem solving cycle (figure 1.2). Initially the MPMN metamodel is presented to classify and position the extension concepts in relation to standard BPMN elements. Then several design principles are addressed to aid the implementation of the extension concepts. The graphical design process follows which leads to the decision on the final designs for the extension concepts. Finally, the extensions are defined based on the extension mechanism provided by BPMN.

4.1 Conceptual Domain Model of MPMN

The Design Phase should start with the construction of a partial depiction of the MPMN metamodel showing the concepts that are relevant to this research (‘abstract syntax’ [7]). Figure 4.1 shows the metamodel on a high abstraction level in order to position the MPMN extension concepts alongside the standard BPMN elements (no relationships for the MPMN concepts are defined at this stage). The extension concepts are represented in dash lines squares, while the orange lines (with no arrow head) represent the relationships between the elements.

A Task is an atomic Activity (that can not be broken down to a finer level of detail) within a process flow and generally requires a performer for its execution [28]. The performer defines the resource that will perform or will be responsible for an activity, in other words the agent of the activity. Therefore, the ‘Robot’ and ‘Hybrid’ agents are regarded as Task performers and are thus considered a new specialization of the BPMN element ‘Task’.

‘Storage’ is a new concept and is defined under the ‘Flow Node’ element; It inherits the attributes and model associations of FlowNode. This implies that ‘Storage’ can interact with other ‘Flow Nodes’ such as ‘Events’, ‘Activities’, etc.

In order to stay close to standard BPMN, the ‘Transportation’ extension was named ‘Physical Flow’ – mirroring other similar concepts (Sequence Flow, Message Flow, etc.)– referring to the transportation of physical objects. The ‘Physical Flow’ is considered a ‘Flow Element’ and therefore inherits its attributes and model associations. The detailed definitions of these extensions are further discussed in section 4.5.

Referring back to Braun’s [7] procedure model that this research is following, the first three steps are completed at this point. With the identification of the necessary extended elements for MPMN, the final step –the specification of the concrete syntax for MPMN– will be performed in the following chapter.
Figure 4.1: Partial depiction of the MPMN metamodel based on the representation in \[7\]
CHAPTER 4. DESIGN OF MPMN

4.2 Design Principles

A design process should have a clear design goal defined. Moody [27] stresses the efficiency of cognitive effectiveness; Cognitive effectiveness refers to the "speed, ease, and accuracy with which a representation can be processed by the human mind" [22, 27]. The primary aim of the MPMN design, therefore, is to be simple—yet expressive—so that its meaning can be communicated successfully to all the stakeholders of various relevant domains; manufacturing, business, software and robotic engineers, etc.

Prior to the creation and the selection of the extension designs, there is a need to form the basis for the design concepts. Moody [27] documents a basis for constructing visual notations; this research will use several principles of his work as input to the design process.

The first design principle refers to the visual representation of the developed extension symbols. The graphical representation has a great influence on cognitive effectiveness, as it affects understanding [22]. For the identification of suitable symbols for the extensions, brainstorming sessions have been performed (Principle of Semantic Transparency [27]) along with a domain literature study in order to examine what symbols other notations use for similar concepts. The reason behind the study is twofold: Firstly, in order to avoid the problem of visual dialects (multiple graphical forms representing semantically equivalent concepts) and secondly, to aid perceptual interpretation by novice users. On the principle of Semiotic Clarity, Moody discusses the issues of symbol redundancy (when multiple symbols represent the same concept) and Symbol overload (when two different concepts can be represented by the same symbol). Therefore the four extensions discussed for implementation should have an 1:1 correspondence between the concepts and their symbols. Finally, as per the Principle of perceptual discriminability [27], the designs are to be clearly distinguishable from each other. Therefore:

**Design Principle 1:** The appearance must be descriptive, unique, and specific to each concept.

Secondly, the complexity of the designs shall be kept at a minimum. In this context, 'complexity' refers to the amount of information a diagram element pertains. The goal is to convey the right meaning without overloading the user’s perceptual capacity. This decision is also important for several practical reasons; On one hand BPMN diagrams are not only designed on modelers (such as Camunda\(^1\) or Bizagi\(^2\)) but also drawn by hand. Therefore, the symbols should be simple enough for users who lack sketching skills to draw them. Additionally, complicated symbols might not be sensible when the size of the diagram is significantly small.

**Design Principle 2:** Complexity must be minimized.

It was mentioned earlier that this research focuses on the visualization aspect of the extensions. In addition to the previous design principle, the complexity of the extensions should be minimized beyond the scope of the visual design of the icons; Relationships 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. 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.

\(^1\)www.camunda.org
\(^2\)www.bizagi.com
Design Principle 3: *Execution semantics may be neglected.*

Furthermore, the new designs should allow to be accompanied by text. Text should play a supportive role to the symbols to elevate their expressiveness and clarification. As mentioned in Design Principle 1, the designs will be unique thus text should only improve their expressiveness and not act as the sole mean of distinguishing them among other symbols. In BPMN, elements such as 'Tasks' or 'Flows' already allow text within their design. This behaviour should be preserved in all new extension elements.

Design Principle 4: *Designs should allow text accompaniment.*

It is important that the new extension designs should not be differentiated based on color. There are several issues supporting this principle, the most important being the limitation it imposes to the use of the element with respect to certain users. Given practical issues, such as the possibility of a user being color blind or the scenario where a user models a process by hand and lacks available pen options, the designs should not be individualized solely by color. Therefore the use of color should be overall excluded from the design process of the new elements.

Design Principle 5: *The use of colors should be omitted.*

Finally, MPMN should be compliant to BPMN as a valid extension. Thus it is important that standard BPMN is not altered. The new extensions shall elevate the understanding of the performed manufacturing action without replacing established BPMN elements. The new designs should also be unique with regard to the existing BPMN symbols. The user should be able to model the process without the new elements if needed.

Design Principle 6: *Standard BPMN representation is preserved.*

4.3 Visual Design

This section presents the graphical designs of the extensions. For each extension three concepts are considered. The different concepts derived through brainstorming sketching sessions (see figure D.1 in Appendix D) and examination of domain literature and standards (see figure D.2 in Appendix D). The latter derives from Design Principle 1 (DP1); the aim is to avoid multiple graphical forms representing semantically equivalent concepts. If there is a design in the domain close to the extension concept, that design is considered for the visual representation of the extension. All designs principles discussed in the previous section have been considered and respected at the extend possible per conceptual visual design.

4.3.1 Robot Task

For the Robot Task, three types of designs have been considered; A Robot 'head' (head and torso), an full robotic body and a Robotic Arm. Figure 4.2 shows the chosen icons per category in both white and black. Whereas DP5 is respected and no colors are introduced, each icon is presented in both white and black in order to decide at a later stage which of the two is better visualized within a process model. At this stage the form of the icon is the issue at hand. The designs have been simplified (details were ignored) in order to respect DP2.
4.3.2 Hybrid Task

The concept for Hybrid Task (figure 4.3) combines the 'Human' icon and the 'Robot Task' icons. Each design is half part the human (as the icon usually seen representing the 'User Task') and half part the icons seen in figure 4.2. Again both white and black versions are considered. For the white versions of 'head' and 'body' a dash line divides the human icon from the robot one. Once again details of the icons were kept at a bare minimum to respect DP2.

4.3.3 Storage

For the concept of Storage (figure 4.4) three different types of storing are considered. The first type is a warehouse; three icons representing warehouse establishments are presented in figure 4.4.a. The second type considers storing at a smaller scale; three types of boxes are presented in figure 4.4.b. Whereas the concept of storage as seen in a manufacturing domain is closer to the warehouse rather than a box, for the issue of representing storing in a process model the icon of a 'box' might be intuitive to the user and therefore this type is included to the design of the storage icon. Finally, figure 4.4.c shows the 'storage activity' icon from the ANSI standard [31] (see figure D.2 in Appendix D). As mentioned before (DP1) icons from similar domain concepts should be considered [9]. The triangle icon is expected to be recognized by Operation Management experts especially. Figure 2.3 in chapter 2 shows that the triangle is used as a buffer in certain domains, which strengthens the argument for considering it in the design of the storage icon.
4.3.4 Physical Flow

Finally, for the concept of Physical Flow (figure 4.5) three different types of arrows are considered. Figure 4.5.a shows three types of double lines; this type of an arrow might indicate some kind of flow emphasis to the user or even indicate an association to the conveyor belt (a common transportation method in the manufacturing domain). Figure 4.5.b shows typical arrows bound with three different types of a carrier. Again the carrier is a common transportation method and therefore the user should immediately recognize it as such. Finally, figure 4.5.c shows four types of arrows that are either curved, or carry circles or arrows. These icons aim to show that the arrow 'carries' a load or cargo.

Figure 4.5: Physical Flow alternative designs

4.3.5 Evaluation of the alternative designs

For the evaluation of the different designs a web survey was created and distributed to different users (see appendix B.3). The first part of the survey aimed to measure the effectiveness of the proposed designs by matching the intended message to the received one. In order to received unbiased opinions, no introduction was given to the users. The second part of the survey (discussed in section 4.4) introduced BPMN and the aim of the MPMN extension, before asking the users to make a decision.

Twenty five (25) responses were collected of which the users either have an affiliation to Eindhoven University of Technology (professors, current bachelor, master or PhD students and alumni) or come from a technological background. Approximately 25% are from a CS\(^3\) background, such as IT\(^4\) or Software Engineering, 30% have an Industrial Engineering or Industrial Design background and the rest have an Electrical Engineering, Operations Management or Digital Design background. The members of the HORSE project are considered the only responses that have knowledge on the manufacturing processes, however the majority of the responses from CS or Industrial Engineering background are considered knowledgeable of process modelling in general. Since the goal at this stage is to measure how the intended message was effectively communicated to the users and the extension concepts are simple enough for people with limited manufacturing knowledge to understand (Robot, Storage, etc.), the limited knowledge on manufacturing processes is not regarded as a limitation.

The responses of the first part of the survey are shown in appendix B.1. For the Robot design in figure 4.2.a 75% guessed correctly. Likewise, 72% and 56% guessed correctly for figures 4.2.b and 4.2.c respectively. This was measured by comparing the amount of correct received responses to the intended message (in this case the Robot) over the total amount of responses (25). An answer is considered 'correct' if its meaning is close to the intended one. For example, 'Mobile

---

\(^3\)Computer Science

\(^4\)Information Technology
CHAPTER 4. DESIGN OF MPMN

Robot’, 'Humanoid Robot’, 'Droid’ and 'Artificial intelligence’ are all considered correct interpretations of the ‘Robot’ design. Overall, the robot designs are seen intuitive to different users, considering that many assumed that they were to provide different answers per design. For the Hybrid designs in figure 4.3 we consider them correspondingly recognizable given their similarity to the Robot ones.

For the Storage designs, 60%, 20% and 24% guessed correctly for figures 4.4.a, 4.4.b and 4.4.c respectively. For figure 4.4.b 52% guessed the literal meaning of the design (a ‘box’) which could indicate some connection to the act of storing. For figure 4.4.c the low percentage is justified given the background of the users, as discussed above; the only users that could identify the ANSI symbol had knowledge of Operations Management.

Finally, for the Physical Flow designs, 28%, 52% and 32% guessed correctly for figures 4.5.a, 4.5.b and 4.5.c respectively. Again, the low percentages in figures 4.5.a and 4.5.c are justified given that no specific context was given to the users in the first phase of the survey.

4.4 Final Design

As mentioned in the previous section, the second phase of the survey provides information on BPMN and proceeds in requesting that the users make a decision among the designs once their corresponding concept is identified. For the decision on the final design, in addition to the web survey, a presentation of the research was performed in Thomas Regout International (TRI) – a telescopic slider manufacturer; pilot case of the HORSE project– with the involvement of 8 domain experts (see appendix B.4). During the presentation an unbiased voting session (the presenter did no indicate a preference to any specific design prior to the voting) took place. The final decision among the icon designs considers both the survey results and the voting session during the TRI presentation.

More specifically, every survey user was asked to make a first and second choice per suggested design. The first option is considered twice as important as the second option therefore the results are weighted with 0.665% for the first option and 0.335% for the second option. For example, the "circles or curves" option for 'Physical Flow' was chosen by 6 (out 25) users as their first choice and by 10 as their second; giving it a total percentage of 26% (see (a) from figure 4.6). However, the final decision was taken by also taking into account the experts’ voting mentioned earlier. Different weights were placed to the experts’ and the survey users’ responds as it was considered important that users with relevant domain knowledge should be rated thrice as important as random users for the icon decision. Therefore, given that 2 (out of 8) experts chose the "circles or curves" option, the final percentage for this option was 29% (see (b) from figure 4.6). Same logic applies to all extension concepts designs. The complete results and pie representations of them can be seen in appendix B.5.
Given the collected results, it is feasible to present the final designs ('Concrete Syntax' [7]) of MPMN with the graphics of the extension concepts. For the Robot and Hybrid Tasks the 'white' versions were disregarded as seen less recognizable in a process model. Therefore, the black option of the designs are selected.

Figure 4.7: Visual designs of the MPMN extension concepts
4.5 Extension Elements Definition

Below are the new elements defined as instructed in section 2.3. For each extension element a class diagram from its metamodel is provided (based on the BPMN extension mechanism in figure 2.5) along with a table with its attributes and model associations.

A 'Robot Task' is an activity where the performer executing a task is a Robot. A script shall be provided for the execution of the task by the robot agent. A code is expected to be parsed by the robot controller in order to perform the task.

![Figure 4.8: 'Robot Task' extension class diagram](image)

<table>
<thead>
<tr>
<th>Extension</th>
<th>Extension Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robot Task</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extension Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. implementation: string = &quot;unspecified&quot;</td>
</tr>
<tr>
<td>2. scriptFormat: string [0..1]</td>
</tr>
<tr>
<td>3. script: string [0..1]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extension Attribute Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. a. &quot;unspecified&quot;</td>
</tr>
<tr>
<td>b. &quot;WebService&quot;</td>
</tr>
<tr>
<td>2. string [0..1]</td>
</tr>
<tr>
<td>3. string [0..1]</td>
</tr>
</tbody>
</table>

Figure 4.9: 'Robot Task' extension defined per the extension mechanism
A 'Hybrid Task' is a workflow task with the merge of the Human and Robot tasks; the performer can be both or either of the two.

The Hybrid Task extension combines the User and Robot Tasks into a single task and allows the selection of the agent. The task can be allocated to more than one performer—hence Hybrid—when the activity can be executed by both a human and a robot (either in combination or individually). The class diagram in figure 4.11 shows the 'Rendering' associated with the human agent while also includes the 'script' attributes of the Robot Task.

![Figure 4.10: 'Hybrid Task' extension class diagram]

**Figure 4.10: 'Hybrid Task' extension class diagram**

<table>
<thead>
<tr>
<th>Extension</th>
<th>Extension Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid Task</td>
<td>Extension Attribute Definition</td>
</tr>
<tr>
<td>1. implementation: string = unspecified</td>
<td>This attribute specifies the technology that will be used to implement the Robot Task. The default technology for this task is unspecified.</td>
</tr>
<tr>
<td>2. renderings: Rendering [0..*]</td>
<td>This attribute acts as a hook which allows BPMN adopters to specify task rendering attributes by using the BPMN Extension mechanism.</td>
</tr>
<tr>
<td>3. scriptFormat: string [0..1]</td>
<td>Defines the format of the script run by a Robot performer. This attribute value MUST be specified with a mime-type format.</td>
</tr>
<tr>
<td>4. script: string [0..1]</td>
<td>The modeler MUST include a script that can be run by a Robot performer when the Task is performed.</td>
</tr>
</tbody>
</table>

**Extension Attribute Value**

| 1. a. unspecified b. #Web Service | a. Leaving the implementation technology open b. Web service technology or a URI identifying any other technology or coordination protocol |
| 2. Rendering [0..*] |
| 3. string [0..1] |
| 4. string [0..1] |

**Figure 4.11: 'Hybrid Task' extension defined per the extension mechanism**
A 'Storage' provides a mechanism for Activities to temporarily store items that flow through the Process when they cannot be further processed immediately. The Storage element is seen as the flow representation of a storage space and therefore exists beyond a single process. It inherits the attributes and model associations of 'FlowNode' and requires a maximum capacity to be specified as it cannot be of unlimited space. Given that the storage element does not refer to the action of storing, it should be directly connected with activities that show that material should be placed and retrieved to and from the storage. Finally, since the process stays in a waiting stage while in the storage element, an internal trigger is necessary for it to exit the element.

Figure 4.12: 'Storage' extension class diagram

<table>
<thead>
<tr>
<th>Extension</th>
<th>Extension Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extension Attribute Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. name: string</td>
</tr>
<tr>
<td>2. capacity: integer</td>
</tr>
<tr>
<td>3. exitTrigger: string</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extension Attribute Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. String</td>
</tr>
<tr>
<td>2. Integer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. String</th>
</tr>
</thead>
<tbody>
<tr>
<td>The string can define:</td>
</tr>
<tr>
<td>a. datetime</td>
</tr>
<tr>
<td>b. duration</td>
</tr>
<tr>
<td>c. event (ex. message)</td>
</tr>
<tr>
<td>d. script</td>
</tr>
</tbody>
</table>

Figure 4.13: 'Storage' extension defined per the Extension mechanism
A 'Physical Flow' is used to show the order that activities will be performed in a process while indicating that there is material physically flowing through. The Physical Flow element inherits the attributes and model associations of 'FlowElement'. The definition of the Physical Flow mirrors the 'Sequence Flow' with the exception of the introduction of Storage as a target element; That is due to the fact that a Storage element can also be a target to the Physical Flow.

Figure 4.14: 'Physical Flow' extension class diagram
After defining each extension concept, figure 4.1 can be redesigned with the inclusion of the relationships between standard BPMN elements and the MPMN extension concepts. Figure 4.16 shows the redesigned partial metamodel.

Extending BPMN for modeling manufacturing processes

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Implementation

This chapter focuses on the Implementation Phase –for the MPMN extension– of the problem solving cycle (figure 1.2). Initially, the creation of the MPMN extension shapes is shown and later the grammar rules for their use are defined.

5.1 Creation of the MPMN stencil

Originally, an attempt was made to implement the extensions in bpmn.io\(^1\) with the use of the bpmn.js toolkit. The extension elements were to be implemented as custom elements with Java coding but at the current stage of the toolkit that proved to be unfeasible. Therefore, the MPMN shapes – as presented in section 4.4 – were implemented in Visio\(^2\) for visualization purposes. Visio provides a BPMN stencil with all basic BPMN elements; this is used as the base for the MPMN stencil. For each of the extensions the shape was created and the appropriate attributes were assigned to it. The Visio stencil for the MPMN extension can be seen in figure 5.1.

![MPMN stencil for Visio](image)

Figure 5.1: MPMN stencil for Visio

\(^1\)https://bpmn.io
\(^2\)http://products.office.com/microsoft-visio-2013
5.1.1 Robot and Hybrid Task shapes

The 'Robot Task' uses the basic BPMN Task as its base (as defined in figure 4.1). All shape data associated with the Task (provided by the basic BPMN stencil) are imported to the Robot Task (such as 'LoopType' or 'ActivityType' to define sub-processes or a parallel loop, etc.). Further attributes for the Robot Task as defined in section 4.5 were added accordingly. Figure 5.2 shows the shape editor for the Robot Task. The same logic applies to the 'Hybrid Task' (figure 5.3).

Figure 5.2: Robot Visio shape

Figure 5.3: Hybrid Visio shape
Figure 5.4 shows the data editor for the 'Hybrid Task' where all appropriate attributes were assigned to the shape. The shape data for the other extensions were created in a similar way.

![Image: Hybrid visio shape data]

Figure 5.4: Hybrid visio shape data

### 5.1.2 Robot and Hybrid Task syntax

In order to avoid ambiguity in the modeling of MPMN elements we need to define certain consistency rules. In the case of the Robot and Hybrid Tasks their use is pretty straightforward. Since both of these extensions are a new specialization of the BPMN Task, their use within the process model complies with the same grammatical rules. The distinction between the two, as well as among other BPMN Tasks is the agent performing the Task (as discussed in section 4.5). Therefore no special grammar rules are necessary for these two extension elements.
5.1.3 Physical Flow shape

The ‘Physical Flow’ is a new introduction to the basic BPMN stencil. The shape data for this extension mirrors the ones of the BPMN ‘Sequence Flow’ with the introduction of the two new attributes associated with the Physical Flow; Type (of transportation) and Weight (of carried material).

![Physical Flow visio shape](image)

Figure 5.5: Physical Flow visio shape

5.1.4 Physical Flow syntax

The ‘Physical Flow’, as discussed before, is similar to the Sequence Flow but it is used to indicate that material are transported between one Flow Element and the next. Therefore a ‘Physical Flow’ should be placed after any element that indicates transportation of physical objects. Transportation can take place within a given work station, between different work stations in the same factory and even beyond the scale of a single factory (conveyor belts, human agents, carts, trucks etc. may transfer material). Therefore the issue of the level of granularity for the use of the ‘Physical Flow’ should be addressed.

The ‘Physical Flow’ should be modeled in place of the ‘Sequence Flow’ whenever its use adds value to the process model. Given that the MPMN extension does not overwrite any standard BPMN elements and does not force its use, the process engineer should have the authority to decide which transportation is insignificant and therefore using the Physical Flow would not contribute to the process model. Finally, in the case of gateways that indicate some type of behavior control, the Control Flow may be split from the Physical Flow; in such a case the Physical flow(s) after the gateway lead to the next element where the material is expected and the rest of the flows after the gateway can be modelled with a Sequence Flow. Such a scenario can be seen in figure 6.4 in the following chapter.
5.1.5 Storage shape

The ‘Storage’ shape is not associated with any existing BPMN shape—as already indicated in figure 4.1—and therefore was created from scratch. The shape of a flipped triangle along with the textbox for its name visualize the Storage extension. The appropriate attributes as discussed in section 4.5 are defined within its shape data.

![Storage visio shape](image)

Figure 5.6: Storage visio shape

5.1.6 Storage syntax

Finally, grammar rules for the 'Storage' extension should be defined to avoid any confusion or ambiguity. As mentioned in section 4.5, the Storage extension is seen as the flow representation of the physical location and not the action of storing. This implies that it should be connected with activities that show that some material should be placed into the storage (before) and then retrieved from it (after). When modeling the storage therefore, we expect a physical flow before the element and a sequence flow afterwards. The second physical flow will be connected to the activity following the storage that indicates the retrieval of the material. This modeling decision might be seen as not visually intuitive (as some users might expect the physical flow connected immediately after the storage element), it is however semantically correct given the conceptual definition of the storage as a physical space.

In section 4.2, Design Principle 3 stressed the issue of neglecting execution semantics in order to ensure clear visualization of the extension elements. This holds significantly true to the Storage element; in its definition seen in figure 4.12 we make a point of the exitTrigger. The way the storage element is conceived would hold the process in a waiting state unless there is some trigger to make it exit that state and proceed to the next element. For this reason several trigger types have been identified given that the storage extension inherits the attributes and associations of the 'Flow Node' element.
The Storage element can be exited by a(n):

1. **DateTime** – Given a certain date and time.
2. **Duration** – After staying in the storage for a certain amount of time.
3. **Event** – After a message or timer event triggers its completion.
4. **Script** – Given a certain script source code.

These triggers might need to be explicitly modelled in the process (especially in the case of the event) for the model to be executable. However, taking into account the scope of this research along with DD3, we consider those aspects internal to the element and thus will not be explicitly modelled with MPMN.

Lastly, the Storage element provides the ‘capacity’ attribute. This is to specify the maximum space in the physical storage and help the processes keep track of its availability. Such a function can be feasible with a global process variable so that different processes can access the correct information. In the case that the storage is full (and the availability zero or below the required space) an exception would inform the engine.

### 5.1.7 MPMN syntax

Figure 5.7 shows a simple process to showcase the syntax of the extensions as described above. Realistic manufacturing process models are presented in the next chapter.

![Figure 5.7: Simple MPMN process](image-url)
Evaluation

This chapter focuses on the Evaluation Phase – of the proposed MPMN extension concepts – of the problem solving cycle (figure 1.2). For this phase, realistic manufacturing processes from the HORSE project are modelled in standard BPMN and compared to their MPMN re-modelled versions. Domain experts were interviewed and requested to contribute to the evaluation through a survey.

6.1 Case Study application of MPMN

To illustrate the use of MPMN in real-life processes, we refer to a case study from the TRI factory where BPMN process models were created for the HORSE project.

Figure 6.1 shows an overall process model of the TRI activities modelled with standard BPMN. TRI’s end-to-end production process consists of four production areas, rather independent to each other – they are executed with different schedules and therefore can not be triggered directly by the previous one. These are modelled in different pools.

Figure 6.2 shows the same processes modelled with MPMN. The extension elements of Storage and Physical Flow are included in the modelling process. The main – and greatly significant – difference between the two models lies in the clear merging of the different processes into one single process. This is greatly due to the Storage element that binds the different processes.

Diving within the ‘P2 loading’ sub-process, figure 6.3 shows the BPMN model with its details. There are four Lanes to differentiate among the Human operator, the Hybrid one, a Loading robot and a Crane. In figure 6.4 the same process in modelled with MPMN. The four lanes are preserved simply for comparison reasons. The same agents take part only instead of using the User Task for the three types of operators that are not a human, the ‘Hybrid Task’ and the ‘Robot Task’ are included. This process also shows the case where the physical flow is split after the gateway (as mentioned in section 4.4) and therefore only visualizes the transportation of physical material towards the Task that requires it.
TRI_Tool-assembly
TRI_PA1_future
TRI_PA2_future
TRI_PA3_future

Production order received
Single tool assembly
Tool set assembly
for production

Transport tool set to P1

Tools assembled

Taakkaart received
Production preparation for P1

Standard cold forming
Special product cold forming
Additional cold forming

Transport to P2
P2 started
P2 loading
Galvanisation
P2 unloading
Transport to P3
P2 complete
P3 started
Retrieve from P3 storage

Auto assembly
Semi-auto assembly
Manual assembly

Transport to warehouse
P3 completed

Figure 6.1: Manufacturing process modeled with standard BPMN
Figure 6.3: 'Loading' sub-process modelled with standard BPMN.
Figure 6.4: Re-modelling of sub-process 'Loading'
CHAPTER 6. EVALUATION

6.2 Expert evaluation

After modelling the manufacturing processes with MPMN, an evaluation model should be used for their assessment. For the evaluation survey, Moody’s Method Evaluation Model [20] provided the inspiration. However this research does not follow the validated questionnaire since the focus was on the visualizing aspect rather than the creation of a tool for execution. Thus even though there is an obvious affiliation between the MPMN evaluation survey and the Method Evaluation Model (see figure C.1 in Appendix C), this research does not claim the validity of the theoretical model. The questions used to evaluate the MPMN extension are divided into the three constructs suggested by Moody and their aim is to retrieve feedback on both the visual perception of the graphical representation of the extension concepts and the clarity of their syntax.

The three primary constructs for the survey are indeed:

1. **Perceived Ease of Use** – The degree to which a person believes that using a particular method would be free of effort.

2. **Perceived Usefulness** – The degree to which a person believes that a particular method will be effective in achieving its intended objectives.

3. **Intention to Use** – The extent to which a person intends to use a particular method.

The defined questions per construct can be seen in figure 6.5 filled with the experts’ feedback (each letter representing a different expert). Prior to the questionnaire, each expert received a short introduction to the four extension elements; their graphical designs were shown and their syntax was explained. Afterwards, the process models in section 6.1 were presented and discussed. Overall, all experts recognized the added value of the extension and would choose to model manufacturing activities with MPMN over standard BPMN.
### Regarding the BPMN extension, MPMN...

<table>
<thead>
<tr>
<th>Perceived ease of use</th>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I find the icons of the new extensions easy to recognize.</td>
<td>f</td>
<td>a</td>
<td>c</td>
<td>e</td>
<td>b</td>
</tr>
<tr>
<td>I find the icons of the new extensions easy to remember.</td>
<td>f</td>
<td>a</td>
<td>c</td>
<td>e</td>
<td>b</td>
</tr>
<tr>
<td>I find the new extension elements understandable.</td>
<td>cf</td>
<td>abd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I find the use of the new extension elements easy to apply.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I understand the differences amongst the extensions.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I understand the differences between the extensions and other standard BPMN elements.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Perceived usefulness</th>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I think the MPMN elements improve the understandability of specific manufacturing activities in BPMN models.</td>
<td>f</td>
<td>abde</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think manufacturing processes are more understandable with the use of the MPMN extensions.</td>
<td>cef</td>
<td>abd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I think the MPMN extension makes it easier to communicate specific manufacturing activities to various stakeholders.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall I find the MPMN extension useful.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall I find the MPMN extension an improvement to standard BPMN for visualizing manufacturing processes.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intension of use</th>
<th>Totally disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Totally agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I would use the MPMN extension over standard BPMN to model manufacturing processes.</td>
<td>cf</td>
<td>abd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I would prefer using standard BPMN to model manufacturing processes.</td>
<td>a</td>
<td>cdef</td>
<td>b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.5: Evaluation survey
CHAPTER 6. EVALUATION

The experts were asked to comment on any identified ambiguity or uncertainly on the clarity of the extension concepts and their use. As expected, most concerns were voiced for the Storage extension. As mentioned earlier, the grammar rules for the use of the element are counter-intuitive. The majority of the interviewees were either confused by the correct use of the Storage in combination with the Physical Flow (whereas Physical Flow by itself was clear) or believed that in a significantly big process model the accuracy of the model might be harder to validate. The reason for both these concerns was the misalignment of the Physical Flow entering the Storage whereas a Sequence Flow exits the element. Overall they concluded that even when the semantics become understandable, the complexity of the readability of the process model is increased.

With respect to the Physical Flow, some experts were perplexed over its correct use. Due to its similarity to the Sequence Flow, they might be unclear on when the Physical Flow should be used instead. These concerns –regarding Storage and Physical Flow– are linked with question 18, where most interviewees agreed that although the extension does not necessarily make the modeling process harder, it does make it more time consuming. However, as the benefits of MPMN make for a good trade off, the extension is preferred over standard BPMN.

Finally, a concern was raised on the 'Intention to use' by two interviewees. The first one believed that the use of MPMN over standard BPMN depends on the audience; For users with good BPMN knowledge such visual extensions might not be necessary given that the process is adequately understood without them at a lower complexity level. The second one indicated that experience has shown that domain experts are used to their way of modeling and are strongly against any extension. Therefore even though that interviewee would choose to use the extension, they believed that others would find the cost of re-designing the processes too high and thus would be against it.

Overall, the feedback was proved to be significantly positive. The raised concerns were expected given the made decisions during the design phase of MPMN. With respect to the Storage, the decision to not perceive it as the action of 'storing' but rather the place of storing creates the confusion over its use in combination with the Physical Flow. In order to properly model both these extensions together by respecting their individual syntax we create an asymmetry; a Physical Flow 'entering' the Storage, yet a Sequence Flow 'exiting' it. This issue could have been overcome by defining Storage in a different way (that would have created another iteration of the problem solving cycle in figure 1.2) but it was not done so due to the recognized importance of visualizing Storage in a different manner. The 'Limitations' section in the final chapter (7) discusses these issues further.
Conclusions

The aim of this research was to extend BPMN such that it improves its usefulness in the manufacturing domain. To achieve this goal the MPMN extension was developed to aid the visualization of activities specific to the manufacturing domain.

This research commenced with an analysis of the manufacturing domain as a whole in order to define its ontology and utilize it to identify the domain’s essential functions. These functions were then mapped to standard BPMN elements so that any deficit element support would be highlighted. Through these steps the necessary extension elements were detected; the Robot and the Hybrid agents, the Storage and the Physical Flow. After the necessary extension elements were systematically identified, visual designs were conceptualized, their syntax were defined and for each extension concept, its individual metamodel was addressed. The attention on this part of the research was due to the fact that this research stressed the importance of creating a valid extension to BPMN —thus each extension element was defined with the extension mechanism provided in the BPMN metamodel. A visual tool accompanies this research for the modeling of the MPMN extension.

With the use of the visual tool, real manufacturing processes were modeled and compared against corresponding ones modelled with standard BPMN. It was concluded that the MPMN extension succeeds in visualizing the extension elements explicitly as aimed by the problem statement. The extension is considered valuable not only for increasing the understandability of manufacturing processes for novice users (by introducing more intuitively visual elements) but also for surpassing BPMN limitations to certain manufacturing process needs (such as the introduction of the Storage to aid the modelling of manufacturing activities into a single process).

The strikingly limited literature on the nature of this research should be acknowledged. Even though a significant amount of research has been done on extending BPMN for various domains, the manufacturing domain lacks representation on the matter. This is seen as rather unfortunate given the number of benefits BPMN can bring to the domain, as specified earlier in this research. It should also be mentioned that even among the large amount of proposed extensions for BPMN, the number of those who propose a valid extension by addressing BPMN’s extension mechanism is fairly low. This further strengthens the importance of the research presented here.

Although the research does not provide a tool to *execute* processes with the MPMN extension (due to time constraints), the definition of each extension element was done in a thorough manner by identifying any necessary additional attributes and associations among the MPMN elements and other standard BPMN elements. This will aid the implementation of an executable toolkit in the future.
7.1 Limitations

Certain limitations of this research have been addressed earlier. Firstly, the issue of providing only a visual tool for the modelling of the MPMN extension signifies that several execution semantics have been intentionally disregarded. Even though detailed definition for each extension element was provided, implementing such a toolkit might still prove to be a challenging — yet feasible — matter.

Directly associated with this matter are the concerns raised by experts during the evaluation of the proposed MPMN extension. As mentioned in the previous chapter, most experts encountered a difficulty in either understanding or accepting the modelling decisions for the Storage extension with respect to the connected Flows (incoming Physical Flow and outgoing Sequence Flow). The syntax of storage drives this modelling decision due to the fact that it represents the physical location of the stored materials. This concern could be addressed sufficiently by re-defining the concept of the Storage as not a physical location but instead the action of storing; That would imply changing the metamodel of this extension concept into an Activity element. This is however the reason why this research chose to define this concept in a different way. Given that the visualization aspect was stressed over the execution, it was important to clearly differentiate the element of Storage from other BPMN elements. Defining the Storage extension as a new specialization of the 'Task' element could solve the concerns raised by the experts but would significantly lower the graphical presence of the element in a process model.

The MPMN extension can be seen as complimentary to standard BPMN given that caution was taken to ensure that none of the existing elements were affected negatively (or worse, overwritten) by the new extension concepts. This decision creates the ambiguity surrounding the proper use of the Physical Flow extension concept. As mentioned on its syntax rules, the matter of the level of granularity over the use of the element is to an extend left to the judgment of the process engineer during the modelling of the process. This is decided on the fact that the engineer should have the authority to decide which physical transportation is significant enough to add value to the process model by being modelled explicitly.

Finally, it is clear that depending on the audience of the process model, the use of standard BPMN might be preferred over the proposed extension. This issue is however not solely directed to the MPMN extension itself but rather BPMN extensions in general. Several experts pointed out that domain experts are reluctant to change and by taking into account the redesign costs (in terms of effort and time) they would opt out of using an extension. This limitation does not hinder the value of the presented work given that out of the four proposed extension concepts, two (Robot and Hybrid Tasks) are seen as crucial to the modelling of manufacturing process, and the other two (Storage and Physical Flow), while surely being able to model in a roundabout manner, significantly improve the visualization of manufacturing process models.
7.2 Further Research

This research could be further explored by first and foremost attempting the implementation of the MPMN extension with an executable toolkit to enable the run of the process models. The tool provided via this research is implemented in Microsoft Visio, given that the focus was on the visualization aspect of the extension concepts. Achieving such an environment will have to address concerns raised on this research, but it would also highlight the importance of the extension in a real-life manufacturing process.

The visual designs of the proposed extension concepts should be addressed as well. This research decided on a design for each identified extension concept through brainstorming sessions and after taking into account relevant standards of the domain. The final four chosen designs were decided upon by evaluating the feedback from an audience (experts and novice users). The importance of the MPMN extension however does not lie on the specific chosen graphical designs. It was observed, for example, that users without any background on Operations Management could not identify the ANSI symbol, and thus it was less intuitive to some than others. Further research building on the MPMN extension could opt for different graphical designs while the value of the proposed MPMN extension could still hold due to the individual identified attributes and defined metamodels. This proves that the value of the work presented here can be identified on several fronts.

In addition, the Physical Flow extension concept could be further explored to incorporate intra-factory transport. Transporting material between different production areas, sites, etc. could be represented in a different manner to show the severity of transport. The MPMN Physical Flow extension concept is designed as a double lined arrow. Extending it to triple or quadruple lines to show different ways of transportation could possibly add value to the visualization of manufacturing process models.

Finally, further work on extending BPMN for the manufacturing domain could be done by considering the un-mapped elements that were neglected due to them being addressed in other domain literature proposals. Given that those proposals are not compatible with MPMN, these concepts could be addressed in order to provide a BPMN extension toolkit to explicitly model manufacturing activities entirely. More specifically, the 'material access' concept would provide a great benefit to the Storage extension concept. Specifying the way material is put and retrieved from the storage (LIFO, FIFO, etc.) is a realistic aspect of the manufacturing domain.
Bibliography


BIBLIOGRAPHY


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Manufacturing

A.1 Taxonomies

Figure A.1: Todd taxonomy
Mass-Reducing

- Single-Point Cutting
  - Boring
  - Shaping/Planing
  - Parting/Grooving
  - Threading (SF)
  - Drilling
  - Reaming
  - Milling/Routing
  - Broaching
  - Threading [MP]
  - Filing
  - Sawing
  - Gear Cutting
  - Grinding
  - Honing
  - Lapping
  - Superfinishing
  - Ultrasonic Machining
  - Jet Machining
  - Squaring
  - Slitting
  - Rotary Shearing
  - Nibbling
  - Conventional Blanking
  - Steel-Rule-Die Blanking
  - Fine Blanking
  - Shaving/Trimming
  - Diaking
  - Punching
  - Perforating
  - Lanc ing
  - Notching

- Multipoint Cutting
  - Reducing [Chips]

- Abrasive Machining

Mechanical Reducing

- Separating [Shear]

Piercing
Mass-Reducing

Single-Point Cutting
- Turning/Facing
  - Boring
  - Shaping/Planing
  - Parting/Grooving
  - Threading (SP)
- Drilling
- Reaming
- Milling/Routing
- Broaching

Thermal Reducing
- Torch Cutting
  - Air Arc Cutting
    - Gas Cutting
      - Plasma Arc Cutting
        - Cavity-Type EDM
          - EDM Grinding
            - EDM Sawing
              - Electron Beam Cutting
                - Laser Beam Cutting
                  - Ion Beam Cutting

Mechanical Reducing
- Chemical Reducing
  - Chemical Milling
    - Immersion Chemical Milling
      - Spray Chemical Milling
        - Cavity-Type ECM
          - Grinder-Type ECM
            - Photo Etching
              - Photo Milling

- Electrochemical Milling
- Photochemical Milling
Mass-Conserving

Casting
- Nonreusable Mold
  - Ceramic Mold Casting
  - Sand Mold Casting
- Reusable Mold
  - Die Casting
    - Permanent Mold Casting
    - Flexible Mold Casting
    - Continuous Casting
  - Ceramic Molding
    - Wet Forming
    - Dry Pressing
- Molding
  - Injection Molding
    - Blow Molding
    - Transfer Molding
    - Compression Molding
  - Polymer Molding
    - Extrusion Molding
    - Thermoform Molding
    - Rotational Molding
- Consolidation
  - Continuous Compacting
    - P/M Extrusion
    - P/M Rolling
  - Compacting
    - Pressing [Compacting]
    - Centrifugal Compacting
    - Explosive Compacting
    - Isostatic Pressing
    - Slip Casting
      [Compacting]
- Deposition
  - Electroforming
- Laminating
  - Filament Winding
    - Sheet Laminating
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  - Spray Lay-Up
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Joining

Mechanical Joining
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- Friction (Inertial) Welding
- Ultrasonic Welding
- Explosive Welding

Electric Arc Welding
- Shielded Metal Arc Welding
- Gas Metal Arc (MIG) Welding
- Gas Tungsten Arc (TIG) Welding
- Submerged Arc Welding
- Carbon Arc Welding
- Stud Welding

Electrical Resistance Welding
- Spot Welding
- Seam Welding
- Projection Welding
- Butt Welding
- Percussion Welding
- Electroslag Welding

Thermal Joining

Thermal Welding
- Gas/Chemical Welding
- Combustible Gas Welding
- Atomic Hydrogen Welding

- Braze Welding
- Gas Brazing
- Carbon Arc Brazing

- Diffusion Bonding
- Electron Beam Welding
- Laser Beam Welding
- Plasma Arc Welding

Brazing

- High Energy Beam Welding

- Infrared Brazing
- Resistance Brazing
- Torch Brazing
- Dip Brazing
- Furnace Brazing
- Induction Brazing

Soldering

- Friction/Ultrasonic Soldering

- Induction Soldering
- Infrared Soldering
- Dip Soldering
- Iron Soldering
- Resistance Soldering
- Torch Soldering
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Adhesive Bonding
Surface Finishing

- Abrasive Blasting
  - Belt Sanding
  - Shot Peening Preparation
  - Wire Brushing
  - Grinding

- Descaling
  - Mechanical Descaling
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      - Thermochemical Deburring
      - Electrochemical Deburring
    - Thermal Deburring
    - Mechanical Deburring
      - Barrel Tumbling
      - Vibratory Finishing
      - Knife Deburring

- Deburring
  - Mechanical Deburring
  - Chemical Deburring
    - Ultrasonic Degreasing
    - Vapor Degreasing
      - Solvent Degreasing
      - Alkali Degreasing

- Degreasing
The process taxonomy used in the CO2PE! - initiative is based on the German standard DIN 8580 (Fertigungsverfahren - Begriffe, Einteilung) and extended with some auxiliary processes like compressed air supply, cooling systems, ... If you couldn’t find your research area, or want to add one to this taxonomy, please contact co2pe@mech.kuleuven.be. An English reference book about this standard, called "Introduction and applications of DIN 8580" (ISBN: 978-84-96742-73-4), is written by students of Prof. Joaquim de Ciurana of the University of Girona (Spain).

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  - 7.2.1. Electrical drives
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- 8.2. Power Studies

- 8.3. Emission Studies
• 7.3. Part Manipulating
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8.3.2. Liquid Emissions
8.3.3. Waste
A.2 Mason Ontology

Figure A.3 shows the Mason ontology [23] with the representation of the objects that are relevant to this research.
Design feedback

This appendix provides the questioning form from the Design phase along with the received feedback.

B.1 Interpretation of the icons

Figure B.1 shows the interpretation of the three versions of the icon for the "Robot" extension.

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<th>Robotic Arm</th>
<th>Robot (head)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robots</td>
<td>Automated machine</td>
<td>User</td>
</tr>
<tr>
<td>Mixed people mixed gender</td>
<td>Industrial robots</td>
<td>Mixed races</td>
</tr>
<tr>
<td>User</td>
<td>System</td>
<td>User</td>
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<tr>
<td>Robot communicator</td>
<td>Working robot</td>
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<tr>
<td>System</td>
<td>Automation/Production</td>
<td>System</td>
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<tr>
<td>Robotics</td>
<td>Automated manufacturing</td>
<td>Artificial intelligence</td>
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<tr>
<td>Robot</td>
<td>Robotic arm</td>
<td>Under supervision</td>
</tr>
<tr>
<td>(service) robot</td>
<td>Manufacturing robot for building</td>
<td>AI helper robot</td>
</tr>
<tr>
<td>Robot</td>
<td>Robot arm</td>
<td>Human</td>
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<td>Mobile robot</td>
<td>Robot arm</td>
<td>Robot</td>
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<td>Two robots</td>
<td>Two robot arms</td>
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<td>automatic processes</td>
<td>automatic processes</td>
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<td>robot</td>
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</tr>
<tr>
<td>robot</td>
<td>robot arm</td>
<td>cyborg :)</td>
</tr>
<tr>
<td>Database</td>
<td>Data flow</td>
<td>User</td>
</tr>
<tr>
<td>white robot and black robot</td>
<td>white machine/tool and black machi</td>
<td>white robot and black robot</td>
</tr>
<tr>
<td>User</td>
<td>Database</td>
<td>User</td>
</tr>
<tr>
<td>Robot task</td>
<td>Robot collection task</td>
<td>Robot decision making task</td>
</tr>
<tr>
<td>Humanoid robot</td>
<td>Industrial robot</td>
<td>Android</td>
</tr>
<tr>
<td>Robot / Droid / Humanoid</td>
<td>Fixed Robot / Robot Arm</td>
<td>Frankenstein?</td>
</tr>
<tr>
<td>Robot</td>
<td>Robotic arm</td>
<td>Robot head</td>
</tr>
</tbody>
</table>

Figure B.1: Responses for the icon of "Robot"
Figure B.2 shows the interpretation of the three versions of the icon for the "Hybrid" extension.

<table>
<thead>
<tr>
<th>Hybrid Robot/Human (body)</th>
<th>Hybrid Robotic Arm/Human</th>
<th>Hybrid Robot/Human (head)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial intelligence</td>
<td>Manually operated machines</td>
<td>Man/machine</td>
</tr>
<tr>
<td>Different background</td>
<td>Different work strategies</td>
<td>No idea</td>
</tr>
<tr>
<td>User-System interaction</td>
<td>User-System interaction</td>
<td>User-System interaction</td>
</tr>
<tr>
<td>Half robot half human</td>
<td>Working robot half human</td>
<td>Human linked with system</td>
</tr>
<tr>
<td>User/System Interaction</td>
<td>User controlled manufacture</td>
<td>User/System interaction</td>
</tr>
<tr>
<td>Human-robot interaction</td>
<td>Human-robot manufacturing</td>
<td>human-AI integration/interaction</td>
</tr>
<tr>
<td>Controller</td>
<td>Robotic Arm under supervision</td>
<td>may be supervision again</td>
</tr>
<tr>
<td>Cyborg/half man and half robot</td>
<td>Half man made and half robot made</td>
<td>Sometimes real personnel serves and other times a robot</td>
</tr>
<tr>
<td>Technical supporter</td>
<td>Robot arm repairman</td>
<td>Half...human half robot??</td>
</tr>
<tr>
<td>Can be done by human or robot</td>
<td>Human operating a robot arm</td>
<td>Artificial intelligence</td>
</tr>
<tr>
<td>Two hybrid workers, both human and artificial intelligence</td>
<td>Two hybrid workers, both human and mechanic power</td>
<td>Two half frankensteins</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Hybrid</td>
<td>Hybrid</td>
</tr>
<tr>
<td>Hybrid process</td>
<td>Hybrid process</td>
<td>hybrid process</td>
</tr>
<tr>
<td>These aren’t meshing up well</td>
<td>Human and bots working together</td>
<td>Human-robot hybrid</td>
</tr>
<tr>
<td>Human and robot agents</td>
<td>Human and robotic arm agents</td>
<td>Human and robot agents</td>
</tr>
<tr>
<td>??</td>
<td>Human and gripper</td>
<td>human</td>
</tr>
<tr>
<td>User assisted by robot</td>
<td>User assisted by robot</td>
<td>Robot</td>
</tr>
<tr>
<td>either a human or robot</td>
<td>machine operator</td>
<td>??</td>
</tr>
<tr>
<td>User</td>
<td>Message flow</td>
<td>User</td>
</tr>
<tr>
<td>white human operating white/black robot</td>
<td>white human operating white/black machine/tool</td>
<td>white human interacting with white/black robot</td>
</tr>
<tr>
<td>Database</td>
<td>Database</td>
<td>User</td>
</tr>
<tr>
<td>Human Robot interaction task</td>
<td>Human Robot collection task</td>
<td>Human Robot interaction decision making task</td>
</tr>
<tr>
<td>Humanoid robot with Artificial Intelligence</td>
<td>Industrial robot AI</td>
<td>Android AI</td>
</tr>
<tr>
<td>Dual Robot and Human Task</td>
<td>Dual Fixed Robot and Human Task</td>
<td>Humanoid?</td>
</tr>
<tr>
<td>Humanoid robot</td>
<td>Humanoid robot</td>
<td>Half robot half human</td>
</tr>
</tbody>
</table>
Figure B.3 shows the interpretation of the three versions of the icon for the "Storage" extension.

<table>
<thead>
<tr>
<th>Warehouse</th>
<th>Boxes</th>
<th>ANSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>Packaging</td>
<td>Errors</td>
</tr>
<tr>
<td>Different workplaces</td>
<td>Different work phases</td>
<td>End point</td>
</tr>
<tr>
<td>Database</td>
<td>File system</td>
<td>Priority Flow</td>
</tr>
<tr>
<td>House</td>
<td>Box storage</td>
<td>Linking system</td>
</tr>
<tr>
<td>Manufacturing domain</td>
<td>Components</td>
<td>Attention or error</td>
</tr>
<tr>
<td>Storage</td>
<td>Packaging</td>
<td>Junction/ decision process</td>
</tr>
<tr>
<td>rear side of a house, kennel, garage</td>
<td>Box With lid, box that can be enclosed with duct tape, box open</td>
<td>Alight here</td>
</tr>
<tr>
<td>Storage building</td>
<td>Boxes</td>
<td>Triangle or printer &quot;stop&quot; button</td>
</tr>
<tr>
<td>Factory</td>
<td>Delivery box</td>
<td>Button</td>
</tr>
<tr>
<td>Warehousing</td>
<td>Packaging</td>
<td>Hazard</td>
</tr>
<tr>
<td>Houses</td>
<td>Boxes</td>
<td>A triangle</td>
</tr>
<tr>
<td>Storage</td>
<td>Storage</td>
<td>Storage</td>
</tr>
<tr>
<td>data warehouse</td>
<td>file storage</td>
<td>two inputs one output</td>
</tr>
<tr>
<td>warehouse</td>
<td>goods - assets</td>
<td>storage</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Parcel (physical object)</td>
<td>Storage</td>
</tr>
<tr>
<td>home</td>
<td>box</td>
<td>stockpoint</td>
</tr>
<tr>
<td>Physical location</td>
<td>Storage</td>
<td>??</td>
</tr>
<tr>
<td>factory or warehouse</td>
<td>box</td>
<td>??</td>
</tr>
<tr>
<td>Database</td>
<td>Message flow/process</td>
<td>Message flow</td>
</tr>
<tr>
<td>database</td>
<td>database</td>
<td>branch of if condition</td>
</tr>
<tr>
<td>Database</td>
<td>Database</td>
<td>MessageFlow</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Storage Box / Unit</td>
<td>Supply point</td>
</tr>
<tr>
<td>Warehouse facility</td>
<td>Cardbox</td>
<td>Gradient</td>
</tr>
<tr>
<td>Warehouse / Loaddock</td>
<td>Box</td>
<td>Inventory Location</td>
</tr>
<tr>
<td>Warehouse</td>
<td>Cardbox</td>
<td>Triangle</td>
</tr>
</tbody>
</table>

Figure B.3: Responses for the icon of "Storage"
Figure B.4 shows the interpretation of the three versions of the icon for the "Physical Flow" extension.

<table>
<thead>
<tr>
<th>Circles/Circles</th>
<th>Carries</th>
<th>Double Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence</td>
<td>Carts</td>
<td>Steps</td>
</tr>
<tr>
<td>Workload evolution</td>
<td>Delivery possibilities</td>
<td>Work processes</td>
</tr>
<tr>
<td>Sequence flow</td>
<td>Input flow</td>
<td>Operation flow</td>
</tr>
<tr>
<td>Flow of information</td>
<td>Buying options</td>
<td>Route flow</td>
</tr>
<tr>
<td>Indication of stages or process</td>
<td>Delivery of components</td>
<td>Progress of a specific task</td>
</tr>
<tr>
<td>Process stage/transition</td>
<td>Transportation of physical object</td>
<td>Fixed or specific process</td>
</tr>
<tr>
<td>Various paths (no stop, 3 intermediate stops, zig zag, a much rapid path)</td>
<td>Various cars available</td>
<td>1. with parallel paths 2. Diverging and converging at some instance 3. Bypassing main path</td>
</tr>
<tr>
<td>Signals</td>
<td>Transportation route direction</td>
<td>Transport with different destinations</td>
</tr>
<tr>
<td>Constrained control flow</td>
<td>Manual transportation</td>
<td>Constrained control flow</td>
</tr>
<tr>
<td>Process flow arrows with different properties</td>
<td>Process flows where consumers or workers make package transactions</td>
<td>Some arrows with properties</td>
</tr>
<tr>
<td>Physical flow</td>
<td>Physical flow</td>
<td>Physical flow</td>
</tr>
<tr>
<td>Association</td>
<td>Storage process</td>
<td>Sequence Flow</td>
</tr>
<tr>
<td>Sequential flow</td>
<td>Transport flow</td>
<td>Parallel flow</td>
</tr>
<tr>
<td>Transmission (flow)</td>
<td>Transportation of objects</td>
<td>The last one could mean transportation of something, the first two no ideal</td>
</tr>
</tbody>
</table>

???

Some discrete (1+2) and continuous (4) flows

Transportation

???

Some type of flow (different type/aim)

Physical transport (e.g. package) | some type of flow |

Message flow

Message flow | Message flow |

Message flow

Retrieval or storage of information | Flow of materials |

Message Flow

MessageFlow | MessageFlow |

Multiple stop flow

Supply / transport flow | Batch flow |

Specific route

Purchase delivery | Time for completion |

Fancy process flow?

Modes of transportation on process flow | Other fancy process flow? |

Line

Product lines | Line bars |

Figure B.4: Responses for the icon of "Physical Flow"
B.2 Responses for the choice of an icon

Figure B.5 shows the choices the people who responded on the form made for the icons of "Robot" and "Hybrid" extensions. Their first and second choice for each is seen next to each other.

<table>
<thead>
<tr>
<th>Which 'Robot Task' design do you prefer?</th>
<th>Which 'Robot Task' (Human-Robot collaboration) design do you prefer?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Torso</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
<tr>
<td>Body</td>
<td>User and Robotic arm</td>
</tr>
<tr>
<td>Robotic arm</td>
<td>User and Robot (torso)</td>
</tr>
</tbody>
</table>

Figure B.5: Responses for "Robot" and "Hybrid" icons
Figure B.6 shows the choices the people who responded on the form made for the icons of "Storage" and "Physical Flow" extensions. Their first and second choice for each is seen next to each other.

<table>
<thead>
<tr>
<th>Which 'Physical Flow' design do you prefer?</th>
<th>Which is your second choice for 'Physical Flow'?</th>
<th>Which 'Storage' design do you prefer?</th>
<th>Which is your second choice for 'Storage'?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circles or Curves</td>
<td>Double lines or mid-bar</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Circles or Curves</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Circles or Curves</td>
<td>Double lines of mid-bar</td>
<td>Box</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circles or Curves</td>
<td>Carrier</td>
<td>Box</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Circles or Curves</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circles or Curves</td>
<td>Double lines of mid-bar</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Circles or Curves</td>
<td>Box</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circles or Curves</td>
<td>Carrier</td>
<td>ANSI standard</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Carrier</td>
<td>Box</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Circles or Curves</td>
<td>ANSI standard</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Carrier</td>
<td>Box</td>
<td>Warehouse</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Circles or Curves</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circles or Curves</td>
<td>Carrier</td>
<td>ANSI standard</td>
<td>ANSI standard</td>
</tr>
<tr>
<td>Double lines of mid-bar</td>
<td>Carrier</td>
<td>Warehouse</td>
<td>Box</td>
</tr>
<tr>
<td>Carrier</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure B.6: Responses for "Physical Flow" and "Storage" icons.

### B.3 The questioning form

A replica of the questioning form can be seen next.
Extending BPMN for the manufacturing Domain

Please fill this form according to your personal opinion. Your answers will help in the decision of the extension designs.

The following designs are considered as BPMN extension icons for the manufacturing domain.

For each of them please write down what you think they represent. You may repeat your answers. ex. User, Database, Message Flow.

Your answer:

Your answer:

Your answer:

Your answer:

Your answer:

Your answer:

Your answer:
Extending BPMN for the manufacturing Domain

**BPMN introduction.**

This section provides some information on BPMN and introduces the designs.

Below you can see some task types.

![Task Types](image1)

Below you can see a simple process example.

![Simple Process Example](image2)

Example processes with the designs seen in the previous section can be seen below.

The example below uses 'Robot Tasks'.

![Example Process Using Robot Tasks](image3)
Which 'Robot Task' design do you prefer? *

Torso:

Body:

Robotic arm:

Which is your second choice for 'Robot Task'?

Torso:

Body:

Robotic arm:

The example below uses 'Hybrid Tasks' (collaboration between Humans and Robots) and 'Physical Flows' (transfer of material).

Which 'Hybrid Task' (Human-Robot collaboration) design do you prefer? *

User and Robot (torso):

User and Robot (body):

User and Robotic arm:
Which is your second choice for 'Hybrid Task'?

User and Robot (torso):

User and Robot (body):

User and Robotic arm:

Which 'Physical Flow' design do you prefer? *

Circles or Curves:

Carrier:

Double lines or mid-bar:

Which is your second choice for 'Transportation'?

Circles or Curves:

Carrier:

Double lines or mid-bar:
The example below uses 'Storages' (modeled similarly to 'Databases' or acting as buffers).

Which 'Storage' design do you prefer? *

Warehouse:

Box:

ANSI standard:

Which is your second choice for 'Storage'?

Warehouse:

Box:

ANSI standard:

You may leave recommendations.
Your answer:

Thank you for your contribution.
You may fill your name and/or profession for our consideration.
Your name:
Your professional field:
APPENDIX B. DESIGN FEEDBACK

B.4 Domain Experts Information

The positions of the domain experts that were contacted can be seen in table B.1. Their names were omitted for discretion.

<table>
<thead>
<tr>
<th>Expert Positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thomas Regout International B.V. Operations Director</td>
</tr>
<tr>
<td>Member of the TU/e BPM team for the HORSE project</td>
</tr>
<tr>
<td>Member of the TU/e BPM team for the HORSE project</td>
</tr>
<tr>
<td>Member of the TU/e BPM team for the HORSE project</td>
</tr>
<tr>
<td>TU/e Msc student on the HORSE project</td>
</tr>
<tr>
<td>TU/e Msc student on the HORSE project</td>
</tr>
<tr>
<td>TU/e Bachelor student on the HORSE project</td>
</tr>
</tbody>
</table>

Table B.1: Positions of the domain experts that contributed to the analysis phase of this research

The results from the experts’ voting is seen in figure B.7.

<table>
<thead>
<tr>
<th>Robot</th>
<th>Hybrid</th>
<th>Physical Flow</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure B.7: Voting results by experts.
B.5 Summary of results

Figure B.8 shows the pie graphs with the percentages of the choices per icon suggestion for the "Robot" and the "Hybrid" extension. Each pie considers first and second choices for each icon. The first option is considered twice as important as the second option; therefore, the results are weighted with 0.665% for the first option and 0.335% for the second option. The same logic applies to all following results.

![Pie chart for "Robot" and "Hybrid" choices](image1)

Figure B.8: Percentage of choices per icon for "Robot" and "Hybrid".

Figure B.9 shows the pie graphs with the percentages of the choices per icon suggestion for the "Robot" and the "Hybrid" extension combined and includes the feedback from experts. Experts' opinions are considered thrice as important as the opinion of people outside this profession field. Therefore, the results are weighted with 0.75% for experts' opinions and 0.25% for non-experts' opinions. The same logic applies to all following results.

![Combined pie chart for "Robot" and "Hybrid" choices](image2)

Figure B.9: Percentage of choices per icon for "Robot" and "Hybrid" combined.
Figure B.10 shows the pie graphs with the percentages of the choices per icon suggestion for the "Physical Flow" extension. The first pie shows the results from the form and the second one includes the feedback from the experts.

Figure B.10: Percentage of choices per icon for the "Physical Flow" extension.

Figure B.11 shows the pie graphs with the percentages of the choices per icon suggestion for the "Storage" extension. The first pie shows the results from the form and the second one includes the feedback from the experts.

Figure B.11: Percentage of choices per icon for the "Storage" extension.
Evaluation Feedback

Experts’ contributing to the evaluation phase

Table C.1 provides information of the domain experts that were interviewed during the evaluation phase of this research; Their names were omitted for discretion. The results of the evaluation phase is seen in figure 6.5 in section 6.2.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Professor of Information Systems at TU/e</td>
</tr>
<tr>
<td>b</td>
<td>Operations director at Thomas Regout International</td>
</tr>
<tr>
<td>c</td>
<td>TU/e Phd student in Information Systems</td>
</tr>
<tr>
<td>d</td>
<td>TU/e Msc student on the HORSE project</td>
</tr>
<tr>
<td>e</td>
<td>IT architecture expert at Philips</td>
</tr>
<tr>
<td>f</td>
<td>Process engineer at Celonis</td>
</tr>
</tbody>
</table>

Table C.1: Experts contributing to the Evaluation
APPENDIX C. EVALUATION FEEDBACK

The evaluation questionnaire as explained in section 6.2 is inspired by Moody’s Method Evaluation Model [20], but due to significant differences between the two the validity of Moody’s model is not claimed in this research.

<table>
<thead>
<tr>
<th>Question</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>I find the icons of the new extensions easy to recognize.</td>
<td></td>
</tr>
<tr>
<td>I found the method easy to learn</td>
<td>Q6</td>
</tr>
<tr>
<td>I find the new extension elements understandable.</td>
<td></td>
</tr>
<tr>
<td>I found the rules of the method clear and easy to understand</td>
<td>Q11</td>
</tr>
<tr>
<td>I understand the differences amongst the extensions.</td>
<td></td>
</tr>
<tr>
<td>I understand the differences between the extensions and other standard BPMN elements.</td>
<td></td>
</tr>
<tr>
<td>I found the procedure for applying the method complex and difficult to follow</td>
<td>Q1</td>
</tr>
<tr>
<td>Overall, I found the method difficult to use</td>
<td>Q4</td>
</tr>
<tr>
<td>I do not understand how to apply the new extensions.</td>
<td></td>
</tr>
<tr>
<td>I do not understand where to apply the new extensions.</td>
<td></td>
</tr>
<tr>
<td>I found it difficult to apply the method to the example data model</td>
<td>Q9</td>
</tr>
<tr>
<td>I am not confident that I am now competent to apply this method in practice</td>
<td>Q14</td>
</tr>
<tr>
<td>I think the MPMN elements improve the understandability of specific manufacturing activities in BPMN models.</td>
<td></td>
</tr>
<tr>
<td>I think manufacturing processes are more understandable with the use of the MPMN extensions.</td>
<td></td>
</tr>
<tr>
<td>I believe that this method would reduce the effort required to document large data models</td>
<td>Q2</td>
</tr>
<tr>
<td>This method would make it easier for users to verify whether data models are correct</td>
<td>Q5</td>
</tr>
<tr>
<td>I think the MPMN extension makes it easier to communicate specific manufacturing activities to various stakeholders.</td>
<td></td>
</tr>
<tr>
<td>Using this method would make it easier to communicate large data models to end users</td>
<td>Q13</td>
</tr>
<tr>
<td>Overall I find the MPMN extension useful.</td>
<td></td>
</tr>
<tr>
<td>Overall, I found the method to be useful</td>
<td>Q7</td>
</tr>
<tr>
<td>Overall I find the MPMN extension an improvement to standard BPMN for visualizing manufacturing processes.</td>
<td></td>
</tr>
<tr>
<td>Overall, I think this method is an improvement to the standard Entity Relationship Model</td>
<td>Q15</td>
</tr>
<tr>
<td>I think manufacturing processes are harder to understand with the use of the MPMN extensions.</td>
<td></td>
</tr>
<tr>
<td>Large data models represented using this method would be more difficult for users to understand</td>
<td>Q3</td>
</tr>
<tr>
<td>I think the MPMN elements add no value to the modeling of manufacturing activities.</td>
<td></td>
</tr>
<tr>
<td>Overall I think the MPMN extension does not provide an effective solution to the problem of representing manufacturing processes explicitly.</td>
<td></td>
</tr>
<tr>
<td>Overall, I think this method does not provide an effective solution to the problem of representing large data models</td>
<td>Q12</td>
</tr>
<tr>
<td>I would use the MPMN extension over standard BPMN to model manufacturing processes.</td>
<td></td>
</tr>
<tr>
<td>I intend to use this method in preference to the standard Entity Relationship Model if I have to work with large data models in the future</td>
<td>Q16</td>
</tr>
<tr>
<td>I would prefer using standard BPMN to model manufacturing processes.</td>
<td></td>
</tr>
<tr>
<td>I would definitely not use this method to document large Entity Relationship models</td>
<td>Q10</td>
</tr>
</tbody>
</table>

Figure C.1: MPMN evaluation questions in relation to Moody’s [20]
Graphical Designs Brainstorming

Brainstorm sketches

Figure D.1: Design sketches
### ANSI flowchart symbols

<table>
<thead>
<tr>
<th>Flowchart Symbol</th>
<th>Name (Alternates)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td></td>
<td>An operation or action step.</td>
</tr>
<tr>
<td>Terminator</td>
<td></td>
<td>A start or stop point in a process.</td>
</tr>
<tr>
<td>Decision</td>
<td></td>
<td>A question or branch in the process.</td>
</tr>
<tr>
<td>Delay</td>
<td></td>
<td>A waiting period.</td>
</tr>
<tr>
<td>Predefined Process</td>
<td></td>
<td>A formally defined sub-process.</td>
</tr>
<tr>
<td>Alternate Process</td>
<td></td>
<td>An alternate to the normal process step.</td>
</tr>
<tr>
<td>Data (I/O)</td>
<td></td>
<td>Indicates data inputs and outputs to and from a process.</td>
</tr>
<tr>
<td>Document</td>
<td></td>
<td>A document or report.</td>
</tr>
<tr>
<td>Multi-Document</td>
<td></td>
<td>Same as Document, except, well, multiple documents.</td>
</tr>
<tr>
<td>Preparation</td>
<td></td>
<td>A preparation or set-up process step.</td>
</tr>
<tr>
<td>Display</td>
<td></td>
<td>A machine display.</td>
</tr>
<tr>
<td>Manual Input</td>
<td></td>
<td>Manually input into a system.</td>
</tr>
<tr>
<td>Manual Operation</td>
<td></td>
<td>A process step that isn’t automated.</td>
</tr>
<tr>
<td>Card</td>
<td></td>
<td>A old computer punch card.</td>
</tr>
<tr>
<td>Punched Tape</td>
<td></td>
<td>An old computer punched tape input.</td>
</tr>
<tr>
<td>Connector</td>
<td></td>
<td>A jump from one point to another.</td>
</tr>
<tr>
<td>Off-Page Connector</td>
<td></td>
<td>Continuation onto another page.</td>
</tr>
<tr>
<td>Transfer</td>
<td></td>
<td>Transfer of materials.</td>
</tr>
<tr>
<td>Or</td>
<td></td>
<td>Logical OR</td>
</tr>
<tr>
<td>Summing Junction</td>
<td></td>
<td>Logical AND</td>
</tr>
<tr>
<td>Collate</td>
<td></td>
<td>Organizing data into a standard format or arrangement.</td>
</tr>
<tr>
<td>Sort</td>
<td></td>
<td>Sorting of data into some pre-defined order.</td>
</tr>
<tr>
<td>Merge (Storage)</td>
<td></td>
<td>Merge multiple processes into one. Also used to show raw material storage.</td>
</tr>
<tr>
<td>Extract (Measurement) (Finished Goods)</td>
<td></td>
<td>Extract (split processes) or more commonly - a measurement or finished goods.</td>
</tr>
<tr>
<td>Stored Data</td>
<td></td>
<td>A general data storage flowchart symbol.</td>
</tr>
<tr>
<td>Magnetic Disk (Database)</td>
<td></td>
<td>A database.</td>
</tr>
<tr>
<td>Direct Access Storage</td>
<td></td>
<td>Storage on a hard drive.</td>
</tr>
<tr>
<td>Internal Storage</td>
<td></td>
<td>Data stored in memory.</td>
</tr>
<tr>
<td>Sequential Access Storage (Magnetic Tape)</td>
<td></td>
<td>An old reel of tape.</td>
</tr>
<tr>
<td>Callout</td>
<td></td>
<td>One of many callout symbols used to add comments to a flowchart</td>
</tr>
<tr>
<td>Flow Line</td>
<td></td>
<td>Indicates the direction of flow for materials and/or information</td>
</tr>
</tbody>
</table>

Figure D.2: ANSI symbols