MASTER

Exception handling in business process management for (smart) manufacturing industries

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Abstract

Exceptions are related to worse operational performance in terms of a longer throughput time and higher costs for the organization. The objective of this research is the design of a generic descriptive process model in Business Process Modeling Notation (BPMN), that acts as a blueprint for the process that needs to be executed when an exception occurs in a manufacturing environment using Manufacturing Execution Systems (MES). Interviews with experts in the manufacturing domain and scientific literature have contributed to the development of this model. For the most important Key Performance Indicators (KPI), a forecasting model was developed, that can provide insight in the impact of specific exceptions on these KPI's. It enables companies to gain more insight in the standardization of the exception handling process.

Preface

The graduation project for ‘Operations Management and Logistics’ students at Eindhoven University of Technology consists of three parts: the literature review, the research proposal and the master thesis project.

This is the report on the master thesis project and its publication marks the end of my graduation internship at Atos and the master study at the University of Technology in Eindhoven. By completing this final part of the master program I obtain my master’s degree in ‘Operations Management and Logistics’.

This thesis is the result of my graduation project performed at Atos. This project also marks the end of my life as a student. I would like to thank my mentor Rik Eshuis in the first place. Eshuis’ extensive knowledge on business process modeling and business process management provided me with valuable input for answering the research questions. This thesis would not have been of the same level without your feedback and support. At the very start of the project we planned our meetings at the Campus, but in the past few months these meetings moved to the online spectrum due to Corona. This had no negative consequences the communication between us. Moreover, I want to thank Remco Dijkman for his feedback that provided me insights from another perspective. I would therefore like to express my sincere gratitude towards both supervisors. I also want to thank Baris Ozkan for willing to be the third assessor of this thesis.

I would like to thank Edgar Oerlemans, my supervisor at Atos. Your experience as a senior consultant were very helpful during the process. Although we haven’t seen each other in real life for a long time, I have enjoyed the cooperation between us. Our weekly calls were very helpful and provided some space for a nice chat.

Lastly, I want to thank my girlfriend Karlijn for always being there for me in the past nine years already. I also want to thank you for your unconditional support during the project. The finalization of this report and thereby the finalization of the master’s in Operations Management and Logistics marks the end of a chapter. I am ready for the next one!

Note*: all abbreviations used in this report are listed on page xii.*

Executive Summary

In this master thesis, research was carried out in the field of smart manufacturing. The focus within this field is on the exception handling process. Exceptions and poor exception handling may lead to worse operational performance in terms of a longer throughput time and eventually higher costs for the organization.

Introduction

Atos is a global IT-company with business analysists working at their clients. Atos is a trusted partner for the clients' digital transformation, with the resources, the scale and the know-how that the clients need. This project was carried out at Atos and had a possibility of contacting different high-tech companies in order to be able to design a process model that includes exception handling. At this moment, there is hardly any scientific paper that can be found on exception handling specific for the manufacturing domain. Manufacturing is related to the ability to convert raw materials into final products by application of processes or by use of man, machinery and resources. Moreover, there are several papers to be found on the recovery from exceptions, but not on the workflow handling. This is also a research gap that has been identified. Lastly, there is not much to be found that focuses specifically on Manufacturing Execution Systems (MES). Therefore, this research contributes to the knowledge of manufacturing domains, workflow handling and MES.

Objective and Research Question

The current problem is that Atos does not have a generic process that acts as a blueprint for what needs to be executed when an exception occurs. The objective of this research is therefore the design of a generic descriptive process model in Business Process Modeling Notation (BPMN), that acts as a blueprint for the process that needs to be executed when an exception occurs in a manufacturing environment.

The main research question, which can be derived from the problem statement, is:

How should generic models for describing and forecasting exceptions be designed in a MES and how can it be implemented for a specific manufacturing process?

To obtain expert knowledge, information of specialists needed to be gained. In this project, semi-structured interviews were used to obtain this information form experts in the field. This way of interviewing is particularly useful when multiple open-ended interview require follow-up queries. Semi-structured interviews are labour intensive but a lot of information and insights was gained from the experts.

Method

Interviews with employees that are expert in the specific manufacturing processes and scientific literature have contributed to the development of this model. Realistic data on processes can be used to classify exceptions according to their potential impact on the manufacturing process. For the most important Key Performance Indicators (KPI), a forecasting model was developed, that can provide insight in the impact of specific exceptions on theses KPI's.

Results

The five exception types (work item failure, constraint violation, resource unavailability, external trigger and deadline expiry) are classified into the exception types 'product', 'process' and 'equipment', as to be seen in Table i.

Literature exceptions	Classification from interview
Work item failure	Product and Equipment
Deadline expiry	Product
Resource unavailability	Equipment
External trigger	Equipment and Product
Constraint violation	Equipment, Product and Process

Table i. Summary of exception types

Different reasons were given in interviews for the occurrence of these exceptions, e.g. an abort initiated by the user of the executing program, failure of a hardware, software or network component associated with the work item or the raw material remains unused for too long. Other examples were the unavailability of some material, machines or operators and lastly, the equipment could be worn out and should be replaced by a new tool. The product, process and equipment exceptions were used as input for calculating the impact of these exceptions.

The next step was identifying the impact of the exceptions on the process performance and forecast the most important KPI's based on realistic data. A KPI is used at multiple levels of an organization and implements the strategic objectives and it is an evaluation index of the core events. It is a measurable value that demonstrates how effectively a company is achieving key business objectives. In production processes, the KPI's indicate how efficient the process is; efficient processes mean less downtime. As identified by means of interviews, OEE is the most important KPI regarding the equipment exceptions. Regarding product exceptions, the most important KPI is First Time Yield. Lastly, regarding process exceptions, C_p and C_{pk} were the most important KPI's. A summary is represented in Table ii.

Exception classification	Identified KPI's
Equipment exceptions	OEE
Product exceptions	FTY
Process exceptions	C_p and C_{pk}

Table ii. Exceptions and related KPI's

Corresponding calculations are done in Excel to calculate the impact on the KPI, based on forecasts of specific parameters. Some Excel parameters need to be filled in by the user beforehand to gain insight in the forecasted performance of the process. Consequently, Excel calculates the impact on the most important KPI's. Since specific parameters are calculated by forecasts, these forecasts could constantly by extended by new data if an exception occurs.

In addition to the Excel file, the generic exception handling model was generated and the Excel sheet, described in the previous paragraph, is used to calculate the impact of specific exceptions and is incorporated as an activity in the generic exception handling model. This makes it possible for Atos to visit their clients with this blueprint of the model in order to see where problems occur.

It was important to get an understanding of the necessities of the model for the client of Atos. Therefore, some interview questions were focused on getting an understanding of the basic prerequisites for the model in order to be used in practice at Atos' clients. The expertise of the MES consultants at Atos was used in order to get to know how this model can be used in different settings, since they are already using models for different topics at their clients. The interviews identified that

Atos' clients have solutions specific for their own process. Moreover, an outcome of the interviews was that procedures are very locally implemented and manufacturing environments are difficult to compare. This means that information from one client cannot be used at another client. Eventually, with the developed generic model in use, same procedures and processes can be used at the different clients which makes it able to compare performances. This is especially useful when a company wants to compare performance of its different sites. This model makes it possible to standardize the process.

Implementation

The implementation of the model should result in successful exception handling for the company. The opinion of Atos' experts on critical success factors in implementation was combined with literature on critical success factors of such an implementation. This resulted in a couple of critical success factors; the model should be **flexible** in order to be **client friendly**. More extensive models are more difficult to implement in current systems and more difficult to understand by the users. Therefore, starting with simple models and being able to extend these models is of extreme importance. The model developed in this thesis has kept this in mind and can be extended, dependent on the type of user.

Moreover, **technology, human, management and process** were identified as critical success factors. The technology factor is defined as the capability to interoperate with other systems. Moreover, successful implementation requires support of upper management and staff. Lastly, "a process-oriented approach to application development", "process awareness at an early stage of the project" and "(organizational) understanding of process concepts" were defined by literature as critical success factors (Reijers, 2006). An implementation plan was developed to be used by Atos to make implementation successful at its clients.

Conclusion

In conclusion, the contributions of this research are on exception handling specific for the manufacturing domain. Papers on exception handling focus mainly on customers cancelling hotel and car reservations (Casati, 1999; Lerner et al., 2010; Reichert & Weber, 2012), for example. In these processes, no physical products or steps of translating a raw material into an end product must be conducted. Therefore, these papers do not focus on the more complex manufacturing processes which may consist of many machines, tools, operations and KPI's. Thus, manufacturing is different since it relates to the ability to convert raw materials into final products by application of processes or by use of man, machinery and resources. This report does not focus on the recovery of exceptions but how to implement exceptions and their corresponding impact on the KPI's in the process. It provides a standardized procedure for a process description where exceptions and their impact are incorporated. The advantage of the sheets in Excel is that the MES Consultants at Atos, together with the client they are working for, can see (after filling out the input parameters) before the start of the process, the forecasted scores on the KPI's. The user can decide whether he is satisfied with this score on KPI's. If so, the normal process execution with possible exceptions can start. If the user is not satisfied with the forecasted scores on the KPI's, input parameters can be adjusted (e.g. schedule less planned downtime, discuss with the client on adjusting LSL and USL etc.). There is not much to be found that focuses specifically on MES. Therefore, this research contributes to the knowledge of implementing this workflow handling procedures with exception handling in MES. Experts of MES have been interviewed in order to investigate whether this model would be implementable in the current systems. It has been adapted and designed in order to be implementable in current systems (of clients). Further research could focus on other prediction techniques, e.g. when the exception will take place. Moreover, since the model was high-level, further research should focus on a specific action plan for the work floor (operators and employees).

The main objective of this research was achieved since the generic descriptive model in BPMN was designed. This process model can act as a blueprint for the process that needs to be executed when an exception occurs in a manufacturing environment. Furthermore, the research questions were all answered by interviews and literature. The methodology of using interviews and literature was suitable for answering this research questions. The generic model for exception handling was designed by means of the input of the sub questions. The Senior MES Consultants at Atos agreed that this model can be implemented at their clients in different settings. This research also aimed to calculate the impact of exceptions and to make forecast for the most important KPI's. This was done by Excel. However, it should be kept in mind that the Excel file is a prototype and no real data was used to calculate the current KPI's. However, the data used is representative and was used to show Atos the calculations on the KPI's. Atos argues that the model and associated Excel file are useful for successful exception handling in practice.

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List of Abbreviations

BPM	Business Process Management
BPMN	Business Process Modelling Notation
BPMS	Business Process Management System
CFFD	Central Filling and Freeze Drying
CWME	Context-aware Workflow Management Engine
DBMS	Database Management System
DSRM	Design Science Research Methodology
FMEA	Failure Mode Effect Analysis
FTY	First Time Yield
KPI	Key Performance Indicator
LSL	Lower Specification Limit
MES	Manufacturing Execution System
OEE	Overall Equipment Effectiveness
PCI	Process Capability Index
USL	Upper Specification Limit
WfMS	Workflow Management System

1 Introduction

1.1 Chapter Introduction

This chapter is the introduction of the report. It introduces the different aspects of the problem and the different stakeholders / participants of the research. Moreover, the research goal, relevance and the structure of the report are given in this chapter. This research was carried out at Atos: a global IT-company with consultants working at Atos' clients.

The next section is divided in several subsections which will be introduced here. It starts with a description of manufacturing processes (section 1.2.1), followed by an introduction of business process management (section 1.2.2). The concept of processes and BPM (business process management) is introduced to provide a context description of the project. Exceptions are described in section 1.2.3 since the focus on this thesis is on exception handling, which is elaborated in the research goal and relevance (section 1.3). A basic prerequisite of handling exceptions is a flexible adaptation of the business process. Therefore, the fourth section discusses flexibility of processes (section 1.2.4). In section 1.2.5, MES is introduced. This is a widely used information system that can monitor manufacturing processes. This thesis is conducted at Atos (section 1.2.6) and Atos is provides support for MES at its clients. Therefore, a possible artefact produced needs to be aligned with this current MES systems. Other organizations are discussed in section 1.2.7, since Atos has several clients that are incorporated in this research by interviews.

1.2 Problem Introduction

1.2.1 Processes

Processes are the core of any business and are critical to the outcome of operations. In particular, production processes are concerned with transforming a range of inputs into outputs required by the customer. It is important to keep in mind that different types of products may need completely different production processes. Operations managers classify production processes in two ways; how inputs (e.g. raw materials, natural resources) are converted into outputs (the final product) and the timing of the process. Considering the timing of the process, a continuous process uses long production runs that may last days, weeks, or months without equipment shutdowns. This type of process is best for high-volume, low-variety products with standardized parts, such as paper (Gitman et al., 2018). In a process with shorter timing, short production runs are used to make batches of different products. On the contrary, low-volume, high variety products are considered as shorter-timing processes. For these machines are shut down to change them to make different products at different times. Products that are produced by customization, is an example (Gitman et al., 2018).

1.2.2 Business Process Management

Business Process Management (BPM) is a methodology that can turn the business into a well-oiled machine. Over the last decade, BPM technologies have become more important resulting in a shift of focus for many organisations. Several organizations (in various work fields) have adopted process orientation with the purpose to leverage their investments in specific technology and to optimize their business (Antunes, 2011). The goal of BPM is to increase the level of automation and implementing structural changes in organizations through better coordination, data and resource management, messaging and service decomposition (Antunes, 2011). Rapid technological growth during the last years causes large dynamic changes to process complexity. Amongst others, this led to the fact that manufacturing operations are vulnerable to various exceptions which occur dynamically and unpredictably (Bruccoleri, Renna, & Perrone, 2005). The occurrence of these exceptions may lead to a degradation of system performance and may interrupt the production process by causing deviations in the scheduled plan. The definition of exceptions is given in the following paragraph. Above that, more information on BPM will be provided in section 2.2.

1.2.3 Exceptions

An exception is a deviation from the original business process definition, which might cause malfunction (Yaxiong, Huibin, & Zhen, 2010). It is an abnormal situation that occurs during the execution of the workflow which can cause critical consequences (Derbali, 2011). Exceptions are inevitable in the application of business processes (Yaxiong et al., 2010). An *Exception* is a commonly occurring term in relation to business processes in both science and business practice. While the term exception suggests that these deviations from business processes are only occurring rarely, exceptions are a normal part of business process execution (Kurz, Fleischmann, Lederer, & Huber, 2013).

Exceptions occur in business processes and organizational processes. Exceptions are related to worse operational performance in terms of a longer throughput time and unexpected exceptions relate to a stronger increase in throughput time than expected exceptions (Dijkman, Van IJzendoorn, Turetken, & De Vries, 2018). Related to this study, poor exception handling will result in longer throughput times and eventually higher costs for the organization.

1.2.4 Flexibility of Processes

The Pareto Principle implies that 80% of all costs are caused by 20% of the exceptions (Gottanka & Meyer, 2012). For process design, it is necessary to have an overview of what exceptions can occur. In modelling, the focus lies on the understanding and application of essential procedures (Gottanka & Meyer, 2012). It is important to minimize unnecessary event to reduce costs, but this can only be achieved when a process analysis is performed. This is in order to eliminate expected and unexpected exceptions.

Currently, organisations struggle since there is insufficient capability for flexible adaptation and handling exceptions in Business Process Management Systems (BPMS) (M. J. Adams, 2007). A basic prerequisite of handling exceptions is a flexible adaptation of the business process. Flexibility is becoming very important in BPMS. The more frequently a process must be adapted due to changed circumstances, the less effective the traditional methods used for process improvement will be. Flexibility is one component in the Devil’s Quadrangle. This Devil’s Quadrangle shows that every improvement in a production process brings a trade-off between four issues: time, cost, flexibility and quality. Figure 1 shows this Devil´s Quadrangle. It describes the dilemma between the factors Quality, Time, Cost and Flexibility which is applicable to the BPM context (Sadiq, Soffer, & Völzer, 2014). The relation between this quadrangle and the BPM context will be described in the next paragraph.

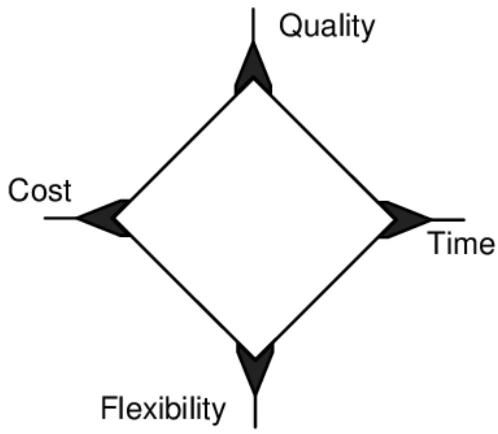

Figure 1. Devil's quadrangle (Sadiq et al., 2014)

The four dimensions (quality, cost, time and flexibility) describe process performance. These factors are dependent on each other. Therefore, it is necessary to take precautions into mind, in order not to completely disrupt the balance between the other factors when optimizing one factor (Sadiq et al., 2014).

Exception handling patterns can contribute to the flexibility of a process, which reduces high costs. Categorization of exceptions combines similar types and helps to create an automated exceptions handler, which can reduce process run time, and helps avoiding interrupts or exception time. High quality of the process can be achieved when the process performs errorless. Correct modelling is extremely important. Exception classification and their handling methods are basic requirements for exception modelling in BPMS. Terminations and changes to the process should be modelled as accurately as possible, in order to obtain the control over the implementation. Therefore, it is necessary to classify the type of exception and the probability of occurrence of the exceptions.

This thesis will focus on Manufacturing Execution Systems (MES) and is performed at Atos. A MES is a process-aware Information System. It can monitor and control complex manufacturing processes. This is elaborated in the next sections.

1.2.5 MES

A MES is an information system that connects, monitors and controls complex manufacturing systems and data flows on the factory floor (Kletti, 2007). The main goal of such system is to ensure effective execution of the manufacturing operations and improve production output. MES offers real-time applications. They generate current and even historical maps for production equipment and can thus be used as a basis for optimization processes (Kletti, 2007). In the past the main emphasis was on achieving improvements in machine utilization, where today the concern is to obtain real-time mapping of the value stream (Kletti, 2007). Exception handling is of great importance in this value stream, as exceptions occur frequently in manufacturing processes. Since exceptions result in longer throughput times (Dijkman et al., 2018), it is important that exceptions occur as little as possible and are handled efficiently when they do occur. MES is the commonly used type of information system at clients of Atos. Therefore, it is important that all artefacts developed can be implemented and used by clients of Atos, in the MES.

1.2.6 ATOS

Atos is a consulting company. It is the worldwide digital leader with more than €11 billion revenue all over the world (ATOS, 2020). Moreover, Atos is a trusted partner for the clients' digital transformation, with the resources, the scale and the know-how that the clients need. Therefore, this project had the possibility of working within different high-tech companies in order to be able to design a process model that suits more companies. Atos implements MES at its clients. These systems are configured by Atos but developed by SAP or Siemens for example. These are information systems are used in manufacturing to track and document the process of transforming raw materials into end products.

1.2.7 Other Organizations

Three other organizations were involved in this project via interviews with employees from these companies. The first is **DAF Trucks N.V.**, which is a technology company and the premier commercial vehicle manufacturer in Europe. DAF is a wholly owned subsidiary of PACCAR Inc, the worldwide quality leader in the design and manufacturing of premium light, medium and heavy-duty commercial vehicles. PACCAR also designs and manufactures advanced diesel engines, provides financial services and information technology and distributes truck parts related to its principal business (DAF, 2020). The second company is **Royal Philips**, which is a leading health technology company focused on improving people's health and enabling better outcomes across the health continuum from healthy living and prevention, to diagnosis, treatment and home care. Philips leverages advanced technology and deep clinical and consumer insights to deliver integrated solutions (Philips, 2020). Headquartered in the Netherlands, the company is a leader in diagnostic imaging, image-guided therapy, patient monitoring and health informatics, as well as in consumer health and home care. The last involved company is **MSD**, which is an American multinational pharmaceutical company and one of the largest pharmaceutical companies in the world. MSD has a long and rich history of working to improve people's health and wellbeing (MSD, 2020). The scientists also help to develop many products to improve animal health, including vaccines and antibiotics.

1.3 Problem Formulation and Relevance

The current problem is that Atos does not have a generic process that acts as a blueprint for what needs to be executed when an exception occurs. This is in line with the finding that business analysists are often busy optimizing processes, rather than focusing on the classification of exceptions in order to optimize the processes (Öztemür, 2015). Moreover, there is hardly any scientific paper that could be found on exception handling specific for the manufacturing domain. Most literature is focussed on exceptions related to a customer cancelling an order, for example. However, manufacturing is different since it relates to the ability to convert raw materials into final products by application of processes or by use of man, machinery and resources. Moreover, there are several papers to be found on the recovery from exceptions (M. J. Adams, Ter Hofstede, Van Der Aalst, & Edmond, 2007; Casati, 1999; Lerner et al., 2010; Reichert & Weber, 2012; Wu, 2009), but not on the workflow handling. This is also a research gap that has been identified in Hommen (2020). The last literature gap is related to MES. There is not much to be found that focuses specifically on these types of systems in relation to exception handling. MES is a commonly used information system for the manufacturing environment within Atos' clients. Therefore, it is important that a model will be designed that can standardize the exception handling process and this model needs to be implemented in a MES, eventually.

In conclusion, this research can contribute to the knowledge of manufacturing domains, workflow handling and MES.

1.4 Research Goal

The objective of this research is the design of a **generic descriptive process model** in Business Process Modeling Notation (**BPMN**), that acts as a blueprint for the process that needs to be executed by the clients of Atos when an exception occurs in a manufacturing environment. Interviews with employees that are expert in the specific manufacturing processes and scientific literature have contributed to the development of this model. Atos sets out to be able to advise its clients better on the exception handling strategy and improve the MES in collaboration with the developers of the MES (e.g. SAP and Siemens). This research aims to extend the existing knowledge in literature with the new findings regarding exception handling and forecasting implemented in a MES. The forecasting will be done in an **Excel file**, which is suitable for making calculations and represent the results in figures. As a result, the deliverable for Atos is the generic descriptive model (in BPMN; this aims to standardize the exception handling process) and the Excel tool (this aims to forecast the impact of exceptions on KPI's).

The model and tool are subsequently to be applied in practice in one or more companies that use MES.

1.5 Structure of Report

The remainder of this report is structured as described in Table 1.

Chapter #	Description
Chapter 2	The theoretical background is discussed. This incorporates the classification of exceptions as found in the scientific literature.
Chapter 3	The (type of) methodology is discussed. Also, the type of interviews that were conducted is explained.
Chapter 4	The type of exceptions as a result from the interviews is discussed.
Chapter 5	The Excel file with the calculations and forecasts of relevant KPI's is explained.
Chapter 6	The generic process model is shown. With this model Atos can provide its clients with a brief overview of what the exception handling process should include.
Chapter 7	In this chapter the demonstration and evaluation, which includes an implementation plan is elaborated.
Chapter 8	The conclusion and discussion are provided in this last regular chapter of the report. This chapter includes the reflection, limitations and possible further research, amongst others.

Table 1. Structure of the Report

1.6 Chapter Conclusion

This chapter introduced the different aspects of the problem and the different stakeholders / participants of the research. Moreover, the research goal, relevance and the structure of the report were given in this chapter. The next chapter will elaborate on the theoretical background and related literature.

2 Theoretical Background and Related Work

2.1 Chapter Introduction

To enable an orientation within the topic of this thesis, this section describes the fundamentals of BPM, along with the different types of exceptions in combination with their sources.

2.2 Fundamentals of BPM

Continuing on the introduction on BPM given in section 1.2.2, this section will provide more background on this topic.

Generally defined, each organisation has defined goals in order to be able to define success in the long term. However, in order to achieve stated goals, activities and tasks must be coordinated and executed in a systematic manner. Business process is the term used to summarize all these tasks and activities in an organisations' process. A process consists of activities and tasks to be performed on the one hand. On the other hand, a process consists of persons, physical objects like raw materials, immaterial objects like electronic records and outcomes. Bernhard Westfechtel defined it as follows: "The business process comprises all activities carried out in an enterprise, including e.g. staffing, financing, production, marketing, etc." (Westfechtel, 1999). Concluding, BPM consist of tasks, activities, persons, events or decisions that are in systematic, coherent relation, in order to accomplish a business goal (Dumas, La Rosa, Mendling, & Reijers, 2013).

It is important that this workflow occurs continuously, without errors. Therefore, it is essential to coordinate, manage, and optimize processes. And now, BPM comes into place. BPM is used not only by organizations, but by all kind of branches. To ensure continuous, errorless production in warehouses. However, it is also used in hospitals, governmental institutions, schools and universities that require the management of processes.

The ultimate aim of BPM is "continuous quality improvement, thereby minimizing costs and process runtime" (Dumas et al., 2013). "It is a generic software system that is driven by explicit process representations to coordinate the enactment of business processes" (Weske, 2007). Concepts and techniques like conducting process models for representations of process or activity instances, are characteristic for BPM (Weske, 2007). However, business processes can be complex and not everything can be easily automated. This is the reason that dynamic process workflow systems are more and more supported and improved by IT-systems, known as BPMS.

Process modelling tools support the improvement of design and representation of business processes. Dumas et al. (2013) mentioned that "You can´t control what you can´t measure". This is an important statement, and in this case refers to the fact that it is important to produce a process model and define Key Performance Indicators (KPI's) first, before going further to being able to classify and forecast exceptions.

Next, the distinction between expected and unexpected exceptions will be elaborated upon. An exception can originate within the process or occur outside process. Exceptions are generated when there is a discrepancy between as-is processes and the modelled processes (Reichert & Dadam, 1998). Exceptions can be divided into one of two kinds: "expected" and "unexpected" exceptions.

Generally said, expected exceptions are predictable and are considered at design time of the process. Contrary, unexpected exceptions are unpredictable and should be handled in a flexible way (e.g. ad-hoc technique) (Russell, van der Aalst, & ter Hofstede, 2006). Unexpected exceptions are considered as a black box. This is due to the fact that they are not incorporated in process models. Unexpected exceptions do not exist until they appear. If an unexpected exception occurs, it is possible that in the future it becomes an expected exception and will be incorporated in the system. As a result, the unexpected exception can be planned for in the process model and is no longer considered as a black box. It is added to the expected exceptions.

Summarizing these two types of exceptions, an expected exception is a situation differing from the 'happy path', but still predictable. Therefore, you can take measures to be able to take quick actions, reduce the time-delays and enhance the quality of the process. On the other hand, when an unexpected exception appears no concrete actions are ready to be taken by the system. This means that it cannot be planned for in advance.

Classification of exceptions and exception handling are of extreme importance in recognizing the causes and types of expected exceptions (Russell, van der Aalst, et al., 2006). The exceptions and its sources must be detected first. This allows for an accurate process modelling and process execution without exceptions. In the next paragraphs, existing literature on exceptions is elaborated.

2.3 Exception Types and Sources

The first type of exceptions that are identified are basic failures. According to Casati (1999), basic failures correspond to failures of the Workflow Management System (WfMS). It can also correspond to the underlying platform of the WfMS, e.g. network, hardware or Database management systems (DBMS) failures. Ngeow, Mustapha, Goh, Low, & Chieng (2007) provide an example of a so-called 'device' (hardware) failure. Malfunctioning of a printer could be the reason for a device failure to occur in the execution of a print task. A possible handling for this failure is that the user is notified and another printer is selected or the task is postponed. An example of a basic failure in the context of manufacturing processes is a network failure that results in the MES being unable to communicate with the machines. Casati (1999) also states that basic failures are handled at the system level, by relying on the capability of the underlying DBMS to maintain a persistent and consistent state, thus supporting forward recovery.

Secondly, exceptions regarding the applications are found in the literature. Application failures are failures of the applications connected to the WfMS (Casati, 1999). Possible failures are that the external application may not return any values to the workflow engine. It may also be out of memory, returning an error code. Application failures have a great impact on the workflow management since applications are not able to be completed. As a consequence, the task in the context of which the application is connected to cannot be completed successfully (Casati, 1999). An application failure could cause unsuccessful abort of an external application. Several components that are connected to the workflow engine may be unable to communicate or perform their function due to internal system error. Communication error occurs when workflow engine fails to receive response from device or other engine (Ngeow et al., 2007).

The third type of exceptions are the expected exceptions. These exceptions can be thought of in the design phase and thus can be included in the process model. The section on expected exceptions is divided into four part, namely: exception types, workflow handling, recovery action and 'other'.

2.4 Expected Exceptions

There are five different types of expected exceptions found in the literature. First of all, from a process perspective, critical exceptions often occur during activity execution (Reichert & Weber, 2012). *Work item failure* during the execution of a workflow process is generally characterised by the inability of the work item to progress any further (Russell, van der Aalst, et al., 2006). This may show itself in a number of possible forms including an abort initiated by the user of the executing program, the failure of a hardware, software or network component associated with the work item. Where the reason for this failure is not captured and dealt within the process model, it needs to be handled elsewhere in order to ensure that both later work items and the process as a whole continue to behave correctly (Russell, Van Der Aalst, & Ter Hofstede, 2006). Workflow exceptions are raised in correspondence of the start or completion of tasks and workflow instances, and are therefore synchronous with the progression of the workflow (Casati, 1999).

Secondly, when a work item reaches a set deadline and a timeout event occurs, is called a *deadline expiry* (M. J. Adams et al., 2007) and is raised at the occurrence of a given timestamp (Casati, 1999). Thus, this type of exception can be detected by measuring time (Mišić, Domazet, Trajanović, Manić, & Zdravković, 2010). It is common to specify a deadline for a work item in a workflow process model. Usually the deadline indicates when the work item should be completed (Russell, Van Der Aalst, et al., 2006). As a consequence, corresponding escalation procedures (e.g., notification of selected users about the expiration) are invoked (Reichert & Weber, 2012).

Thirdly, *resource unavailability* occurs when an attempt has been made to allocate a work item to a resource and the resource reports that it is unable to accept the allocation or the allocation cannot proceed (M. J. Adams et al., 2007). An example of a resource are human actors (Reichert & Weber, 2012). It is often the case that a work item requires access to one or more data resources during its execution. If these are not available to the work item at initiation, then it is usually not possible for the work item to proceed (Russell, Van Der Aalst, et al., 2006).

Exception that are *externally triggered* occur because of an occurrence outside of the process instance that has an effect on the continuing execution of the process (M. J. Adams et al., 2007). It are discrepancies between the real-world and the computerized process (Reichert & Weber, 2012). External exceptions are activated by external events, explicitly notified to the workflow engine by agents or external applications (Casati, 1999). Triggers from sources external to a work item are often used as a means of signalling the occurrence of an event that impacts on the work item and requires some form of handling (Russell, Van Der Aalst, et al., 2006). Moreover, Mišić et al., (2010) state that exceptions based on resources are probably the exceptions that most frequently appear in a workflow.

A *constraint violation* event occurs when a data constraint has been violated for a work item during its execution (M. J. Adams et al., 2007). Violations of constraints over data, resources, or process model elements (e.g., activities) often raise exceptions; e.g., data required for activity execution might be missing (Reichert & Weber, 2012). An example is when the value of some parameter does not lie within a previously determined range (Mišić et al., 2010).

In additional to the above-mentioned exception types, three different ways of handling the workflow for an exception are identified in the literature. This includes what will be done with the products in the process, that still need execution. The first handling method is *continue workflow case*. The case can be continued, with no intervention occurring in the execution of any other work items (Russell, Van Der Aalst, et al., 2006). Reichert & Weber (2012) describe a handling pattern named 'immediate fixing', that deals with an exception immediately, because it is not possible to stop the execution of that particular case. Thus, the workflow case is continued. Secondly, *remove current case* from the workflow can be used as handling method. It removes the current work item; consequently the execution ends, and the work item is marked with a status of cancelled (M. J. Adams et al., 2007). Certain exceptions require cancelling process behaviour. This might include the cancelation of the entire process or of process parts (Reichert & Weber, 2012). Lastly, *all cases can be removed* from the workflow. This removes all case instances for the specification in which the work item is defined, or of which the case is an instance (M. J. Adams et al., 2007).

Three different recovery actions are identified in the literature. This means how to recover from the exception and restart the 'normal' process. First, there is a possibility to take *no action*. It ignores the exception of the node and continues to execute with the implementation result (Wu, 2009). The second option is a *rollback* procedure. If it cannot execute continually because of the state and data losing caused by exception, it should restart the process from the exception node or the pre-node (Wu, 2009). If a running sub-transaction fails, it can be rolled back (Reichert & Weber, 2012). The last option is to *compensate* the exception. This is similar to undoing already completed work (Reichert & Weber, 2012). In order to guarantee that the process will not be affected, the influence that has been generated should be eliminated. That is compensation operation. For simple process, it can be recovered to the environment before exception is occurred through one compensation operation. But for complex process, it may need several compensation operations to recover (Wu, 2009). When a step is unable to reach its goal, backward recovery is performed by compensating completed steps, typically in the reverse order of their forward execution, up to a point from which forward execution can be resumed along a different path (Casati, 1999). Lastly, after elaborate research, no appropriate information was found on the exception handling implementations specific for the manufacturing domain.

2.5 Unexpected Exceptions

Unexpected exceptions correspond to unpredicted situations for which the system cannot suggest any solutions. The paper by Mourão & Antunes (2005) distinguishes three functions in exception handling: *exception detection* (can be manual or automatic)*, situation diagnosis* (can be classified using the following dimensions: scope, way of detection, event type, impact, solution difficultness, reaction time and time frame to solution) *and exception recovery actions*.

WfMS is generally there to provide essential and effective support to BPM. However, many events, are generally not considered and, thus, not integrated in the definition of the workflow at design time. These kind of exceptions are known as unexpected exceptions (Derbali, 2011).

Unexpected exceptions refer to situations, unplanned at design-time, that may emerge when the process is running and can be detected only during the execution of a process instance, when a difference between the computerized version of the process and the corresponding real-world process occurs (Marrella, Mecella, & Sardiña, 2018). When an exception is detected, the system may first check the availability of a predefined exception handler, and if no handler was defined it can rely on an automated recovery process (Marrella & Mecella, 2018). The process designer often lacks the needed knowledge to model all the possible exceptions, or this knowledge can become obsolete as process instances are executed and evolve, by making useless its initial effort (Marrella et al., 2018).

Typical strategies applied when defining exception handlers for expected exceptions have been encountered with exception handling patterns. This means that for any given exception, a predefined explicit handling pattern is defined as a sequence of corrective actions to resolve the issue (Marrella et al., 2018). On the other hand, the handling of unanticipated exceptions does not assume the availability of predefined exception handlers and relies on the possibility of performing ad hoc changes over process instances at runtime (Marrella et al., 2018).

Adaptation to unexpected exception aims to handle the execution of a workflow when an unforeseen event occurs at run-time. Usually, this kind of adaptation requires human intervention by using their knowledge and skills. Unfortunately, these human interventions increase the cost of the management particularly in terms of time (Linden et al., 2013). When an unexpected exception occurs, mostly, the only available options are suspension while the exception is handled manually or termination of the case, but since most processes are long and complex, neither option presents a satisfactory solution (M. J. Adams et al., 2007). Since these exceptions have not been foreseen and modelled, both their detection and handling requires human intervention (Casati, 1999).

2.6 Chapter Conclusion

This chapter described the fundamentals of BPM, along with the different types of exceptions in combination with their sources. This was done to provide with an overview of the available information on the topic of this thesis. In conclusion, this research will focus on expected exceptions since these can be modelled and forecasts can be made hereupon. The findings of this chapter are used in the next chapter (Research Methodology) as a basis to provide with an overview of how each sub question was answered.

3 Research Methodology

3.1 Chapter Introduction

This chapter aims at clarifying the methodology. This was done based on a research methodology that will be described in the next paragraphs. Moreover, the setup of the interviews is described along with the selection criteria for the interviewees.

3.2 Research Questions and Research Approach

The main research question, which was derived from the problem statement, is:

How should generic models for describing and forecasting exceptions be designed to be used in a MES and how can it be implemented for a specific manufacturing process?

The term 'generic models' refers to the BPMN model for standardization of the exception handling process and a forecasting model, represented by an Excel tool. This aims to forecast the impact of the exceptions on KPI's.

In answering the main question, multiple sub questions were answered first. These questions, structured according to the steps provided by the Design Science Research Methodology (DSRM) by (Peffers, Tuunanen, & Rothenberger, 2008), guided through the project and together provided an answer to the main research question. The DSRM presented in this section incorporates principles, practices, and procedures required to carry out such research. The design science process included six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication (Figure 2).

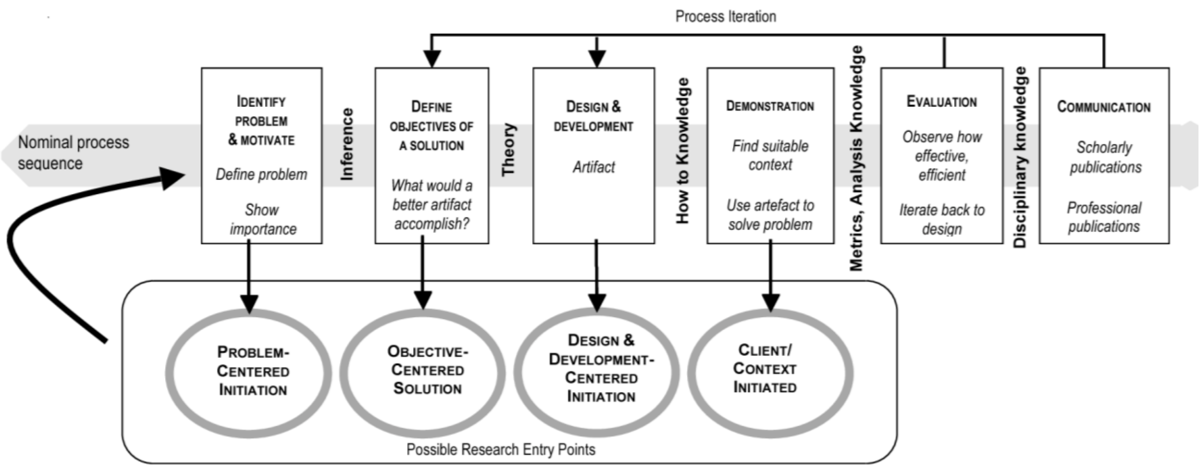

Figure 2. DSRM Process Model (Peffers et al., 2008)

In the DSRM by Peffers et al. (2008) there were four possible research entry points. The entry point for this project was the Objective-Centered Solution (Figure 2). This entry point is related to the objectives of a solution. This means that this entry point focussed on the fact that there was something that could be improved. The objective of this research was to realize better exception handling and forecasting in manufacturing processes. Atos saw possibilities of improved exception handling analysis and forecasting.

The DSRM Process model contained some steps, which are associated with research questions. These will be explained below.

Define objectives of a solution:

Q1: What kind of product, process and equipment exceptions can occur in a (smart) manufacturing domain and why do they occur?

Methodology used for answering this question:

The input for answering this research question were **literature** and **interviews**. Atos has identified, during the investigation stage, that exceptions occurring in a manufacturing environment were classified into product, process and equipment exceptions. However, literature classified exceptions according to other exception types (Appendix A). For example, Adams et al. (2007), Casati (1999), Lerner et al. (2010), Mišić et al. (2010), & Reichert & Weber, (2012) discuss work item failure, deadline expiry, resource unavailability, external trigger and constraint violation as exception types. Product, process and equipment exceptions were hardly found in literature. This meant that the interviews were used to connect the literature stated exception types into the classification of Atos.

Q2: What is the impact of the different types of exceptions on the process performance?

Methodology used for answering this question:

The input for answering this research question were **literature** and **interviews**. Atos has explained, during the investigation stage, that they aimed at ordering the exceptions according to their impact on KPI's. Since Atos stated that the Overall Equipment Effectiveness (OEE) KPI is an appropriate measure for analysing the performance of the equipment in a process, literature was used to identify and calculate the OEE. The article of Ahire & Relkar (2012) was an appropriate article that explained OEE in order to be able to calculate this at Atos. The interview was used to investigate other KPI's that could be used to determine the impact on the process, identify these KPI's and ask for appropriate data on calculating the KPI's.

Q3: How can the most important KPI's be forecasted with past data on exceptions?

Methodology used for answering this question:

The input for answering this research question were **literature** and **interviews**. Some questions in interviews were aimed at finding whether there was any existing measure for the forecasting of exceptions. If this was the case, this would have been the starting point. If not, their ideas on how to best forecast exceptions were used to create possible forecast exceptions methods. Literature also contains forecasting methods. These were examined to see whether they are usable in this setting.

Design and development:

Q4: How should generic models for describing and forecasting exceptions be designed in a Manufacturing Execution System (MES)?

Methodology used for answering this question:

The input for answering this research question were **literature** and **interviews**. In the end, this generic model was generated. As a start, literature was used, with the most important article being Ahire & Relkar (2012). This article discusses the connection of Failure Mode Effect Analysis (FMEA) with OEE. FMEA is often used at Atos and at clients. Interviews were used to verify the model generated based on literature.

Demonstration:

Q5: Can the generic models for exception handling be applied in practice for a specific manufacturing process?

Methodology used for answering this question:

The input for answering this research question was **interviews**. It was important to get an understanding of the necessities of the model to be put in practice. Therefore, some interview questions were focused on getting an understanding of the basic prerequisites for the model in order to be used in practice at Atos' clients. Their expertise was used in order to get to know how this model can be used in different settings, since they are already using models for different topics at their clients.

Evaluation:

Q6: How can the implementation of the model result in a successful exception handling procedure for a (smart) manufacturing company?

Methodology used for answering this question:

The input for answering this research question were **interviews** and **literature**. Literature was used in order to search for best practices. The opinion of experts at Atos was used in order to investigate what necessities the model should contain in order to be sustainable usable in the future.

3.3 Research Scope

The plan of doing analysis at Atos and its clients was identified as the following and in the following order (Table 2). However this table does not combine the actions with the research questions. This will be done in Figure 3.

Interviews with experts	Questions that can be asked. • What exceptions occur frequently? • For each type of exception, what is the loss in time? Or is it different. • What resources lose time to the exception? (e.g. machine, worker, etc.) • What is, in your opinion, the biggest bottleneck in the process?
Calculate KPI's	For example, use KPI: OEE = Availability * Performance * Quality Able to check which part (availability, performance or quality) scores the lowest. This is done for other KPI's as well.
Prototype in Excel	A prototype was made in Excel that use realistic data in order to show how the prototype works: the Excel sheets calculate the most important KPI's, based on input parameters (e.g. which product are you going to produce and which machine are you going to use). Forecasts are added, that should be based on past data of the clients of Atos, but the Excel file now includes other representative data, since Atos clients will not distribute their data to others outside the organisation.
Forecasts	Real forecasts can only be made under certain conditions; the specific data should be available at Atos' clients and enough data should be available. Again, the forecasts are based on realistic data. However, Atos can fill in the real data of their customers when they are going to use this Excel in practice.

Table 2. Action Plan

Research sub questions	Input	Output
1: *What kind of product, process and equipment exceptions can occur in a (smart) manufacturing domain and why do they occur?*	1. Find literature on possible exceptions. 2. Interview: Exceptions found in literature need to be categorized in three categories identified by Atos (product, process and equipment).	**List:** The exceptions found in literature classified into the exception types stated by Atos
2: *What is the impact of the different types of exceptions on the process performance?*	1. Sub question 1: Focus on exception types 2. Search for literature on KPI's in relation to exceptions 3. Interview: Identify important KPI's used in relation to exceptions identified.	**Excel file:** Identify most important KPI's regarding the exception types and the corresponding calculations and input parameters needed.
3: *How can the most important KPI's be forecasted with past data on exceptions?*	1. Sub question 2: Use the identified KPI's. 2. Interview: Ask for already used methods of forecasting and ask for appropriate data. 3. Find literature on forecasting methods.	**Excel file:** Calculate with realistic forecasting data the impact on KPI's (identified in sub question2).
4: *How should generic models for describing and forecasting exceptions be designed in a Manufacturing Execution System (MES)?*	1. Literature: starting point on making the model based on relevant literature. 2. Interview: The starting point of the model is discussed during the interview to get feedback and make necessary improvements.	**A model:** Develop a BPMN model that acts as a blueprint for the standardization of the exception handling process.
5: *Can the generic models for exception handling be applied in practice for a specific manufacturing process?*	1. Sub question 4: Input is the model. 2. Interview: Ask questions whether the model could be applied in practice at Atos' clients and what is needed to align systems	**Text:** Elaborate on requirement for applicability.
6: *How can the implementation of the model result in a successful exception handling procedure for a (smart) manufacturing company?*	1. Sub question 5: The applicability should be tested before implementing. 2. Literature: Search for critical success factors for implementation. 3. Interview: Complete list of critical success factors and specify it to specific setting.	**List:** Critical success factors was used to create a **table** with implementation plan.

Figure 3. Sub questions input and output

The aim of this research is to deliver a framework for Atos in order to be used at the clients and assist in appropriate exception handling.

3.4 Literature Search

The input of the sub questions were literature and interviews. The literature study of Hommen (2020), in combination with further research on specific topics, was used as an input for retrieving appropriate articles. The query used in the literature review (Hommen 2020) incorporated exception handling in business process management as search terms. The search (exception handling in BPM domain) consist of three different parts, in the following order.

- The first part of the query is 'exception handling' and all relevant synonyms of this term.
- The second part combines the first part with an 'AND' split: it consists of 'business process management' and all relevant synonyms of this term, such as edBPM.
- The third part combines the first part with an 'AND' split: it consists of 'alert' and all relevant synonyms of this term.

This search provided valuable input for the different types of exceptions that can occur, which refers to sub question 1. However, other sub questions need input from research as well. The results of the literature review (Hommen, 2020) did not provide enough information for answering sub questions 2,3,4 & 6. Some information was still missing, e.g. articles on forecasting, BPMN models and critical success factors. The following search terms were used to find appropriate articles on the other sub questions in Scopus.

The search of sub question 2 consists of the search terms:

- The first part of the query is 'product exceptions' and all relevant synonyms of this term.
- The second part combines the first part with an 'OR' split: it consists of 'process exceptions' and all relevant synonyms of this term.
- The third part combines the first two parts with an 'OR' split: it consists of 'equipment exceptions' and all relevant synonyms of this term.
- The last part combines the other parts with an 'AND' split: it consists of 'KPI's' and all relevant synonyms.

The search of sub question 3 consists of the search terms:

- The first part of the query is 'forecasting' and all relevant synonyms of this term.
- The second part combines the first part with an 'AND' split: it consists of 'exceptions' and all synonyms of this term.
- The third part combines the second part with an 'OR' split: it consists of 'business process management' and all relevant synonyms of this term.

The search of sub question 4 consists of the search terms:

- The first part of the query is 'model' and all relevant synonyms of this term.
- The second part combines the first part with an 'AND' split: it consists of 'exception Handling' and all synonyms of this term.
- The third part combines the second part with an 'AND' split: it consists of 'information system' and all relevant synonyms (e.g. MES) of this term.

Sub question 5 did not need any input from literature.

The search of sub question 6 consists of the search terms:

- The first part of the query is 'critical success factors' and all relevant synonyms of this term.
- The second part combines the first part with an 'AND' split: is consists of 'implementation' and all relevant synonyms of this term.
- The third part combines the second part with an 'AND' split: it consists of 'BPMN model' and all relevant synonyms of this term.

All sub questions that needed input from literature were to be found in scientific databases.

3.5 Interview

3.5.1 Interview Type

To obtain expert knowledge, information of specialists needs to be gained. There are different methods to gain this information. One option is using identical, closed ended questions. This reflects a highly structured survey, typically with large samples. The second option is a focus group, which engages fewer people for a much longer period (approximately two hours). This focus groups consist of open-ended questions with the aim to collect data, through interactive and directed discussions by the researcher. The third possibility is to conduct semi-structured interviews. This type of interview is conducted with one respondent at a time in a conversational manner. Defined questions will often be followed by why or how questions. The ongoing dialogue can therefore be in specific directions as well as leaving room for the respondent to address unforeseen issues (W. C. Adams, 2015). One hour is considered a reasonable maximum length for semi-structured interviews in order to minimize fatigue for both the interviewer and respondent (W. C. Adams, 2015).

In this project, semi-structured interviews were used to obtain this information form experts in the field. This way of interviewing is particularly useful when multiple open-ended interview require follow-up queries. Semi-structured interviews are labour intensive but a lot of information and insights was gained from the experts.

A focus group is not used since the optimum is ten to twelve per session for a longer period. Closed-ended questions are also not used since the interactive effect is of extreme importance in this setting, to obtain valuable and usable knowledge.

3.5.2 Selection Criteria

The interviews were held with different experts in the field. These participants needed to be selected beforehand. One important criterion for selection was that the expert has knowledge about one of the three types of exceptions (process, product or equipment). The second selection criterion was that every type of exception (process, product or equipment) was represented by at least one expert working in the field of that type of exception. The last selection criterion was that the interviewees should be from different companies, since all companies have different systems and methods of working and the model developed aimed to be flexible and used for different clients. The interviewees were found by contacting clients and employees of Atos.

3.5.3 Interview Recording

Another valuable addition that is recording the interview, if permission is granted. This allowed for a more active engagement by the interviewer, because the next question can be thought of instead of having to concentrate on writing down answers. Between-whiles, it can be constructive to restate concisely in one or two sentences, using mainly the respondent's own words, what was just said. This technique of active listening reinforces that the interviewer is indeed intently interested (W. C. Adams, 2015).

3.5.4 Interview Questions

Since a lot had to be answered by interview questions, the interview was discussed beforehand with the supervisor of Atos. This resulted in a list of questions which can be seen in Appendix B. All sub questions were answered by this interview. Therefore, the same initial questions were asked to each interviewee. However, during the interview, the interviewer anticipated to the provided answers to start discussion on the topics.

3.6 Chapter Conclusion

In this chapter the methodology based in the DSRM is described. Moreover, the setup of the interviews was described along with the selection criteria for the interviewees. With this methodology the research questions were answered, which is elaborated in the next chapters.

4 Result: Type of Exceptions

4.1 Chapter Introduction

The chapter will start with a short description on the interview participants. After this, the descriptions of the exceptions provided by chapter 2 are partly re-used, in order to give clarity on these descriptions before starting to discuss the results of the interview. After providing the descriptions on the exceptions, this chapter will elaborate on the outcomes of the interviews regarding the classification of the exceptions into the corresponding exception types. This chapter will answer sub question 1.

4.2 Interview Participants

Ideally experts on manufacturing processes as well as operators would have been interviewed. Due to the manufacturing site closing as a result of COVID-19, only experts were interviewed, since it was not possible to interview the people that fulfil an operating role on the work floor. The interviews were held after the concept process model was designed. This made it possible to ask questions for answering the sub questions and get insights in the current version of the process model, in order to make it perfectly suitable to the operations. To be more specific, the first page of questions (Appendix B) were asked before the concept process model was shown to get their fresh thoughts on the subject without pushing them in one direction. After this phase, the (concept) process model was shown and the last page of questions were related to this process model. Hereafter follows a list of the interviewees.

- The first participant of the interview was a senior MES consultant from Atos, currently based at Philips. His expertise is in the field of product exceptions, which makes it interesting to get insight in his expertise of product exceptions in the field.
- The second participant of the interview was a manufacturing engineer from DAF. His main interest is in equipment exceptions and the KPI; OEE. He is a project leader specialized in equipment exceptions.
- The third participant was a Senior MES consultant from Atos, currently based at DAF. He has knowledge in several areas, including process exceptions. He is the developer of the Method for MES (M4MES) methodology that Atos used to start the discussion with its client on how the MES should be developed.
- The fourth participant is an FPU expert at MSD. His expertise is in the field of process exceptions.
- The fifth participant is an expert Central Filling and Freeze Drying (CFFD) at MSD.

4.3 Exceptions in Literature

The first sub question; *What kind of product, process and equipment exceptions can occur in a (smart) manufacturing domain and why do they occur?* will be answered in the next sections.

First, a literature study was conducted in order to get a complete understanding of the current exceptions identified in literature. The focus is on expected exceptions since these can be modelled. After identifying the expected exceptions stated in literature, interviews are used in order to be able to convert them into the exception types stated at Atos. This means that the same exceptions will be used as identified in literature, since these are stated to be complete, however they will be used in a different framework, to make the outcomes usable by Atos.

Work item failure: From a process perspective, critical exceptions often occur during activity execution (Reichert & Weber, 2012). Work item failure during the execution of a workflow process is generally characterised by the inability of the work item to progress any further. This may manifest itself in several possible forms including an abort initiated by the user of the executing program, the failure of a hardware, software or network component associated with the work item. Where the reason for this failure is not captured and dealt within the process model, it needs to be handled elsewhere in order to ensure that both later work items and the process continue to behave correctly (Russell, van der Aalst, et al., 2006). Workflow exceptions are raised in correspondence of the start or completion of tasks and workflow instances and are therefore synchronous with the progression of the workflow (Casati, 1999).

Deadline expiry: A timeout event occurs when a work item reaches a set deadline (M. J. Adams et al., 2007) and is raised at the occurrence of a given timestamp (Casati, 1999). Thus, this type of exception can be detected by measuring time (Mišić et al., 2010). It is common to specify a deadline for a work item in a workflow process model. Usually the deadline indicates when the work item should be completed (Russell, van der Aalst, et al., 2006). Consequently, corresponding escalation procedures (e.g., notification of selected users about the expiration) are invoked (Reichert & Weber, 2012).

Resource unavailability: This event occurs when an attempt has been made to allocate a work item to a resource and the resource reports that it is unable to accept the allocation or the allocation cannot proceed (M. J. Adams et al., 2007). An example of a resource are human actors (Reichert & Weber, 2012). It is often the case that a work item requires access to one or more data resources during its execution. If these are not available to the work item at initiation, then it is usually not possible for the work item to proceed (Russell, van der Aalst, et al., 2006).

External trigger: Externally triggered exceptions occur because of an occurrence outside of the process instance that influences the continuing execution of the process (M. J. Adams et al., 2007). They are discrepancies between the real-world and the computerized process (Reichert & Weber, 2012). External exceptions are activated by external events, explicitly notified to the workflow engine by agents or external applications (Casati, 1999). Triggers from sources external to a work item are often used as a means of signalling the occurrence of an event that impacts on the work item and requires some form of handling (Russell, van der Aalst, et al., 2006). Moreover, Mišić et al. (2010) state that exceptions based on resources are probably the exceptions that most frequently appear in a workflow.

Constraint violation: This event occurs when a data constraint has been violated for a work item during its execution (M. J. Adams et al., 2007). Violations of constraints over data, resources, or process model elements (e.g., activities) often raise exceptions; e.g., data required for activity execution might be missing (Reichert & Weber, 2012). An example is when the value of some parameter does not lie within a previously determined range (Mišić et al., 2010).

4.4 Product, Process and Equipment Exceptions

The next step was to convert these types of exceptions in the framework of Atos. Atos uses the classification of product, process and equipment type of exceptions and the interviews were also done with specialists in these three exception types. They categorize their exceptions into these three types since the corresponding KPI's that are used at clients are also classified into these three categories. Moreover, Atos has specialists in product exceptions and specialists in the equipment and product exceptions. Therefore, some employees know much about product, while others know everything about equipment types.

The interviews with the Senior MES consultant in product exceptions, the Senior MES Consultant in process exceptions and the Manufacturing Engineer in Equipment exceptions resulted in the conclusion elaborated in the next paragraphs.

As identified during the interview with the Senior MES Consultant in Product Exceptions; Constraint Violation, Deadline Expiry, Work Item Failure and External Trigger were classified as this type of exception. Constraint Violation occurs very often, since items often not conform to stated requirements, due to different reasons. A deadline expiry exception also occurs very often. It can occur that the resource or raw material remains unused for too long, resulting in resources that cannot be used anymore and losses of stock for the product. Work Item Failure is also classified as a product type of exception when the product cannot proceed in the process. For example, an abort initiated by the user of the executing program for various reasons. External Trigger is also included in the product type of exception. An example of this type of exception for product type could be that there is something wrong with one upstream product and therefore, the other products are checked as well. This was all stated by the Senior MES Consultant in Product Exceptions.

As identified during the interview with the Manufacturing Engineer in Equipment Exceptions; Constraint Violation, Resource Unavailability, Work Item Failure and External Trigger were classified as this type of exception. A Constraint Violation can occur when a machine tool has wear (should be replaced by a new one) and the product deviates more and more from its values. Resource unavailability happens when some material, machines or operators is unavailable. Therefore, it can be classified in equipment type of exception. Work Item Failure was identified as a product and equipment type of exception: it results in equipment type exceptions when there is a failure of a hardware, software or network component associated with the work item. Lastly, an External Trigger related to equipment exceptions could be that a machine upstream in the process has problems meaning that the current machine should wait and cannot do its work anymore.

As identified during the interview with the Senior MES Consultant in Process Exceptions; Constraint Violation is the main reason for process exceptions. As identified, Constraint violation exceptions occur very often, indicating that a product does not conform to the required standards. These standards are often set by the client.

This is summarized in Table 3 on the next page.

Literature exceptions	Classification from interview	Additional explanation from interview:
Work item failure	Product and equipment	The product in operation is classified as the work item. There could be different reasons why the product cannot proceed in the process; an abort initiated by the user of the executing program for various reasons. However, it results in equipment type exceptions when there is a failure of a hardware, software or network component associated with the work item.
Deadline expiry	Product	Deadline expiry exceptions occur very often. It can occur that the resource or raw material remains unused for too long, resulting in resources that cannot be used anymore and losses of stock for the product.
Resource unavailability	Equipment	Resource unavailability contains the unavailability of some material, machines or operators. Within Atos' clients, all these unavailability's occur. Therefore, it can be classified in equipment and process type.
External trigger	Equipment and Product	This contains any discrepancies between the real-world and the computerized process. It is related to equipment exceptions when a machine upstream in the process has problems meaning that the current machine should wait and cannot do its work anymore. An example related to the product type of exception is that there is something wrong with one upstream product and therefore, the other products are checked as well. It can happen due to various other reasons but is always classified in the equipment and product type.
Constraint violation	Equipment, Process and Product	Constraint violation exceptions occur very often, indicating that a product does not conform to the required standards. For example, the test results can be between 7 and 10 while a result of 10,5 could be ok as well. However, this must be discussed with the operator. On the other hand, constraint violations also occur because then the machine has wear and the product deviates more and more from its values.

Table 3. Summary Exception Classification

4.5 Chapter Conclusion

The five exception types (work item failure, constraint violation, resource unavailability, external trigger and deadline expiry) were classified into the exception types stated by Atos (product, process and equipment). Different reasons were given in interviews for the occurrence of these exceptions, e.g. an abort initiated by the user of the executing program, failure of a hardware, software or network component associated with the work item or the raw material remains unused for too long. Other examples were the unavailability of some material, machines or operators and lastly, the equipment could be worn out and should be replaced by a new tool. Based on these examples in interviews, Table 3 provides insight in the classification of these exceptions. The product, process and equipment exceptions will be used as input for the calculation of the impact of these exceptions. This will be elaborated upon in the next chapter.

5 Result: KPI Forecast Excel

5.1 Chapter Introduction

In this chapter the Class diagram that was created and used to build the Excel file is shown and explained. Moreover, the Excel file that contains the calculations and forecasts of different KPI's is elaborated. This chapter will answer sub question 2 & 3.

5.2 Class Diagram

In this section the data that is used for the process model and for forecasting the impact of the exceptions on the process performance is shown. The Class diagram (Figure 4) visualises how different data is linked. This data model is created in cooperation with a senior consultant in MES specialised in process exceptions working at Atos and is checked with the participants in the interviews.

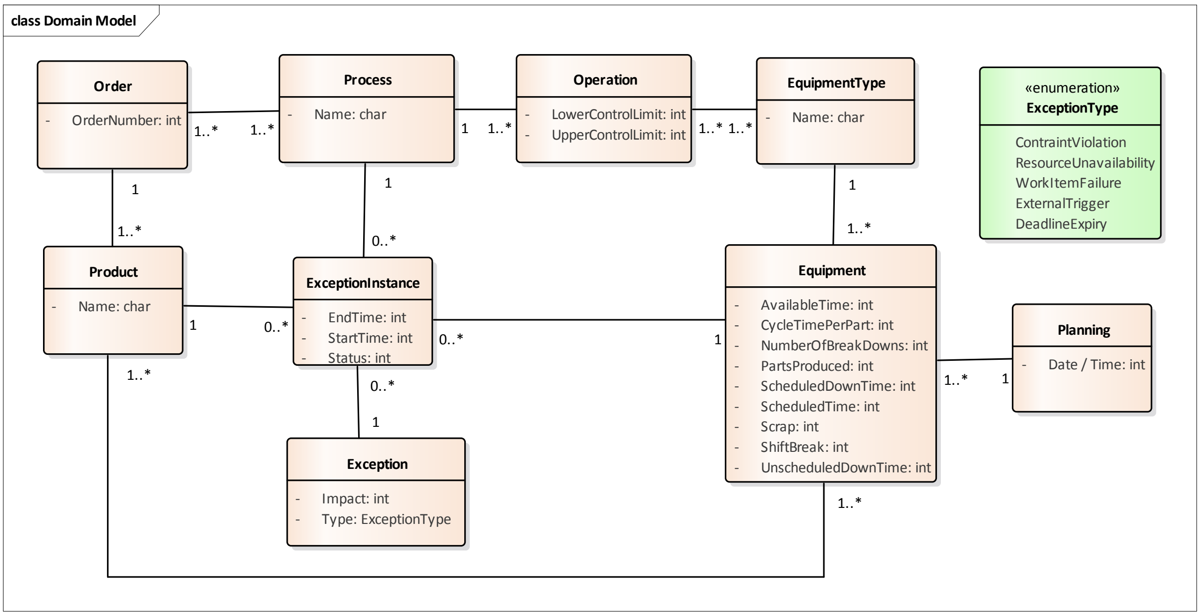

Figure 4. Class Diagram

In Figure 4 the class diagram shows that an *Order* is connected to one or more *Processes*. For simplicity and the possibility to expand according to the wishes of the client, the order contains only *OrderNumber* as attribute. The same holds for *Process*, which has *Name* as attribute. *Process* is connected to *Operation*, which consists of the control limits. An *Operation* is performed by a specific *EquipmentType*. The actual *Equipment* will perform the action and is scheduled according to the *Planning*. *Equipment* holds the different attributes that are recorded and used in the Excel file that will be discussed in the next chapter.

The *ExceptionInstance* is connected to *Equipment*, *Process*, *Product and Exception*. *Exception* contains an attribute that holds the different types of exceptions. *ExceptionInstances* can occur to the *Equipment*, *Process* or *Product*. *Equipment* is linked to *Product*, since a product is always made by a specific equipment.

The next step is using KPI's to show the impact of exceptions on the performance of the process. The data model that was described in this section was as a data structure for the Excel file that is introduced in the next section.

5.3 Impact of Expected Exceptions

Since sub question 1 classified the expected exceptions into the corresponding exception types, sub question 2 *(What is the impact of the different types of exceptions on the process performance?)* and sub question 3 (*How can the most important KPI's be forecasted with past data on exceptions?)* will be answered in this section.

The first step is to identify, for each exception type, a KPI that is (most) relevant. This was done by means of the interviews since the literature search did not provide valuable results on KPI's for this specific types of exceptions. This means that literature was used to give a definition and elaborate on the most important KPI's, instead of searching for the most important KPI. These were provided by interviews. The following question was asked during the interview to answer sub question 2; *Is the impact of exceptions on the production process measured? If so, how? If not, what are the main KPIs and how can they be linked to each other?*

A Key Performance Indicator (KPI) is used at multiple levels of an organization and implements the strategic objectives and it is an evaluation index of the core events (Pan & Wei, 2012). It is a measurable value that demonstrates how effectively a company is achieving key business objectives. In production processes, the KPI's indicate how efficient the process is; efficient processes mean less downtime.

The second step is to show the impact of exceptions on the different KPI's. This will be done in Excel since this has the ability to clearly show the different data needed, the calculations made and the outcomes in graphs.

Lastly, some forecasts will be made based on realistic data which represent past data of different parameters. This will all be clearly described in the following sections.

Figure 5 describes the moments in time the different exceptions are measured. Process exceptions are measured after each modification of the product. It checks whether the product still confirms to the requirements of the clients. Equipment exceptions focus on the downtime and scrap resulting from equipment performance. Last of all, the product exceptions focus on the final product.

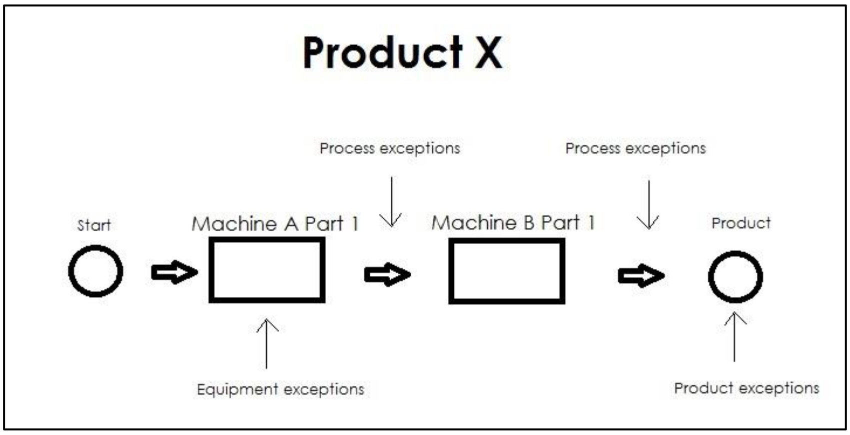

Figure 5. Exception measurement overview

5.3.1 General Translation into Excel File

However, some input parameters need to be filled in by the user. This is shown in Figure 6. These input parameters will be used for the all exception types. In Figure 7, Figure 8 and Figure 9, the corresponding input values can be found that need to be filled in in Figure 6. For example, for

'Operations name' one should fill in A or B (Figure 7) and then the calculations will be based on the corresponding values of the specific operation.

Yellow columns to be filled in	
Operations name (see 'Operation')	A
Which product? (see 'Product')	1
Number of units at start of the process	400
Specifically for equipment exceptions	
Machine/Part? (see 'Machine / Part')	1
Scheduled time? (in minutes)	2000
Scheduled downtime?	180

Figure 6. Input parameters

Operation ↓	USL	LSL	AVERAGE	STANDARD DEVIATION
A	16	4	9,779	2,407
B	12	6	8,920	1,502

Figure 7. Operations

Product ↓	Machine/part I	Machine/part II
1	1	2
2	1	3
3	2	3

Figure 8. Product types

Machine / Part ↓	Machine/part	Cycle time per part (in minutes)	Scrap	Time needed to produce
1	Machine A Part 1	3,00	50,00	20,00
2	Machine A Part 2	3,00	25,00	20,00
3	Machine B Part 1	5,00	11,00	33,33
4	…			
5	…			

Figure 9. Machine / Part combination

As to be seen in Figure 9, the list of machine / part combinations is extendible by the user. The data is shown as an example and gives an indication of what the sheets should look like with real time data. Due to COVID-19, it was not possible to visit factory floors and work with real time data. However, interviewees have provided feedback and tested the Excel in order to make sure that it will be useable when they visit clients.

5.3.2 Equipment Exceptions

5.3.2.1 Identification of the most important KPI

First, the manufacturing engineer specialized in Equipment Exceptions identified **OEE** as the most important KPI regarding the **equipment exceptions.** Since Atos uses this KPI and the interviewee agrees that this is a good measure for the equipment type, this KPI will be used to calculate the impact of the exception on the process performance.

In the next paragraphs, the OEE will be elaborated first, following the calculation (in an Excel sheet) with the impact of the exceptions on the process performance and the forecast.

5.3.2.2 Description of this KPI

Nakajima (1988) provided a quantitative metric called Overall Equipment Effectiveness (OEE) for measuring productivity of individual equipment in a manufacturing environment. The OEE is described by means of the following formulae:

$$OEE = Availability\ (A) * Performance\ (P) * Quality\ (Q)$$

$$A = \frac{actual\ production\ time}{available\ production\ time}$$

$$P = \frac{actual\ output}{expected\ output}$$

$$Q = \frac{good\ product}{actual\ output}$$

Availability takes into account unplanned and planned stops, for example. An availability score of 100% means the process is always running during planned production time. A reduced score can be caused by machine idle time, failures or line restraints. Setup time, no operator at machine or preventive maintenance are examples of idle time.

Performance takes into account reduced rated and slow cycles, for example. A Performance score of 100% means when the process is running, it is running as fast as possible. A reduced score can be caused by reduced speed of the machine or minor stoppages. Reduced speed is sometimes needed when the machine shows signs of wear.

Quality takes into account defects. A Quality score of 100% means there are no defects, only good parts are being produced. A reduced score can be caused by products on which rework needs to be performed or need to be scrapped.

OEE takes into account all losses that are above mentioned. An OEE score of 100% means you are manufacturing only good parts, as fast as possible, with no stop time. Therefore, the OEE should be as high as possible.

Since the OEE is described and the definition is set clear, the Excel file will be described in the following section. This is used to calculate the impact of the exceptions on process performance and make forecasts based on realistic data.

5.3.2.3 Translation into Excel file

Figure 10 shows the calculation of the OEE KPI. These values are calculated automatically after filling in the input parameters. Every machine/part combination corresponds to a cycle time per part and scrap, which will be filled in automatically after indicating the type of machine/part. Moreover, scheduled time will be copied from the input parameters (Figure 6). Scheduled downtime includes scheduled breaks and were also copied from the input parameters.

Four exceptions (resource unavailability, constraint violation, external trigger and work item failure) are identified for the equipment exception type which have an impact on the forecasted downtime.

5.3.2.4 Forecasts

Unplanned downtime (in minutes) should be forecasted by means of the type of exceptions occurring. Four types of exceptions could occur in the equipment exception process. These are work item failure, constraint violation, resource unavailability and external trigger. Excel contains another sheet with all data that is used to calculate the OEE. This data is, at this time, based on realistic ideas of interviewees.

However, Atos' clients should complete and constantly update the list of data in order to make appropriate forecasts. For example, Atos should add data on the percentage of unplanned downtime when each type of exception occurs. The average value of this data for each type of exception is included in Figure 11. This means that this is a forecast of the unplanned downtime based on past data.

$$unplanned\ downtime\ (in\ minutes) = Scheduled\ time * \frac{forecast\ downtime\ in\ \%}{100}$$

EQUIPMENT EXCEPTION PROCEDURE	
Which machine/part?	1
Scheduled time (in minutes)	2000
Scheduled downtime (in minutes)	180
Unplanned downtime (in minutes)	221
Available time (minutes)	1599
Parts produced	357
Cycle time per part (in minutes)	3
Scrap (count)	50
Good units	307
Units started	400
Availability	0,799
Performance	0,671
Quality	0,860
OEE	0,461

Figure 10. Equipment Exception Procedure

Moreover, Figure 11 shows that average downtime is highest for work item failure, meaning that this exception has the most impact at the moment.

	Exceptions	Forecast downtime (in % from scheduled time)
1	Work item failure	3,31
2	Constraint violation	2,96
3	Resource unavailability	2,87
4	External trigger	1,94

Figure 11. Downtime for exception types

The second forecast is done based on a machine / part combination. This is done because a machine can be used to make different kinds of parts. For each part the performance of the machine may differ due to a different process. In Figure 12 the numbers can be seen. These values are used in the calculation for 'parts produced' (Figure 10).

$$Parts\ produced = Units\ at\ start\ of\ process * \frac{forecast\ parts\ producted}{100}$$

	Machine/part	Forecast parts produced (in % from ideally produced)
1	Machine A Part 1	89,35
2	Machine A Part 2	89,94
3	Machine B Part 1	88,49

Figure 12. Machine / Part forecast performance

5.3.2.5 How to use it

In Figure 13 the final metrics of the of OEE can be seen. These numbers are calculated based on all the explanations that were given. By entering different input parameters, or using different data, the equipment performance will differ.

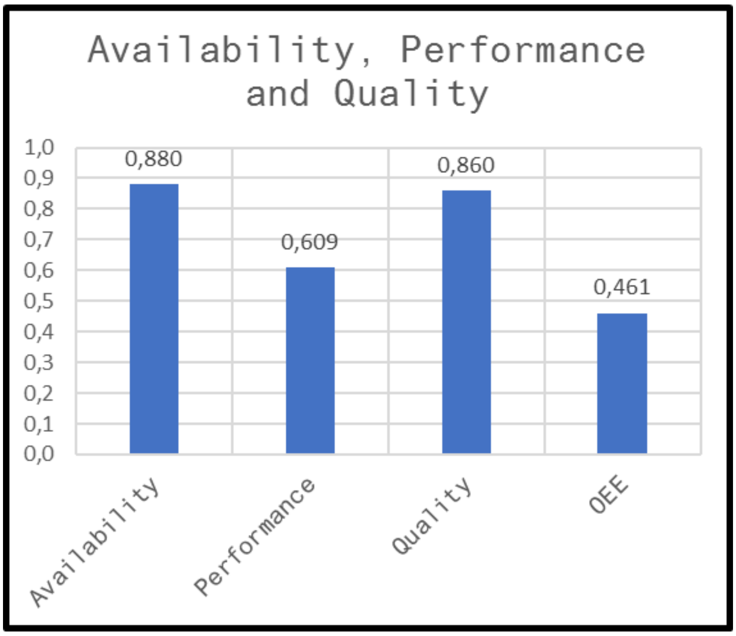

Figure 13. OEE visualisation

5.3.3 Process Exceptions

5.3.3.1 Identification of the most important KPI

According to the interviews, the most important KPI's of the **process exceptions** are**: C_p and C_{pk}.**

C_p and C_{pk} belong to the so-called Process Capability Indices (PCIs). These are numerical measures that assess whether the performance of the process in relation to its set limits is sufficient.

5.3.3.2 Description of this KPI

The C_p index focuses on the overall process variability relative to the manufacturing tolerance as a measure of process precision (or product consistency). C_p is simpler and cannot provide an assessment of process centering, while C_{pk} takes both the magnitude of process variance and the process departure from the midpoint into account.

To give a more clear feeling of C_{pk}, the next example is given (provided by iSixSigma-Editorial (2020)):

"Consider a car and a garage. The garage defines the specification limits; the car defines the output of the process. If the car is only a little bit smaller than the garage, you had better park it right in the middle of the garage (centre of the specification) if you want to get all of the car in the garage. If the car is wider than the garage, it does not matter if you have it centred; it will not fit. If the car is a lot smaller than the garage (Six Sigma process), it doesn't matter if you park it exactly in the middle; it will fit and you have plenty of room on either side. If you have a process that is in control and with little variation, you should be able to park the car easily within the garage and thus meet customer requirements. C_{pk} tells you the relationship between the size of the car, the size of the garage and how far away from the middle of the garage you parked the car. The value itself can be thought of the amount the car can widen before hitting the nearest limit (garage door edge)" (iSixSigma-Editorial, 2020).

C_{pk} =1/2: you are outside the specification limit

C_{pk} =1: you are just inside the specification limits

C_{pk} =2: you are inside the specification limits

C_{pk} =3 you are far inside the specification limits (meaning your width can grow 3 times before touching the limits)

C_p and C_{pk} are considered short-term potential capability measures for a process. C_p and C_{pk} are called Process Capability and are calculated as the following:

$$Cp = \frac{USL - LSL}{6 * \sigma}$$

$$Cpk = \min\left[\frac{USL - X_{mean}}{3 * \sigma}; \frac{X_{mean} - LSL}{3 * \sigma}\right]$$

Upper Specification Limit (USL) is the upper limit for process performance (measured by the product specifications).
Lower Specification Limit (LSL) is the lower limit for process performance (measured by the product specifications).
X_{mean} is the average of the process specifications.
σ is the standard deviation of this specifications.

5.3.3.3 Translation into Excel file

For the process exception, one type of exception was identified in literature: **constraint violation**. Therefore, all these deviations in the process exception type will be assigned to constraint violation.

5.3.3.4 Forecast

In Figure 14 the calculation of the C_p and C_{pk} is shown. These can be forecasted based on historical data on process specifications. The user can fill in the operation for which the calculation needs to be done. The USL and LSL are specified for a specific operation and are defined by the client. The average and standard deviation are calculated from past data and used to provide with values for Cp and Cpk.

PROCESS EXCEPTION PROCEDURE	
Operation name	A
USL	16,000
LSL	4,000
Average	9,779
Standard deviation	2,407
Cp	0,831
Cpk	4,991

Figure 14. Process Exception Procedure

5.3.3.5 How to use it

In Figure 15 the final metrics of the of C_p and C_{pk} can be seen. These numbers are calculated based on the explanations that were given. By entering different input parameters, or using different data, the process performance will differ. This process performance is only dependent on the USL and LSL of the client, the average and standard deviation on past data on process specifications.

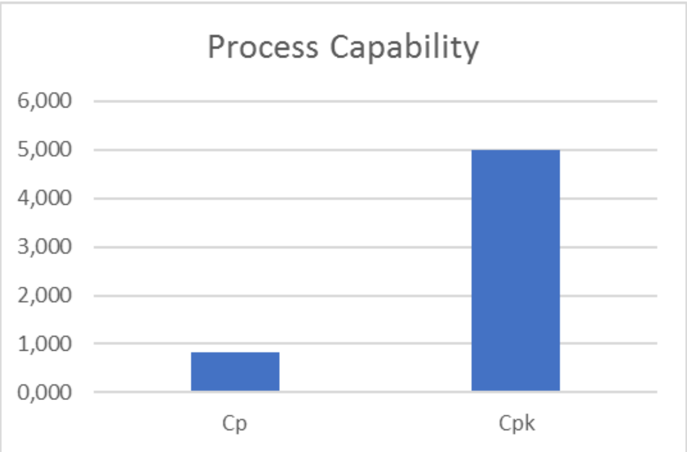

Figure 15. Process Capability visualisation

5.3.4 Product Exceptions

5.3.4.1 Identification of the most important KPI

Third and last, the Senior MES Consultant specialized in Process Exceptions identified **First Time Yield** (FTY) as the most important KPI currently using regarding the **product exceptions.** Since Atos uses this KPI and the interviewee again agrees that this is a good measure for the product type, this KPI will be used to calculate the impact of the exception on the process. The different exceptions identified as being part of the product exception type (Work Item Failure; Constraint Violation & Deadline Expiry; in sub question 1) will also be included in the calculation. This means that for the product type of exception, it is to be seen what exception has most influence on the KPI; FTY.

5.3.4.2 Description of this KPI

FTY is defined as the number of units coming out of a process divided by the number of units going into that process over a specified period of time. Only good units with no rework or scrap are counted as good units.

$$FTY = \frac{\#\, units\ out\ of\ step}{\#\, units\ into\ step}$$

5.3.4.3 Translation into Excel file

Figure 16 shows the product exception procedure. It is important to start with the type of product and number of units at the start of the process. The type of product was identified at the input parameters. Each type of product corresponds to some machine/part combinations. For example: In order to be able to make a bike, the chassis should be manufactured at machine A and part A is used as input for this machine (a resource) in order to develop the chassis. The second step is to attach the tires to the chassis. This is done at machine B with part A. This machine part combinations correspond to a certain product. All these machine/part combinations were identified in the equipment exception procedure and correspond to some scrap. This scrap was subtracted from the number of units at the start of the process. This parameter was also identified with the input parameters. The last step is to subtract some deadline expiry scrap and scrap based on the process specifications. This is forecasting and will be explained in the following section.

5.3.4.4 Forecasts

The process specifications are identified by the client (LSL and USL as identified in the last section). If the process specifications (based on past data) do not conform to the stated requirements (LSL and USL), they cannot be used anymore. Therefore, the amount of specifications outside these limits is identified as 'Scrap'.

PRODUCT EXCEPTION PROCEDURE	
Which product?	1
Number of units at the start of the process	400
Machine/part combination I	1
Machine/part combination II	2
Total scrap machine/parts	75
Deadline Expiry Scrap (%)	1,947
Scrap	2
Number of units at the end of the process	315
First time yield	**0,788**

Figure 16. Product Exception Procedure

Deadline expiry is also forecasted by means of data on percentages that a certain product falls short on deadline expiry. This means that it will also be identified as scrap. Number of units at the end of the process was the last parameter to be determined in order to be able to calculate the First Time Yield. This will be calculated as a following.

$$\begin{aligned} &Number\ of\ units\ at\ the\ end\ of\ the\ process \\ &\quad = number\ of\ units\ at\ the\ start\ of\ the\ process \\ &\quad - total\ scrap\ machine\ parts \\ &\quad - \frac{deadline\ expiry\ scrap\ \%}{100} * number\ of\ units\ at\ the\ start\ of\ the\ process \\ &\quad - Scrap \end{aligned}$$

5.3.4.5 How to use it

This means that there is some interaction with the other exception types (if Q is low in OEE calculation, the FTY will be affected too). Besides, the machine part combinations and the total scrap (identified by the equipment exception procedure) of these machine/part combinations is subtracted from the number of units at the start of the process. This covers the Work Item Failure, Constraint Violation and External Trigger since these are already included at the equipment exception level. There is one exception type that remains; Deadline Expiry. This is added based on forecasts.

The scrap identified by the LSL and USL in combination with data on process specifications is also incorporated. Eventually, by filling in the input parameters, the FTY (Figure 17) will be calculated automatically.

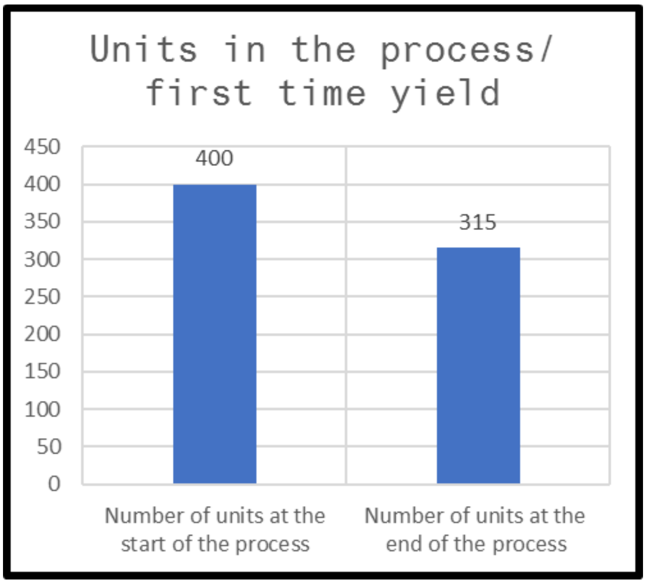

Figure 17. First Time Yield visualisation

5.4 Chapter Conclusion

In this chapter the Class diagram that was created and used to build the Excel file was shown and explained. Moreover, the Excel file that contains the calculations and forecasts of different KPI's was elaborated. In the next chapter the generic process model that uses these calculations is shown. In this process model the calculations are incorporated in some of the activities that are modelled.

6 Result: Process Model

6.1 Chapter Introduction

In this chapter the generic process model is shown. With this model Atos can provide its clients with a brief overview of what the exception handling process should include. The Excel calculations from the previous chapter are incorporated in some of the activities of the process models. This chapter will answer sub question 4.

6.2 Generic models for describing and forecasting exceptions

Sub question 4 will be answered in this section and was stated as the following: '*How should generic models for describing and forecasting exceptions be designed in a Manufacturing Execution System (MES)?*'

The literature search (described in section 3.4) provided an important article for the input of the model: Ahire & Relkar (2012). This article focused on FMEA. This will be combined with input by experts in the field (the interviews), a process model that can be used at Atos' clients as a starting point, is designed. This starting points means that they can adjust the model based on their specific requirements. It describes the activities for handling an exception that is related to the equipment, product or process.

In their research paper, Ahire & Relkar (2012) attempt to establish a relationship between OEE and FMEA. OEE is a performance measure metric and considers all important measures of productivity. By applying FMEA the root cause of any OEE measure can be found out. It will help to improve OEE and correspondingly productivity (Ahire & Relkar, 2012).

In Figure 18, the process model for handling the exceptions can be seen. The basis is the normal process execution. When an exception occurs, the system will examine what type of exception it concerns and what handling strategy will be performed (e.g. equipment, process, product). However, the first step in the process is 'Fill in Input Parameters'. This is done before the process is started. By filling out this sheet in Excel, the KPI's corresponding to the exception types are calculated by a forecast. If the user is satisfied with this score on KPI's, the normal process execution with possible exceptions can start. If the user is not satisfied with the forecasted scores on the KPI's, input parameters can be adjusted (e.g. schedule less planned downtime, discuss with the client on adjusting LSL and USL etc.). After being satisfied by the scores on the KPI's, the process can start.

This process model has a simplified view because there are several collapsed activities. The name of the activity corresponds with the name of each figure. In the following figures these activities are shown.

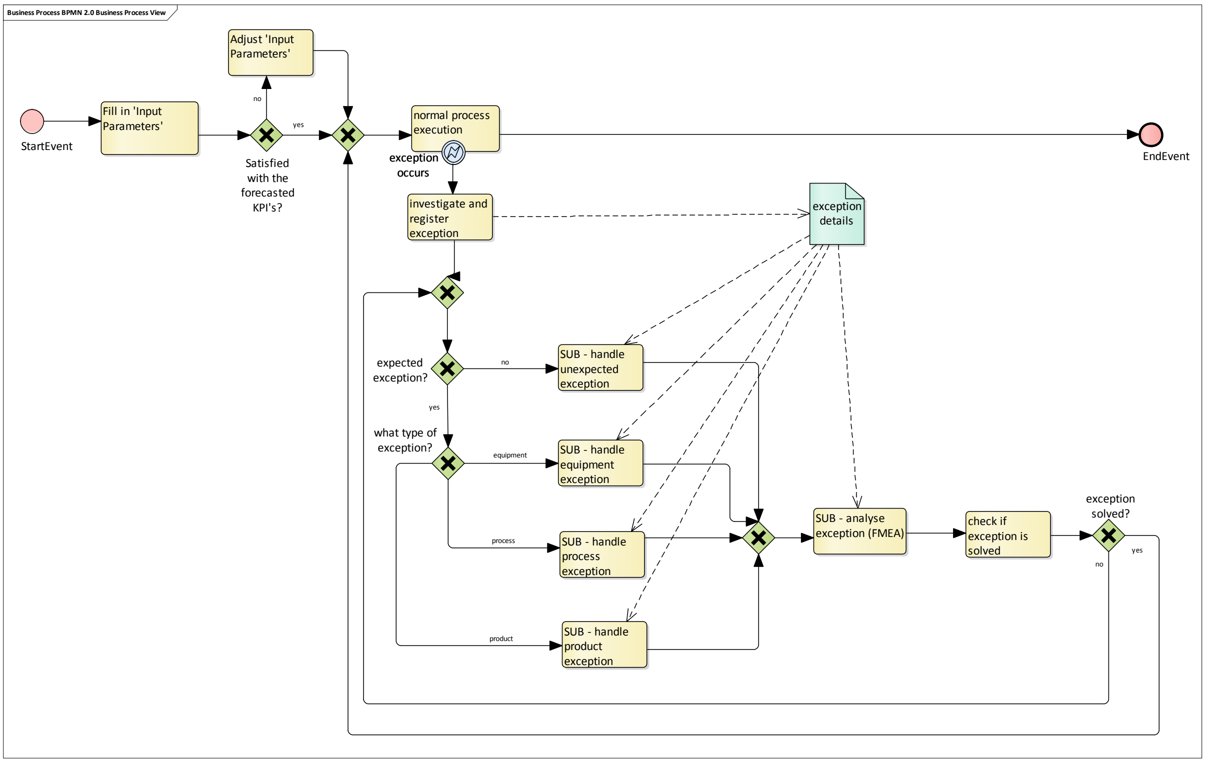

Figure 18. Exception process model

Starting with Figure 19, the FMEA activities are elaborated. In Figure 20 the equipment exception procedure is shown. If an exception occurs, the downtime is forecasted (by means of the Excel). This is useful because the operator can estimate if this downtime is enough for performing other activities (e.g. work at other machines) in the meantime in order to be efficient. By means of the Excel, OEE is also forecasted and the impact of the exception is determined. When the exception is solved and the process starts running again, the downtime is registered in order to be useful for future forecasts.

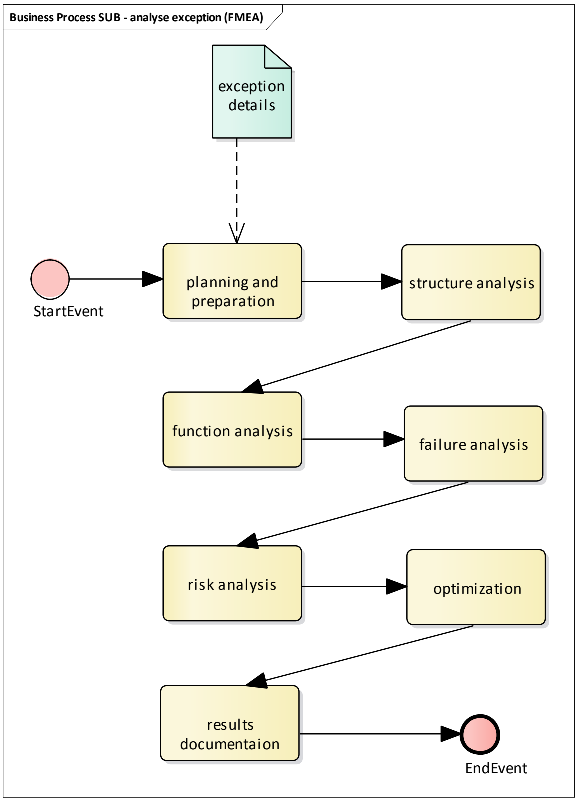

Figure 19. SUB - analyse exception (FMEA)

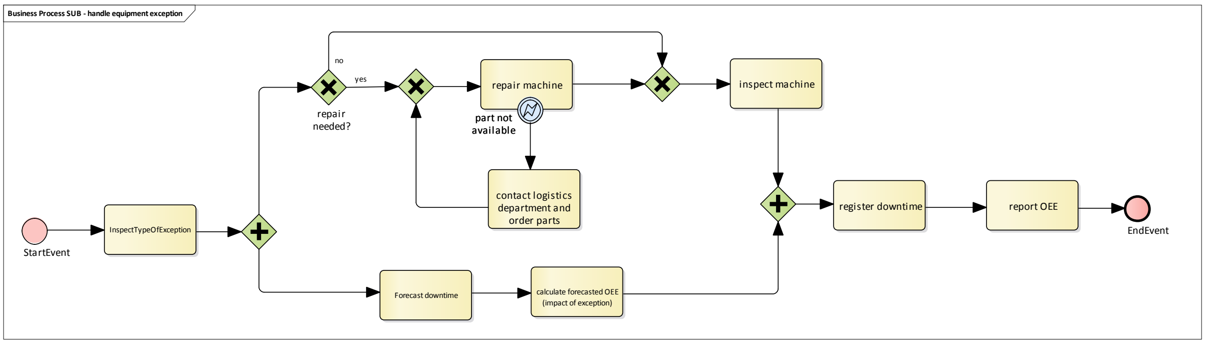

Figure 20. SUB - equipment exception

In Figure 21 the process exception handling activity is shown. In this sequence, forecasting does not provide added value since process specifications are known immediately. This means that it is useful for Figure 18. In the future, more data on process specifications means that more accurate forecasts on the KPI's can be made before the process starts, in order to make better decisions on starting the process.

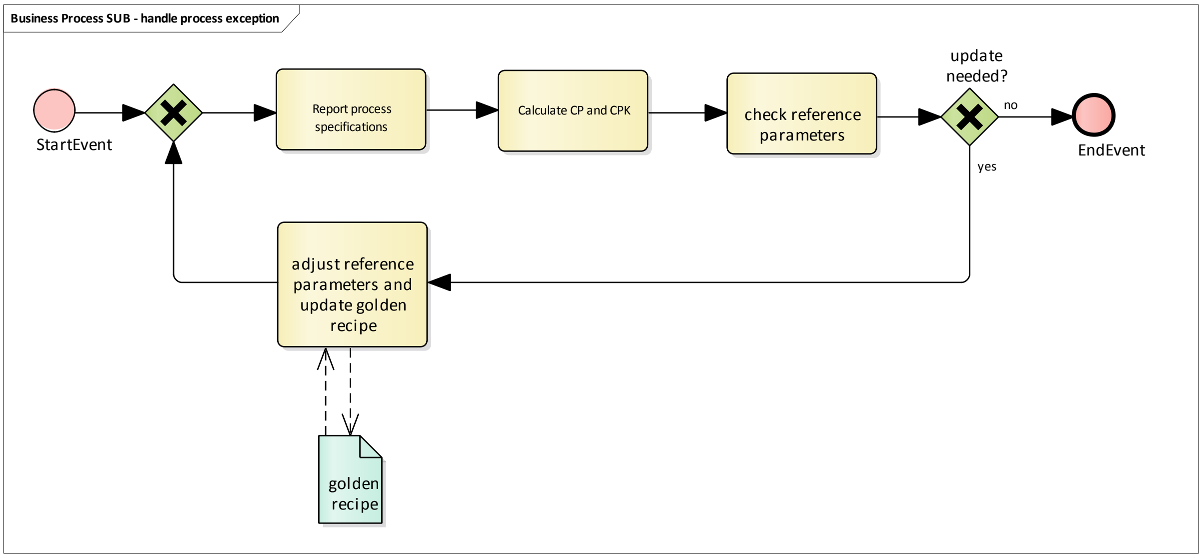

Figure 21. SUB - process exception

In Figure 22 the product exception handling activities are shown. The same explanation as Figure 21 (process exceptions) holds here. The data on the amount of scrap and rework is known immediately. This means that it will be reported and more accurate decisions (Figure 18) on starting the process can be taken.

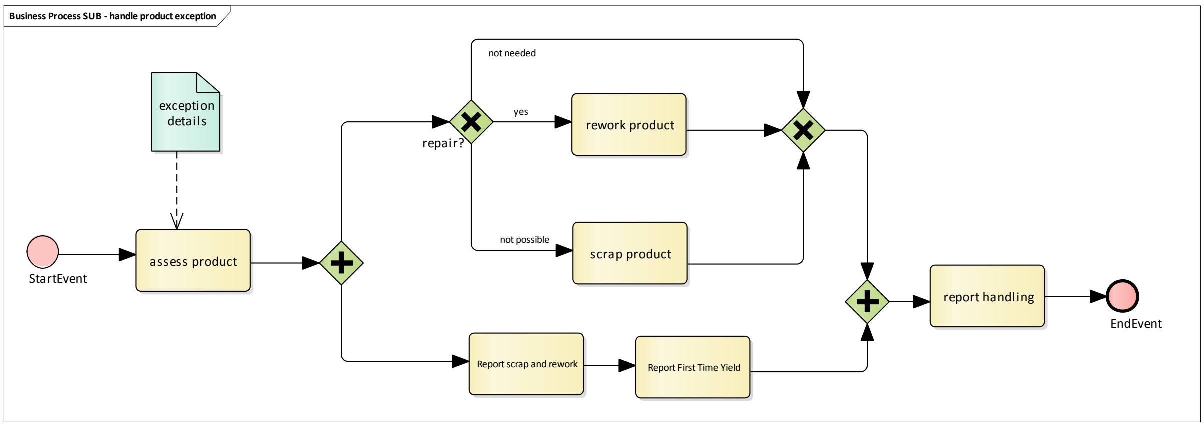

Figure 22. SUB - product exception

Lastly, in Figure 23, the unexpected exception handling procedure is elaborated. Unexpected exceptions cannot be forecasted nor handled by the system. Therefore, it is of great importance to register these exceptions and see if similar exceptions have occurred in the past. By doing this, unknown – unexpected – exceptions can become one of the expected exceptions in the future.

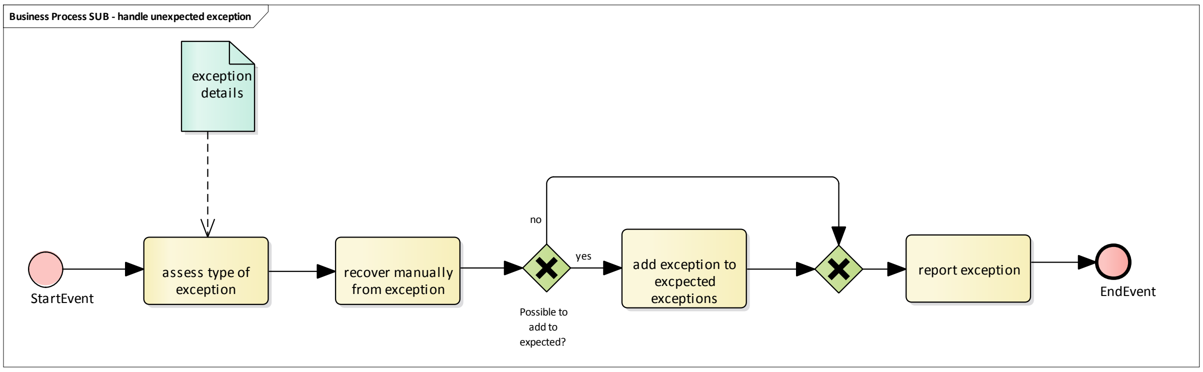

Figure 23. SUB - unexpected exception

6.3 Chapter Conclusion

In this chapter the generic process model was shown. With this model Atos can provide its clients with a brief overview of what the exception handling process should include. In the next chapter the implementation plan is described, which provides with more insight in how the model should be used.

7 Demonstration and Evaluation

7.1 Chapter Introduction

This chapter will discuss on whether the generic process model from the previous chapter can be applied in practice for the current manufacturing processes at clients of Atos. This was answered by means of the interview answers. There are some limitations to this form of studying applicability, these are discussed in the Limitations section (section 8.5). The specific interview question referring to this application in practice is; 'Would this be applicable to multiple production processes?' This was an open-ended question and provide a start for the discussion. The interviewer asked follow-up questions in order to get the most input out of the interview and questions. Moreover, answers to other questions could be useful as well, this it is a semi-structured interview which does not restrict answers and stimulates interaction after each question. After discussing on the application in practice, the critical success factors for implementation and an implementation plan will be discussed to ensure successful implementation. This chapter answers sub question 5 & 6.

7.2 Application of the Model

This section will be answering sub question 5 (*Can the generic models for exception handling be applied in practice for a specific manufacturing process?).*

First, the Senior MES Consultant specialized in Process Exceptions specified that the applied model can be used in practice at different clients. It can be used to see whether the process flows as expected and it makes it easier for clients to pinpoint on the problems in the process and the factors that need more attention and improvement. The MES system could be adapted to this process model. Moreover, according to him, Atos does not have a standard process description. The specific process descriptions that Atos uses, are not always adaptable to specific manufacturing environments at the clients. This model can be used to show clients what exceptions can occur and how these can be solved.

Clients have or get solutions specific for their own process. Procedures are very locally implemented and manufacturing environments are difficult to compare. This means that information from one client cannot be used at another client. With this model, same procedures and processes can be used at the different clients which makes it able to compare performances. Comparing performances between different manufacturing environments and clients has several advantages. First, by using a generic model, the user can effectively translate their knowledge into score-based applications and non-specialist users can interpret them as well. Above that, the means to calculate scores on the KPI's are predetermined and defined in a scoring model, which makes the calculation of each score objective and uniform (Jansma, 2018). Decisions are no longer subject to different interpretations or personal experiences. Moreover, the organization can decide by themselves which key criteria are identified in order to assign different values to characteristics applicable to their own situation. Moreover, by standardizing the decision-making process through the implementation of a scoring model, the best decisions can be made faster and fully automated.

This makes it also easier to map whether the manufacturing environment is "under control" (is doing well) or whether the environment runs "out of control".

Lastly, according to the Senior MES Consultant specialized in the Process Exceptions, one of main problems that managers and team leaders are dealing with is; What are the most important problems that have occurred during that week?

At this moment, every operator only knows what problems occur at their own piece of the production process. With a generic model, overall conclusions can be discussed with all members involved in the manufacturing environment.

The manufacturing engineer specialised in Equipment Exceptions added that all types of exceptions are currently addressed very separately from each other. By means of this model, he can get more insight in other types of exceptions.

Lastly, the Senior MES Consultant specialized in Product Exceptions identified that it is useful to look at the process with this generic applied model. Furthermore, Philips is trying to set up a global standard for the product exception part, which complies in general terms to this model.

Therefore, all interviewees confirmed that this model could be applied in practice (in different settings at different organizations). Some points for improvement were provided by the interviewees, which were incorporated in the model. The FPU expert at MSD specialized in Process Exceptions argued that it would be difficult to translate this model to a concrete action plan for operators and employees (at the working floor). This is more high-level. However, this was the aim of the research and could be an input for future research.

7.3 Critical Success Factors for the Implementation

This section will be answering sub question 6 (*How can the implementation of the model result in a successful exception handling procedure for a (smart) manufacturing company?).* The input for what needed to be done and managed in order to successfully implement this model is provided by the interviews and literature. First, interview findings will be discussed and simultaneously combined with findings of existing literature.

The Senior MES Consultant specialized in Product Exceptions identified the most important (possible) bottlenecks for successful implementation. He argued that the model should be as flexible and client friendly as possible. Moreover, the more extensive the model, the more difficult it is to implement. Therefore, it is important that it as simple as possible in order to be able to be understood by as much of our colleagues as possible. Above that, providing a simplistic model that is flexible provides Atos the opportunity to extend it, if needed. With this model there is a standard way of working and the organization is not dependent on one expert employee. One expert employee implies that all knowledge is gone, once he leaves.

According to Reijers (2006), typical advantages for implementing such a model is that it may result, if accurately used, in reduced lead times, less hand-off errors, and more flexibility to change the structure of supported business processes. However, it is important to keep in mind that the process of implementing can be complex and time-consuming, if some factors are not properly addressed. One of these factors is; *the level of process orientation* within the organization (Parkes, 2002). This model will support different business processes that flow across the organization and across departments in the organization. Therefore, it is essential that the mindset of organisations is right; meaning that processes by themselves are seen as valuable to improve business performance. Moreover, Groiss & Eder (1997) identified pronounced technology perspective as an important factor for successful implementation. This is defined as the capability to interoperate with other systems. Groiss & Eder (1997) also explain that in these dynamic businesses, interoperability will remain an important issue in implementation of systems. Above that, other researchers (e.g. Kobielus (1997)) recognized that exploiting the interoperability capability is key in making a workflow project successful. Above that, he identified another factor: scalability. This factor, in addition to technology, is addressed in the model (chapter 6). Interviews have concluded that this model is implementable within the current system/technology of clients and the interviews identified the importance of flexible, simple models in order to be extendable and scalable. This was considered while designing and finalizing this model.

Kobielus (1997) identified the technology and scalability factor. However, he also puts equal emphasis on management and human factors by suggesting that successful implementation required support of upper management and staff. These factors are also recognized by Antonucci (1997) and Chaffey (1998). Stohr & Zhao (2001) identify specific issues like poor change management, resistance from bureaucratic organisations, and lack of sustained top management support as important reasons for failure of successful implementation of the model.

The work of Poelmans (2002) primarily focuses on end-user acceptance as a factor in successful implementations. His case studies and interaction with 200 end-users show that, among other factors, perceived ease of use and end-user influence are crucial in making the model and corresponding implementation a success. Perceived ease of use was also reflected by the MES Consultant which was addressed by making the model as simple and flexible as possible.

The last factor influencing successful implementation is the process dimension/factor. The Howe School of Technology Management conducted a study in 2003 among over twenty workflow researchers and users. They were asked for critical factors in process automation (Zur Muehlen, Stohr, & Bin Lai, 2003). The named management factors ("management support" and "top management focus"), technology factors ("selection of the right tools" and "mature technology"), and human aspects ("effective communication with employees" and "deep user participation") as could be expected on the basis of earlier paragraphs. In addition, participants mentioned as critical factors; "a process-oriented approach to application development", "process awareness at an early stage of the project" and "(organizational) understanding of process concepts". These concepts point at another factor; namely the process dimension/factor.

Further research (Sinur & Thompson, 2003) also identified the importance of a process attitude. They identified "cultural aversion to process" as important in the failure of successful implementation. The only empirical testing (Parkes, 2002) showed that process design issues were one of the highest impact issues on implementation success. Reijers (2006) also interviewed a group of 10 employees in different roles (e.g. consultants, managers of implementation and sales representatives) from a BPMS vendor. This study identified 17 critical success factors for BPMS implementation. Process orientation of the company scored second highest in the amount of citations associated with failure of implementations. Lastly, Reijers (2006) concluded that there is a relationship between process orientation and the success of an implementation. This study suggests that insufficient process orientation may be related to problems that affect the cost and speed of implementations. This is in line with findings from research (e.g. Parkes (2002)) where a lack of process orientation is as very important for the failure of implementations and the trade press (Sinur & Thompson, 2003) that warns for a lack of process awareness.

This model implemented the process orientation by means of integrating the different types of exceptions into one model. This aims to prevent operators from thinking about their own department only. The importance is on having an overview of the most important bottlenecks and exceptions in the entire process and its effect on KPI's. Therefore, it is not necessarily aimed at one department, meaning that results on the occurrence of exceptions is also comparable across different organizations and companies.

In addition to the conclusions of Reijers (2006), Ramanathan (2017) argued that MES implementations fail if there is a lack of commitment from management for MES development. Above that, they fail if there is a lack of involving the right people of different departments. Besides, a lack of existing internal IT systems is a reason for failure of MES implementations. Moreover, the model would not work if the processes were not well-defined and consequently, a model could not match the current processes perfectly. This again highlights the importance of the four factors; human, management, technology and process.

In conclusion, several researches have argued that the human, management, technology and process factors are of extreme importance for the success of an implementation. This is also supported by research specifically for MES implementations.

7.4 Implementation Plan

In this section, an implementation plan is shown which is based on the critical success factors identified in the previous section. This is a specific plan to be used in practice by Atos, when visiting its clients and implementing the generic models described in the Results section. Based on the factors described above, a specified implementation plan is described in Table 4. This can be used by MES consultants from Atos to visit clients and implement the model properly.

Step	Description
1	Visit client with the process model and forecasting model. Discuss with the clients the types of exceptions occurring at their company. Check if this is in line with the exceptions that occur. If not, the model can be adjusted and new exceptions can be added to the model by the Atos consultant. If yes, the model can be used directly.
2	Identify current technologies used at the client and the current systems used. Investigate whether this model could be aligned to current systems. According to the interviews, the clients argued that aligning the system (MES) with the model was no problem. The model was made as simplistic as possible in order to be flexible and implementable at most clients. However, this check on **technology** needs to be done beforehand (technology factor).
3	The third step is starting to collaborate with the management and staff functions in order to make sure there is enough required support for implementation. Using this model and aligning it with current systems requires an easy-to-use model in order to be understandable by most colleagues **(human factor)**. Furthermore, by creating support and enthusiasm of management **(management factor)**, the model will be a success. Therefore, a meeting with management and staff should be planned. After they support the ideas, a second meeting with colleagues should be planned in order to explain the model and check whether they understand it (which makes it easy-to-use).
4	All operators from different departments should shift to process-thinking instead of only thinking about their own department. Therefore, it is important to create process awareness at an early stage of the project **(process factor)**. This means that before implementing, the operators should be briefed and introduced to the new model (and the different processes associated with it). This meeting can be planned by the managers, supervisors or the change management department, depending on the specific company.
5	Implementation of the model. When all previous steps were successfully finished, the model can be implemented. Monitoring the exceptions that occur is important and constantly fitting and extending the model with exceptions happening and other exception handling procedures is key.

Table 4. Implementation Plan

7.5 Chapter Conclusion

In this chapter the discussion on whether the generic process model from the previous chapter can be applied in practice for the current manufacturing processes at clients of Atos is started. This was answered by means of the interview answers. The implementation plan provided with different factors that are an important consideration for a successful implementation. In the next chapter the general conclusions and discussion is elaborated.

8 Conclusion, Discussion and Outlook

8.1 Chapter Introduction

This section shows the conclusions that are drawn based on this study. Secondly, the practical implementations will be discussed, followed by the limitations for this research and directions for further analysis.

8.2 Conclusions

The objective of this research is to design and investigate how to implement a generic descriptive process model in BPMN, that acts as a blueprint for the process that needs to be executed when an exception occurs in a manufacturing environment. Six sub-questions were formulated to answer the research question.

Q1: What kind of product, process and equipment exceptions can occur in a (smart) manufacturing domain and why do they occur?

The input for answering this research question was literature and interviews. Atos has identified, during the investigation stage, that their exceptions will be classified into product, process and equipment exceptions. However, BPM literature classifies exceptions according to other exception types; work item failure, deadline expiry, resource unavailability, external trigger and constraint violation as exception types. The classification that Atos uses (dividing these exceptions into the categories *product*, *process* and *equipment* exceptions) is hardly found in literature. This means that the interview was used to connect the literature stated exception types into the classification of Atos.

Most exceptions types were classified into more than one category, as to be seen in Table 5.

Literature exceptions	Classification from interview
Work item failure	Product and Equipment
Deadline expiry	Product
Resource unavailability	Equipment
External trigger	Equipment and Product
Constraint violation	Equipment, Product and Process

Table 5. Exception Classification

Different reasons were found for the occurrence of these exceptions, e.g. an abort initiated by the user of the executing program, failure of a hardware, software or network component associated with the work item or the raw material remains unused for too long. Other examples were the unavailability of some material, machines or operators and lastly, the machine could be worn out and should be replaced by a new machine. The classification represented in this sub question will be used in sub question 2:

Q2: What is the impact of the different types of exceptions on the process performance?

The input for answering this research question was literature and interviews. Atos has explained, during the investigation stage, that they aim to order the exceptions according to their impact on KPI's.

Therefore, for each exception classification the a commonly used KPI was identified during the interviews. This is represented in Table 6 on the next page.

Exception classification	Identified KPI's
Equipment exceptions	OEE
Product exceptions	FTY
Process exceptions	C_p and C_{pk}

Table 6. KPI for each Exception Classification

The interview was used to identify the KPI's that could be used to determine the impact on the process, identify these KPI's and ask for appropriate data on calculating the KPI's. When the KPI's were identified, the corresponding calculations were done in Excel. This is represented in the paragraphs 'Impact of expected exceptions' in the Results section. The Excel file showed some cells that had to be filled in by the user (e.g. the scheduled time and planned downtime) and after filling out these cells, the impact of the exceptions on the KPI's were calculated automatically. There is a different sheet for each exception classification (e.g. equipment, product and process).

Q3: How can the most important KPI's be forecasted with past data on exceptions?

The input for answering this research question was literature and interviews. Some questions in interviews were asked to see whether there was any existing measure for the forecasting of exceptions. If this was the case, this was be the starting point. If not, their ideas on how to best forecast exceptions were used to create possible forecasting exceptions methods. They argued that they rarely forecast / predict exception types. Therefore, data needed to be gathered in order to forecast when exceptions will occur. This is done by realistic data (representing past data) and will be constantly extended by data if an exception happens. This is confirmed by Atos and they state that this is a good starting point in order to forecast unplanned downtime and other input parameters of different exceptions at their clients. By being able to forecast, the starting point of using the model is filling in the needed input parameters and the metrics of KPI are automatically calculated. In this way, the client could decide whether he is satisfied with the outcomes and the process can be started or whether some things need to be changed in the process or input parameters beforehand. This is all incorporated in the same Excel file as sub question 2.

Q4: How should generic models for describing and forecasting exceptions be designed in a Manufacturing Execution System (MES)?

The input for answering this research question was literature and interviews. In the end, this generic model was generated and the input was also the Excel sheet of the previous sub questions. The impact of the exceptions, the KPI's and type of exceptions were implemented in this model. Furthermore, all steps in the process were incorporated. This makes it possible for Atos to visit their clients with this model in order to see where problems occur. By filling out this sheet in Excel, the KPI's relevant for the exception types are forecasted. If the user is satisfied with this score on KPI's, the normal process execution with possible exceptions can start. If the user is not satisfied with the forecasted scores on the KPI's, input parameters can be adjusted (e.g. schedule less planned downtime, discuss with the client on adjusting LSL and USL etc.). Therefore, the advantage of a forecast is to be able to see if the forecasted scores on the KPI's are accepted and the process can start. The Excel file can help in identifying the occurrence of exceptions and their impact on KPI's, to see whether this is a problem in existing manufacturing.

Q5: Can the generic models for exception handling be applied in practice for a specific manufacturing process?

The input for answering this research question were the interviews. It was important to get an understanding of the necessities of the model for the client of Atos. Therefore, some interview questions were focused on getting an understanding of the basic prerequisites for the model in order to be used in practice at Atos' clients. Their expertise of Atos was used in order to get to know how this model can be used in different settings, since they are already using models for different topics at their clients. The interviews identified that clients of Atos have or get solutions specific for their own process. Procedures are very locally implemented and manufacturing environments are difficult to compare. This means that information from one client cannot be used at another client. With this model, same procedures and processes can be used at the different clients which makes it able to compare performances. Moreover, there was no standardized procedure before. This model makes it possible to standardize the process.

Q6: How can the implementation of the model result in a successful exception handling procedure for a (smart) manufacturing company?

The input for answering this research question was interviews and literature. Literature was used in order to search for best practices. The opinion of experts at Atos was used in order to investigate what necessities the model should contain in order to be sustainable usable in the future. This resulted in the factors for successful implementation, summarized from the report in Table 7.

Source	Factors	Explanation
Atos	1. Flexible 2. Client-friendly	The more extensive the model, the more difficult it is to implement. It is important that it as simple as possible in order to be able to be understood by as much of our colleagues as possible. Above that, providing a simplistic model that is flexible provides us the opportunity to extend it, if needed.
Literature	1. Technology 2. Human 3. Management 4. Process	Groiss & Eder (1997) identified pronounced technology perspective as an important factor for successful implementation. This is defined as the capability to interoperate with other systems. Kobielus (1997) identified the technology and scalable factor. However, he also puts equal emphasis on management and human factors by suggesting that successful implementation required support of upper management and staff. In addition, participants of a study of Zur Muehlen et al. (2003) mentioned among others, "a process oriented approach to application development", "process awareness at an early stage of the project" and "(organizational) understanding of process concepts" as factors for successful implementation.

Table 7. Implementation Factors

Based on these factors an implementation plan was developed in order to guide Atos in successful implementation of the models.

8.3 Reflection

The main objective of this research was achieved since the generic descriptive model in BPMN was designed. This process model can act as a blueprint for the process that needs to be executed when an exception occurs in a manufacturing environment. Furthermore, the research questions were all answered by interviews and literature. This was a good method, since all research questions provided valuable insights for answering the main research question. The generic model for exception handling was designed by means of the input of the sub questions. The Senior MES Consultants at Atos agreed that this model can be implemented at their clients in different settings. This research also aimed to calculate the impact of exceptions and to make forecast for the most important KPI's. This was done by Excel. However, it should be kept in mind that the Excel file is a prototype and no real data was used to calculate the current KPI's. However, the data used is representative and was used to calculate the KPI's in order to show Atos how to use this Excel file. Atos argues that the model and associated Excel file are useful for successful exception handling in practice. The contributions and limitations are stated in the following sections.

8.4 Summary of Contributions

This report contributes to the practical use for exception handling in BPM for (smart) manufacturing industries. It provides a standardized process for Atos, to be usable at their clients and to be implemented in current systems.

Summarized, this report contributes to existing literature in the following ways:

- There is hardly any scientific paper that was found on exception handling specific for the manufacturing domain. Papers on exception handling focus mainly on customers cancelling hotel and car reservations (Casati, 1999; Lerner et al., 2010; Reichert & Weber, 2012), for example. In these processes, no physical products or steps of translating a raw material into an end product must be conducted. Therefore, these papers do not focus on the more complex manufacturing processes which may consist of many machines, tools, operations and KPI's. Thus, manufacturing is different since it relates to the ability to convert raw materials into final products by application of processes or by use of man, machinery and resources. This report focuses on exception handling specific for the manufacturing domain, which makes it a contribution to existing literature.
- Moreover, there are several papers to be found on the recovery from exceptions (M. J. Adams et al., 2007; Casati, 1999; Lerner et al., 2010; Reichert & Weber, 2012; Wu, 2009), but not on the workflow handling. This is also a research gap that has been identified in Hommen (2020). This report does not focus on the recovery of exceptions but how to implement exceptions and their corresponding impact on the KPI's in the process. It provides a standardized procedure for process description where exceptions and their impact are incorporated.
- The last literature gap is related to MES. There is not much to be found that focuses specifically on these types of systems. Therefore, this research contributes to the knowledge of implementing this workflow handling procedures with exception handling in MES. Experts of MES have been interviewed in order to investigate whether this model would be implementable in the current systems. It has been adapted and designed in order to be implementable in current systems (of clients).

8.5 Limitations of this Research

This section describes the limitations of this research. First and foremost, the most important limitation was, uncontrollable by us all. This report is written in times of COVID-19 virus infection. This means that data could not be gathered in order to make more forecasts and implement the model and the Excel file in the real business environment (with clients of Atos). Above that, there are several other limitations:

- To make appropriate calculations on the impact on the KPI's, the use of company data (clients of Atos) was considered first. However, they were not able and willing to provide this data to others outside the organisation. They were not able to provide this data since that required a physical introduction to the company and its systems, and this was made impossible due COVID-19 and the closing of the corresponding manufacturing sites. This made it impossible to use company data. Therefore, secondly, the use of a public data set was considered. However, the public data sets were very large and did not provide the right input parameters that were needed in the Excel file. Therefore, a limitation of this research is that it does not incorporate "real" data but instead representative, realistic data.
- A limitation is the sample size of the interview. An expert from the equipment, product and process exception domain was interviewed. This was enough information to answer the research questions. However, a larger sample size would be beneficial to get even more insights and recommendations.
- By studying the applicability (section 7.1 & 7.2) with only interviews, there is a risk of a biased interviewee, since he is used to the ways of working at his own company. Moreover, literature on applicability was not incorporated, since this does not specifically focus on MES systems within companies. To gain as much valuable insights in applicability for Atos and its clients, interviews were chosen. However, this is a subjective measure.
- Excel sheets are developed for the product, process and equipment types of exceptions. These conduct different formulas. If the types of exceptions will be extended in the future, a new Excel sheet needs to be developed, which will be time-consuming.

8.6 Further Research

Further research should focus on the real implementation of the model in the manufacturing domains. As identified by FPU expert at MSD specialized in Process Exceptions argued that it would be difficult to translate this model to a concrete action plan for operators and employees (at the working floor). This is more high-level, but this was the goal of this research. However, this could be an input for future research. Moreover, data should be gathered and different forecasting / prediction techniques could be helpful (e.g. forecast when the exception will take place). When factory floors can be visited, this will be useful to add to the existing study. Since Atos is a consulting company, the input of interviews was beneficial to investigate what is needed to implement it at different clients, meaning that it can be specialized to different companies. It needs to be tested in different settings at Atos and probably slightly adaptable to the specific context. Since the model is made flexible, it is possible to implement it at the clients of Atos.

8.7 Chapter Conclusion

This section showed the conclusions that are drawn based on this study. The practical implementations were also discussed, followed by the limitations for this research and directions for further analysis. Several limitations were discussed in this chapter, as well as possible further research.

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Appendix A: Exception Classification from Literature

		Search	1		2															
			Marrella & Mecella, 2018	Marrella, Mecella, & Sardiña, 2018	Derbali, 2011	Linden et al., 2013	Mourão & Antunes, 2005	Mourão & Antunes, 2007	Mišić, Domazet, Trajanović, Manić, & Zdravković, 2010	Lerner et al., 2010	Adams, Ter Hofstede, Van Der Aalst, & Edmond, 2007	Reichert & Weber, 2012	Casati, 1999	Wu, 2009	Ngeow, Mustapha, Goh, Low, & Chieng, 2007	Kurz, Fleischmann, Lederer, & Huber, 2013	Borkowski, Fdhila, Nardelli, Rinderle-Ma, & Schulte, 2019	Carter & Orlowska, 2007	Chakravarty & Singh, 2008	Fleischmann, Schmidt, Stary, & Strecker, 2013
		Basic failure											+		+					
		Application failure											+		+					
Expected exceptions	Exception types	Work item failure									+	+	+							
		Deadline expiry							+	+	+	+	+							
		Resource unavailability							+	+	+	+								
		External trigger							+	+	+	+	+							
		Constraint violation							+		+	+								
	Workflow handling	Continue workflow case										+								
		Remove current case									+	+								
		Remove all cases									+	+								
	Recovery action	No action												+						
		Rollback								+		+		+						
		Compensate								+	+	+	+	+						
		Other														+	+	+	+	+
		Unexpected exceptions	+	+	+	+	+	+			+		+			+				

Appendix B: Interview Questions

Interviewvragen voor Exception handling in MES

Bedankt dat je wil deelnemen aan dit interview. Je kan deze interviewvragen alvast doornemen om een idee te krijgen waar het over zal gaan.

Mijn naam is Ken Hommen en ik doe, in samenwerking met Atos Nederland B.V. en de Technische Universiteit van Eindhoven, een onderzoek naar het verbeteren van ‘exception handling in smart manufacturing’. De term ‘exception’ doet vermoeden dat deze maar een enkele keer voorkomen. Echter, zoals je misschien weet zijn exceptions normaal voor ieder productieproces en komen deze veel voor. Exceptions zorgen voor een langere doorlooptijd van het proces en daarom is het belangrijk om ze te voorkomen of er zo snel mogelijk van te herstellen.

Dit interview is opgedeeld in twee delen. Na het eerste deel wordt een procesmodel getoond dat gebruikt kan worden als blauwdruk voor het proces dat uitgevoerd moet worden nadat een exception is opgetreden in het productieproces. Dit om de exception te verhelpen en te analyseren.

Het eerste deel van het interview zal ongeveer 10 minuten in beslag nemen. Daarna nemen we 10 minuten de tijd om het procesmodel door te nemen. De vragen die daarna volgen in deel 2 zullen ongeveer 15 minuten in beslag nemen.

In de appendix van dit document bevindt zich een tabel met de exceptions geclassificeerd zoals in de wetenschappelijke literatuur. Deze zal gebruikt worden bij vraag 3 van het interview.

Deel 1 (10 minuten)

1. Welke tekortkomingen zijn er op dit moment omtrent exception handling?

2. Hoe zou je de effectiviteit van het exception handling proces in het algemeen op dit moment beschrijven?

In de Appendix staan exceptions weergegeven zoals gevonden in wetenschappelijke literatuur.

3. Exceptions worden in productieprocessen verdeeld in drie categorieën (proces, product, equipment). De literatuur onderscheidt ook verschillende typen exceptions (zie appendix). Wat zijn voorbeelden van exceptions binnen deze categorieën en kun je de typen uit de literatuur koppelen aan deze drie categorieën? Welke van deze exceptions kom je vaak tegen? Hoe wordt dit opgelost?

4. Wordt de impact van exceptions op het productieproces gemeten? Hoe wordt dit gemeten en wat zijn de belangrijkste KPI's en hoe zijn deze te linken aan elkaar?

5. Wat zou je willen zien in een model met betrekking tot exception handling?

Het exception procesmodel zal nu worden getoond.

Deel 2 (15 minuten)

6. Welke onduidelijkheden/bezwaren/twijfels heb je na het bekijken van het exception procesmodel? Sluit het aan bij de huidige manier van werken?

7. Wat voegt het model toe aan de huidige manier van werken?

8. Welk systeem wordt nu gebruikt voor het registreren van exceptions?

9. Welk gedeelte van het model wordt al ondersteund door het huidige systeem?

10. Zou dit toepasbaar zijn bij meerdere productieprocessen?

11. Hoe kan het model geïmplementeerd worden? Wat is daarvoor nodig?

12. Wat zou je willen zien in een model met betrekking tot exception handling?

13. Tot slot: wordt er een methode gebruikt om het voordoen van exceptions te voorspellen? Heb je hier suggesties voor?

Appendix

De tabel hieronder geeft aan wat ik in de literatuur heb gevonden over de verschillende typen exceptions die er zijn. Er zijn grofweg vier verschillende typen. Mijn onderzoek richt zich met name op expected exceptions.

<table>
<tr><td colspan="2">Basic failure - failures of the Workflow Management System</td></tr>
<tr><td colspan="2">Application failure - failures of the applications connected to the Workflow Management System</td></tr>
<tr><td rowspan="5">Expected exception</td><td>Work item failure - inability of the work item to progress any further</td></tr>
<tr><td>Deadline expiry - a timeout event occurs when a work item reaches a set deadline</td></tr>
<tr><td>Resource unavailability - the resource reports that it is unable to accept the allocation or the allocation cannot proceed</td></tr>
<tr><td>External trigger - occur because of an occurrence outside of the process instance that influences the continuing execution of the process</td></tr>
<tr><td>Constraint violation - a data constraint has been violated for a work item during its execution</td></tr>
<tr><td colspan="2">Unexpected exception - unpredicted situations for which the system cannot suggest any solution</td></tr>
</table>