OPTIMIZATION OF INTERNAL LOGISTICS USING A COMBINED BPMN AND SIMULATION APPROACH

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ABSTRACT

The optimization of material flow systems requires a profound understanding of the underlying processes. Business Process Model and Notation (BPMN) is an established way of creating a process model that allows an interdisciplinary analysis and optimization. Quantitative exploration of systems using discrete-event simulation can help to enrich these insights. For that reason, this paper introduces a combined BPMN-simulation approach that connects the advantages of both modeling frameworks. By synthesizing systems from generic modules, a comprehensive yet structured optimization process chain is developed. A case study evaluation based on key metrics for material flow operations proves the applicability of the methodology.

INTRODUCTION

Creating a virtual model of a material flow (MF) system promises higher availabilities and shorter throughput times. To achieve this, the model needs to contain data from various sources in the MF domain (e. g. stacker cranes or conveyor belts). However, the application of this approach in real-world systems is often impaired by complex and distributed processes in heterogenous organizations (Pires et. al. 2019). The necessary transparency can be generated by defining and implementing a proper process visualization. Business Process Model and Notation (BPMN) is a widespread standard for this task since the created models can be understood by experts from various domains. However, the focus of this modeling language primarily lies on administrative processes. (Muehlen and Recker 2013) The most common process type modeled with it is the information flow. In theory, BPMN can also be used to represent MFs as well as the movement of workers, forklift trucks, and other mobile resources. Common notations in this domain, such as flow charts or value stream mapping, often cannot meet the requirements for these particular use cases. Flow charts, for instance, suffer from a low level of standardization and development, and are unsuitable for depicting more complex process properties. Value stream mapping, on the other hand, does not depict sequence flows as accurately and in detail as BPMN, for example because events are not mapped (Garcia et. al. 2012). That makes it difficult to subsequently create a discrete-event simulation (DES). Additionally, this notation focuses heavily on manufacturing settings and is therefore difficult to understand for users outside of the domain of production management (Forno et. al. 2014).

But although BPMN possesses several properties that make it attractive to be applied to MF processes, there are only a few examples where it is actually used in this field (Zor and Leymann 2011). One potential reason for this is the lack of a scientific foundation for modeling strategies in the internal logistics domain (Robinson 2006). A generalized and well-structured approach that considers the specific characteristics of both modeling frameworks can offer guidance for practitioners and help them to model MF systems in a predictable amount of time.

Central Concepts & Related Research

When modeling administrative processes with BPMN, the sequence flow (SF) is used to show the chronological order in which events and activities take place. However, MF systems are characterized by a greater variety of different process types, which raises the question of how these can be mapped in BPMN. An intuitive option is to use the SF as a representation of the MF, resulting in a material-oriented model. Alternatively, the model can be resource-oriented, meaning that the SF represents the movements of mobile resources, e. g. workers. A third option is the addition of MF-specific elements to the BPMN syntax (Zor and Leymann 2011). While this somewhat reduces the ambiguity of the SF, it also makes the models more complex and limits the choice of modeling software. That is why the BPMN models shown in this article use the standard BPMN syntax and are either material- or resource-oriented.

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Another challenge arises from the fact that the activities in MF systems are usually object-constrained, meaning that their execution requires the availability of certain objects (Wagner 2021). Depicting these relationships between objects and activities is essential for the modeling of MF systems, but it is also beyond the possibilities of the BPMN syntax. The different approaches discussed above, being exclusively visual, do not address this problem. That is why this article proposes the use of an additional tool in the form of DES. Being widely used in the MF domain, DES includes various possibilities to represent object-constrained activities. Since BPMN does not cover these activities, DES has the potential to work as a complement for BPMN. By synthesizing the two modeling approaches, the high variety of MF processes can be represented. The question of how those two tools can be combined has already been partly explored outside the manufacturing domain, e. g. by extending the DES framework to include tools for business process modeling (Wagner et. al. 2009). However, as of today, this is not yet supported by existing DES software. The reverse approach, adding DES elements to the BPMN syntax, is developed as a BPMN variation called "DPMN" (Guizzardi and Wagner 2011, Wagner 2018 & 2021). While this new modeling language can depict object-constrained activities in a qualitative way, existing DES software is still required to perform simulation experiments and generate quantitative results. Moreover, it is uncertain to what extent DPMN is applicable to MF systems.

Summing up, the ever-recurring goal of an MF operator to optimize the system could be met more effectively by creating support in the shape of a proper system model. It seems to be a promising approach to combine BPMN and DES using the existing modeling syntax and established software. However, there is no current research which sufficiently covers this topic.

Research Questions

Therefore, the first objective of this article is to assess if and to what degree BPMN is a suitable tool to model and illustrate MF systems, especially as a complement for DES. Based on that, a standardized methodology is proposed that combines both techniques to increase their usability and reduce the effort spent for modeling. This approach is expected to provide better insights into the process. Hence, the following two questions are investigated in this article:

1. How must a modeling approach for material flow systems be designed to ensure a sensible combination of BPMN process modeling and DES?
2. How can improvements for a material flow system be found based on its BPMN process model?

MATERIALS

Characteristics of Material Flow Systems

MF systems contain all operations which are necessary for the processing and distribution of goods within a defined area. Thus, they execute the physical component of an enterprise logistics process. MF processes lead to a transformation of transported goods regarding time, location, quantity, composition, and quality. For different types of transformations, MF systems contain different subsystems like conveying, storage, or handling. Although very different in terms of their technical design, these subsystems follow similar requirements from a process-overarching perspective. Key performance indicators (KPIs) for logistics contain, for instance, the throughput, which is the number of TUs processed in a certain timeframe. (Hompel et. al. 2018) An important concept from lean management are the seven forms of waste. They allow for a distinction between those activities which directly contribute to the value of goods and those which do not. Particularly in the field of MF, unnecessary transportation processes are one form of waste. (Guenthner and Boppert 2013) Those KPIs allow the controlling of how well an MF system can be optimized with a certain improvement. They therefore are an important aspect of an optimization methodology.

A typical challenge that needs to be dealt with in the MF domain is queueing systems. If a certain process can only handle one object at a time, but several objects require the availability of that process, all of these objects but one form a queue. Depending on whether – over a certain period of time – the number of arriving objects is smaller or larger than the number of processed objects, the queue either shrinks or grows. (Hompel et. al. 2018) Since neither arrival nor processing time are constant but rather can follow a complex distribution, analytical modelling of queueing system is a challenging task. (Arnold and Furmans 2019)

Business Process Model and Notation

The process models in this article follow the standard BPMN syntax and have been created with the software "Modelio" (SOFTEAM 2020, GitHub 2021).

In BPMN, a process is represented as a sequence of events and activities, connected by the SF. Various gateways allow for branching and merging of the SF to depict process variations. Additional elements like messages and data objects make BPMN useful for the modeling of information flow. (OMG 2011) Applied to MF systems, the SF can represent the movement of different objects, making the model material- or resource-oriented. However, BPMN does not offer any possibility of representing the scarcity of these objects resulting from object-constrained activities. While so-called pools and lanes can be used in BPMN to represent certain resources (e. g. the worker who is responsible for a task), the usefulness of this option is limited by the fact that each element can be part of only one lane (and each lane can be part of only one pool) (OMG 2011). This does properly represent the complexity that is typical for more detailed models of MF systems.

Discrete-Event Simulation

DES on the other hand focuses more on the objects that a system consists of. How they are represented can vary depending on the simulation software, but common elements include TUs, containers, conveyors, workstations, assembly stations, resources, and submodels (JaamSim 2021a). A DES model also contains information about processes, but usually without an explicit visualization. However, in contrast to BPMN, visual representation is not the main purpose of a DES model anyway. Instead, the model is used to receive quantitative information about the system by performing simulation experiments. (VDI 2018) An example for this would be the simulation of a queuing system: Instead of trying to calculate dynamic queuing lengths and waiting times analytically, the system behavior is modeled and simulated using simple elements like entity generators, statistical distributions, queues, and servers. Based on these, various simulation experiments can be conducted to represent different operating scenarios and predict the system behavior quantitatively and in detail. In many cases, DES can deliver very accurate solutions for this type of problem while requiring less modeling effort than other tools (Arnold and Furmans 2019).

The simulation models for this article have been created with the DES software "JaamSim" (JaamSim 2021a & 2021b).

METHODOLOGY

Combining BPMN & DES

As discussed above, each of the two modeling tools focuses on its own aspects of an MF system. Combining them makes it possible to create a more comprehensive model by using their respective advantages, and to reduce the modeling effort by using similarities and synergies. Figure 1 shows a methodology for the modeling and simulation of MF systems in which the BPMN model is used both as a result in itself and as a starting point for the creation of the DES model. A key element of this methodology is the use of generic modules, which is illustrated with an example later in this article.

The purposes of the system analysis as the first step of the methodology are to document external requirements, to gather information about the system and to decide on a sensible substructure. Qualitative information covers the different process paths which simulation entities can follow, the order of conveying and processing operations and the connected paths of simulation entities in assembly processes. This kind of information is necessary for the process modeling. That is, for creating a BPMN model, the modeler needs to understand all different process variants in the system but without the necessity of specific values, e. g. process times. To generate the DES model; however, quantitative data is necessary as well. The parametrization of the simulation requires inputs for conveying times, process times, and inter-arrival times of entity generators. In addition to that, if downtimes of processes are supposed to be represented, statistical distributions of breakdowns and maintenance must be provided.

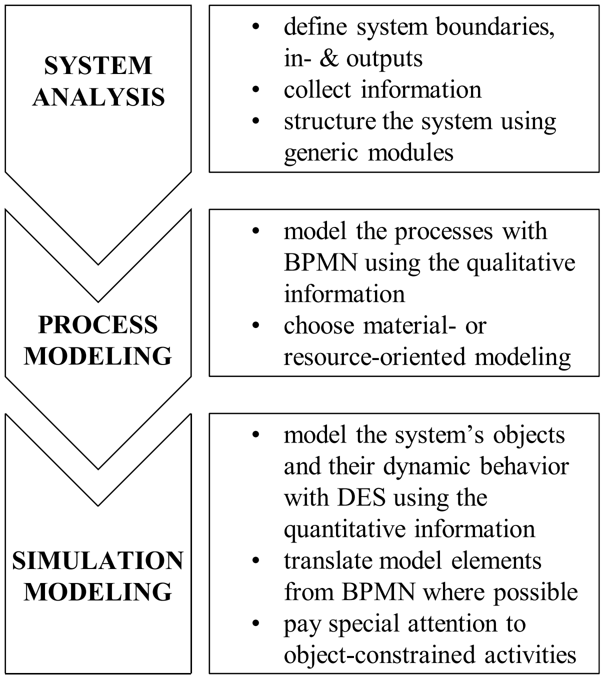

Figure 1: Systematic Modeling and Simulation of an MF System using both BPMN and DES

Regarding the second step of the methodology and the decision for material- or resource-oriented modeling in BPMN, a sensible approach is to use the SF to represent the more complicated (or more important) process type. Some examples for this are shown in this article.

Lastly, when creating the simulation model, the necessary effort can be reduced by translating between BPMN and DES. This is especially useful in material-oriented BPMN models, where the visualized sequence of activities shows strong similarities to the material flow in a DES model. Although the specific use always depends on the system, the modeling perspective, and other factors, it is generally possible to map certain elements between the two modeling tools. Table 1 shows selected examples. They are intended not only to show the underlying idea of translating between BPMN and DES, but also to clarify the content of figures 2 – 6. Although this table contains only a small subset of BPMN elements, it can be assumed that the vast majority of processes in MF systems can be mapped with it. This is firstly because only 20 % of the BPMN syntax is regularly used in practice (Muehlen and Recker 2013), and secondly because many qualitative and data-based relationships are mapped in BPMN via naming and comments, without requiring additional modeling elements.

Table 1: Comparison of Model Elements between BPMN & DES

BPMN	DES
Start Event	SubModelStart
End Event	SubModelEnd
Intermediate Event	Queue
Process TU	Server
Assemble TUs	Assemble
Add TUs to transport tool	AddTo
Remove TUs from transport tool	RemoveFrom
Transport TU	EntityConveyor
Subprocess	SubModel
Branching Gateway	Branch
Sequence Flow	Entity Flow
Message Flow between End and Start Event	Entity Flow

Generic Modules

When modeling complex systems in BPMN, it is recommended to identify subprocesses that are similar to each other and model them by creating and reusing a generic module, much as the source code of a computer program may define a function once and then call it multiple times (White 2004). Similarly, in DES, submodels are used to create a hierarchical structure, using generic modules here as well. It is therefore possible to translate not only individual elements, but even entire compound modules between BPMN and DES. In the logistics domain, most subsystems can be attributed to one of the basic functions mentioned above. This opens the possibility of creating a selection of generic modules that can be used for many different MF systems using different parameters, much like a software library. This, too, promises a reduction in the amount of work that must be invested in modeling an MF system with the described methodology. Generic modules provide support when structuring systems or modeling processes, objects, and their dynamic behavior.

An example for this is shown in the following. This module called “Deliver TUs” describes the movement of a vehicle transporting TUs between different workplaces in a recurring sequence. Figure 2 shows the depiction of this process in BPMN, where a resource-oriented model is used. Those activities that take place at the same location can be grouped into a subprocess (see Figure 3), which can then be translated into a DES submodel (see Figure 4).

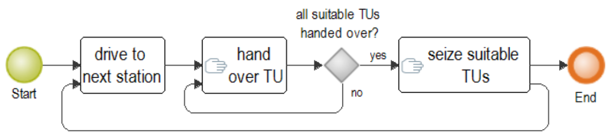

Figure 2: Module “Deliver TUs”: BPMN Process Model

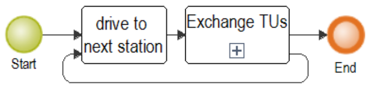

Figure 3: Module “Deliver TUs”: BPMN Process Model with subprocess “Exchange TUs”

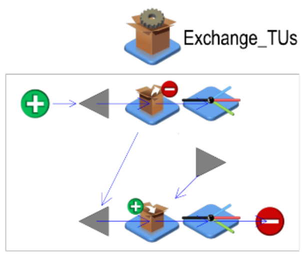

Figure 4: Module “Deliver TUs”, subprocess “Exchange TUs”: DES Model

When a simulation entity (representing a vehicle) enters the DES submodel, it will first pass through the upper part, releasing all suitable TUs to the Branch object, and then move on to the lower part, seizing all suitable TUs from the queue in the middle.

CASE STUDY

To evaluate the methodology described above, it has been applied to several real MF systems. One of these case studies, a production plant for motorcycles in Berlin, is shown in this section (BMW 2021, Welt 2017). Both qualitative and quantitative information for this system was gathered in workshops with process owners and cross-checked with specifications provided by developers of MF technology (e. g. conveying speed of belt conveyors). This MF system includes two assembly lines, "engine assembly" and "assembly", that each consist of several stations. The supply of components from the manufacturing department to these assembly stations is realized using a milk run delivery. This milk run is not used for the transport between the two assembly departments. Figure 5 and Figure 6 show parts of the BPMN and DES model for this system, respectively. The milk run delivery is a typical element of MF systems and can therefore be modeled generically, using the module "Deliver TUs" shown above, and additional EntityConveyors between the departments in the DES model, which represent the movement of the transport vehicles. In the BPMN model, activities labeled "[…]" are placeholders for additional processes, the illustration of which would go beyond the limits of this article.

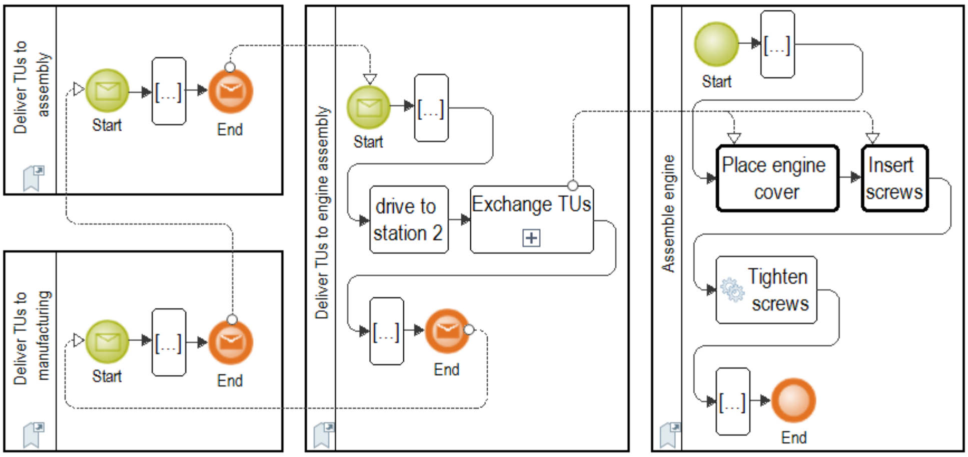

Figure 5: Motorcycle Production: Extract from the BPMN Process Model

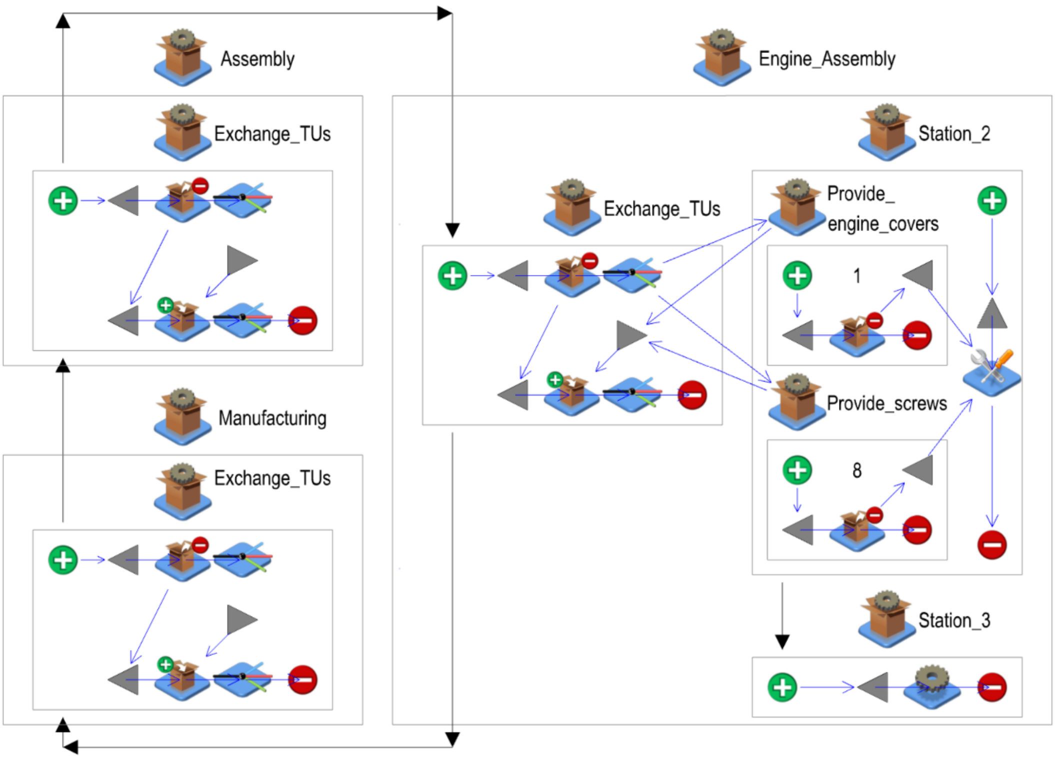

Figure 6: Motorcycle Production: Extract from the DES Model

As previously mentioned, modeling administrative processes with BPMN can be used to visualize weaknesses and help with improving the system. Using this case study, two examples show that the same is true for BPMN models of MF processes.

Firstly, Figure 5 shows that all the vehicles that deliver components pass through the departments of manufacturing, assembly, and engine assembly in the same order. There is no movement of individual components between assembly and engine assembly, so this procedure is inefficient. It can be improved by dividing the schedule so that the two assembly departments are supplied separately. The quantitative evaluation of this process change in the DES model shows that it could reduce the required number of vehicles by 25 %, thereby avoiding a waste of resources in the form of unnecessary WIP and transportation of material.

Secondly, a further consideration of the BPMN model reveals a potential improvement regarding equipment downtimes: In the engine assembly, a breakdown of the machine responsible for tightening the screws will result in a heavy accumulation of material right after station 2 or a shutdown of the assembly line. Depending on the reliability of this process, it could be sensible to implement a preventive measure, e. g. adding the activity "tighten screws" to the tasks of station 2 in case of a machine failure. This suggestion can be implemented into the BPMN model using additional gateways and intermediate events. Applying this change in the DES model shows that the "emergency plan" keeps the average throughput during a representative machine downtime at 60 % of its normal value. Without it, the machine failure would result in an increase in queue lengths and throughput times until station 3 is running again and the system can level off again.

DISCUSSION

Based on the results of the previous section, the two initial questions can be answered. For the combined modeling approach, it was first examined to what extent the BPMN syntax enables the mapping of different logistical processes. In this context, the principles of material- and resource-orientation were introduced. While the former is more suitable for linear connections of manufacturing and assembly steps, the latter should be used to depict transport processes in which material is picked up and delivered at several points. Especially when modeling in a material-oriented manner, most elements can be translated into DES without major problems. However, as the evaluation of important approaches from the literature showed, BPMN has proven to be largely unsuitable for mapping object-constrained activities and their quantitative effects, given that pools and lanes usually cannot represent the relationships in complex MF processes.

Lastly, it could be shown that BPMN models of MF systems are suitable to visualize typical improvement potentials of these systems as well as the qualitative advantages of the optimized processes. Changes in the MF can be modeled in BPMN by re-arranging the sequence flow between activities and events. Due to the lack of quantitative information in the BPMN models, DES is then used to test and evaluate the identified process improvements based on MF KPIs. It can be concluded that existing methodologies for systematic optimization are also applicable within this framework.

Although the presented methodology has a significant potential to increase the system performance while reducing the modeling effort, there are some limitations for its application. Modeling object-based activities with BPMN is hardly feasible and the scarcity of resources and other objects cannot be illustrated. Nonetheless, the approach can be applied to real-world industrial scenarios and process insights can be enhanced. The methodology clearly separates requirements and solutions and improves the usability, also by incorporating generic modules.

Compared to the related publications mentioned above, the methodology presented in this article applies BPMN specifically to MF systems without requiring any modifications of the existing syntax. Quite the reverse, combining BPMN and DES makes it possible to concentrate only on the common, useful, and well-understood modeling elements in each tool. This also results in a greater variety of eligible software, which is beneficial for applications both in industrial and academic settings.

SUMMARY

In this paper, a methodology for the modeling of MF systems using both BPMN and DES was presented. As a first part of it, the comparison between elements from both approaches allows for a translation from one framework into the other. Secondly, by synthesizing MF systems from generic modules, a plannable and time-saving modeling process could be created. The combination of standardized and well-known elements from both modeling languages allows for a methodology which is easy to understand and suitable for multidisciplinary teams. A case study at an MF process within a manufacturing system showed that the approach enables the identification and assessment of optimization potentials without the need for a costly real-world test run. Further research in this area could extend the "translations" to include rarer BPMN and DES elements, as well as expand the selection of generic modules to include other typical use cases in the MF domain. Regarding the detection and elimination of process weaknesses, the developed methodology could benefit from a more systematic approach specifically focused on the combination of BPMN and DES in the field of MF systems.

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