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DESIGN AND APPLICATION OF AN ONTOLOGY FOR DEMAND FULFILLMENT IN SEMICONDUCTOR SUPPLY CHAINS

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ABSTRACT

Ensuring interoperability of different information systems for planning and control is a challenging task in semiconductor supply chains. This is partially caused by the sheer size of the involved production facilities and the supply chains in the semiconductor domain, the permanent appearance of uncertainty, and the rapid technological changes which lead to sophisticated planning and control systems in this domain. Ontologies are a promising approach to support interoperability among such systems. Demand fulfillment is an important function in semiconductor supply chains. However, at the same time, it is a planning function that is not very well understood. In the present paper, a domain- and task ontology for demand fulfillment is designed based on a domain analysis. The usage of the proposed ontology is illustrated by means of an example.

1 INTRODUCTION

Planning and control of semiconductor supply chains is a challenging task due to the sheer size of the involved production facilities and supply chains in the semiconductor domain, the permanent appearance of uncertainty, and the rapid technological changes (Chien et al. 2011; Mönch et al. 2018a). This leads to a variety of information systems in semiconductor supply chains that are involved in making planning and control decisions (Fordyce et al. 2011; Chien et al. 2016; Mönch et al. 2013). Ensuring interoperability among the different information systems is challenging due to proprietary data formats, naming conventions introduced by the vendors, but also by different company-specific standards. The latter reason is especially important if mergers or joint ventures of different companies take place.

Ontologies are considered as a reasonable approach to deal with the interoperability problem in different manufacturing domains (Uschold et al. 1998). There are also specific ontologies for supply chain management (Grubic and Fan 2010; Scheuermann and Leukel 2014a among others). The digital reference (DR) (Ehm et al. 2019) is a semiconductor manufacturing-specific ontology. An ontology for planning and control tasks for semiconductor supply chain is designed by Herding and Mönch (2016b). However, there is no dedicated ontology for demand fulfillment activities in semiconductor supply chains with the rare exception of Soares et al. (2010) where a very basic demand fulfillment ontology is described. In the present paper, we are interested in designing and applying an ontology for demand fulfillment activities in semiconductor supply chains. For this purpose, we first present the results of a

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domain analysis which serves as base for specifying important concepts and their relations. We then apply the ontology for the communication between software agents.

The paper is organized as follows. In the next section, we will describe the problem in detail. Section 3 is devoted to the design of the ontology. An application of the ontology is discussed in Section 4. Conclusions and future research directions are provided in Section 5.

2 PROBLEM SETTING

2.1 Demand Fulfillment

Next, we describe the demand fulfillment function. It consists of the three subfunctions (Fleischmann and Meyr 2004; Kilger and Meyr 2015):

- allocation planning
- order promising
- order repromising.

We will describe these subfunctions in more detail. The available to promise (ATP) notion plays a central role for demand fulfillment. ATP quantities are stocks at hand or projected supplies. The ATP calculations for a single product g can we described in a slightly simplified form as follows (Fleischmann and Meyr 2004), where we assume that a planning window of length T is divided into equidistant periods $t = 1, \ldots, T$. The following data is given:

I_{g0}: initial inventory of product g

S_{gt}: projected supply of product g in period t

C_{gt}: aggregate promised orders for product g in period t.

The inventory of product g in period t can be calculated as follows:

$$I_{gt} = I_{g0} + \sum_{s=0}^{t}\left(S_{gs} - C_{gs}\right), \quad t = 1, \ldots, T. \tag{1}$$

The cumulated ATP quantities in period t are given as:

$$cATP_{gt} := \min\left\{I_{gs} | t \leq s \leq T\right\}, \quad t = 1, \ldots, T. \tag{2}$$

These quantities are the total ATP of product g that can be used in period t. The yet uncommitted quantities of product g that become available in period t and can be consumed in periods $t \leq s \leq T$ is given by

$$ATP_{gt} := cATP_{gt} - cATP_{g,t-1}, \quad t = 1, \ldots, T. \tag{3}$$

Note that if $S_{gt} - C_{gt} \geq 0$ for all $t = 1, \ldots, T$ we obtain $ATP_{gt} := S_{gt} - C_{gt}$ based on (1)-(3). The provided calculation scheme is flexible. For instance, we obtain $ATP_{gt} := S_{gt}$ when we assume $C_{gt} \equiv 0$, i.e., already promised orders are excluded. Sometimes, these quantities are called raw ATP. The projected supply S_{gt} is a result of master planning where for each facility, product, and period the quantities are computed that have to be completed by the supply chain (Mönch et al. 2018b). In typical supply chains, the ATP quantities are obtained by subtracting the quantities of the confirmed orders from the raw ATP on a daily base. The different types of ATP quantities are used by the subfunctions of demand fulfillment.

Allocation planning deals with assigning scarce ATP quantities to individual customers or customer classes taking into account the given demand. This usually happens before the remaining ATP is calculated from raw ATP. Allocated ATP (AATP) is the result. Order promising is associated with the order entry process. It is responsible for the initial ATP/AATP consumption by orders. When customer orders arrive they are matched with the corresponding ATP or AATP quantities. Three different order promising modes are distinguished:

1. Online order promising: An order is immediately promised after the customer places an order.
2. Batch order promising: All orders placed during the batch interval are simultaneously considered at the end of the batch interval. They are promised at a specific point in time.
3. Hybrid order promising: Online order promising activities are carried out for a certain period of time, followed by a batch promising step afterwards where the previously made promising decisions are confirmed and eventually are improved.

A first promised delivery date $\tau_o^{(i)}$ is chosen for each order o by order promising. $\tau_o^{(i)}$ should be as close as possible to d_o. In the shortage case, i.e. if not enough ATP is available at the desired delivery date d_o, it is often searched for supply alternatives by rules, for instance, for the same product before or after d_o or by substitute products (Kilger and Meyr 2015). Order repromising approaches follow a multi-step procedure:

1. New ATP/AATP quantities are calculated based on updated supply information.
2. The repromising of a subset of the orders or even all unfinished orders is carried out.
3. An ATP/AATP reservation for the repromised orders takes place.
4. The remaining ATP/AATP quantities are transferred to the order promising function for newly arriving orders.

All already promised but unfinished orders are considered within short-term demand supply matching (STDSM) approaches (Fleischmann and Meyr 2004) taking into account the available supply and capacity. The STDSM can be considered as a specific order repromising approach. The objectives are to keep the promised delivery dates as much as possible and to perform the manufacturing processes at the lowest possible costs. The STDSM function is similar to batch promising, but all already promised orders compete for the supply and the capacity in the STDSM, while only the orders arriving in the batch interval are considered in the case of batch order promising. Rule-based order repromising approaches similar to order promising approaches are also possible for order repromising.

The subfunctions are typically carried out in a rolling horizon manner. For this, we assume that there is a planning window which consists of $t = 1, \dots, \mathrm{T}$ planning periods of equal length. Each planning window constitutes a planning epoch. First, at the beginning of a planning epoch, master planning is carried out to determine supply for the ATP calculation, followed by allocation planning to determine AATP quantities. Order repromising is performed next. The remaining ATP/AATP quantities are sent to the order entry process with the associated order promising activities. The procedure is repeated at the begin of the next planning epoch which often starts immediately after the first planning period is over.

2.2 Problem Setting

A conceptualization of a domain is given by objects, concepts, and other entities that are assumed in some domain and the relationships among them. An ontology is an explicit specification of a conceptualization (Gruber 1995). Ontologies are used in manufacturing systems and supply chains to facilitate communication, domain knowledge sharing among decision-makers or software agents, and improve reusability (Chungoora et al. 2013). Moreover, they enhance interoperability between related information systems for planning and control, and domain assumptions are made explicit by ontologies.

In the present paper, we are interested in designing an ontology for demand fulfillment activities in semiconductor supply chains. Demand fulfillment in semiconductor supply chains is an appropriate domain since often related principles are not clearly presented (Mönch et al. 2018b). Hence, concepts must be derived that represent the demand fulfillment domain. In addition to the concepts, domain- and task-related predicates must be identified. Domain-related predicates are facts related to a given semiconductor supply chain, while task-related predicates describe how the objectives of the demand fulfillment process are fulfilled. Finally, activities have to be identified and modeled which allow for interaction between different entities using concepts and predicates. Such an ontology can be useful when demand fulfillment activities are carried out by several services or software agents, autonomous software entities, in a highly automated manner. In this situation, the interaction of the different entities requires a rich communication which cannot be ensured by standard interfaces. In the present paper, we are interested in applying the ontology for implementing demand fulfillment functionality in the **s**emiconductor **s**upply **c**hain **m**ulti-**a**gent **s**ystem (S^2CMAS) (Herding and Mönch 2016a). It is expected that software agents will be important for next-generation information systems when implementing the industry 4.0 vision (VDI/VDE 2019).

2.3 Related Work

Ontologies for supply chain management are surveyed by Grubic and Fan (2010) and Scheuermann and Leukel (2014a), (2014b). However, semiconductor supply chain-specific details are not included. Moreover, demand fulfillment is not considered in these survey papers. An ontology for a printer supply chain is proposed by Yan et al. (2008). Again, semiconductor specifics are not addressed. Only a few semiconductor supply-specific ontologies and reference data models exist so far, namely the production scheduling-related ontologies by Mönch and Stehli (2003) and Mönch and Zimmermann (2008), the planning-related ontology for the S^2CMAS prototype by Herding and Mönch (2016b), the generic data model for operations in wafer fabrication operations proposed by Laipple et al. (2018), and the DR (Ehm et al. 2019; Ehm et al. 2020).

However, demand fulfillment activities are not specifically discussed in these ontologies. The rare exception is Soares et al. (2000) where the virtual enterprise ontology for semiconductor supply chains is outlined. It is related to the order promising process in a wafer fab. However, the remaining demand fulfillment subfunctions are not considered.

Even for domains different from semiconductor manufacturing, there is no ontology described for demand fulfillment and order-management activities so far. We are only aware of Schema.org (2021) where a single order is modeled. In the present paper, we are interested in reducing this gap by designing an ontology for demand fulfillment.

3 DEMAND FULFILLMENT ONTOLOGY

3.1 Overall Approach

The proposed ontology is a hybrid between a domain and a task ontology. Figure 1 provides a UML class diagram that models the data needed by demand fulfillment tasks in semiconductor supply chains. The data model shows the concepts only on a high level. We use the data model as a starting point to derive concepts for demand fulfillment in semiconductor supply chains. Note that some of the concepts are already exist in general-purpose ontologies such as the Enterprise Ontology proposed by Uschold et al. (1996). However, extensions and refinements are required for the semiconductor supply chain domain. These extensions, for instance with respect to product structure, timing aspects, and demand, will be described in more detail when we discuss below the corresponding concepts. In addition to concepts, we will identify activities and predicates.

Due to space limitations, we are only able to present a subset of all concepts, activities, and predicates. The complete ontology including an implementation in Protégé can be found in the electronic companion (Demand Fulfillment Ontology 2021).

3.2 Concepts

We derive the following concepts for demand fulfillment based on the data model from Figure 1. Arrows with a filled diamond shape refer to a composition, while arrows with a hollow triangle shape indicate inheritance relationships between classes. The description of the concepts is organized in such a way that a grouping according to important broader categories takes place.

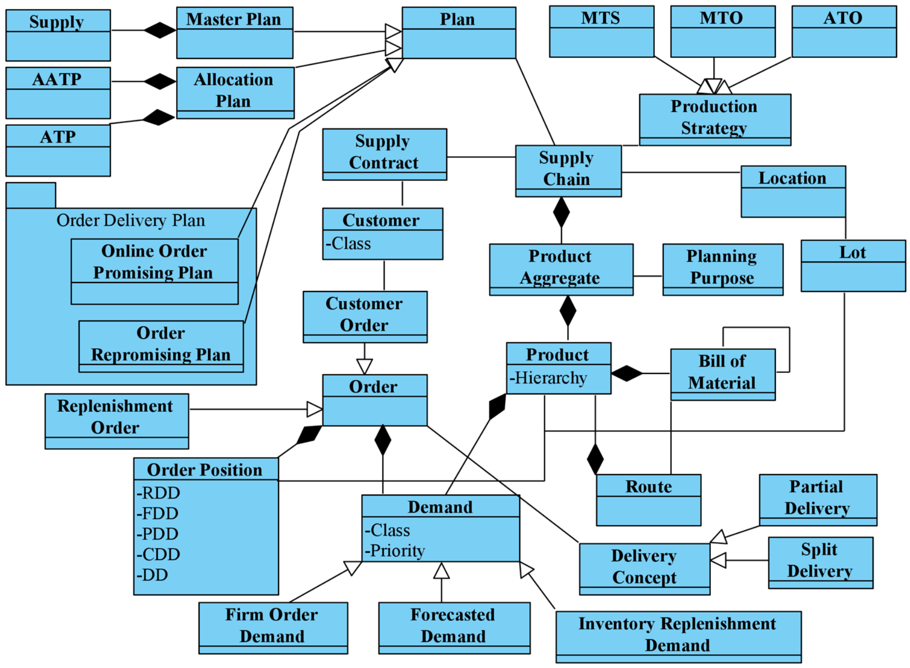

Figure 1: Data model for demand fulfillment in semiconductor supply chains.

3.2.1 Product

Product: A product is a good that fulfills a prescribed set of requirements (for instance, form, fit, and function). A set of alternative bills of materials might be associated with each product. The manufacturing process is complicated by binning and substitution (in production). Binning refers to the process that an item can become one of several products based on tested levels of performance, for instance, speed.

Bill of Materials (BOM): A BOM describes components or rather semi-finished products that are part of a finished product. Substitution, often associated with binning, is based on the possibility that alternative items might be used to finish a process step. This leads to the notion of alternative BOMs.

Route: The term route can be considered on different levels. In the present situation, a route is associated with a product and describes its production flow on the production network level.

Product Hierarchy: This concept characterizes the top-down and bottom-up relationship between different product aggregates. It organizes the product aggregates according to defined criteria.

Product Aggregate: The concept product aggregate is used to group different products based on certain criteria. The grouping criteria depend on the planning purpose (e.g. controlling, production). It is a certain view (external or internal) on a set of products.

3.2.2 Demand

Demand: A demand is a production request for a specific product or service that can have different triggers. Either demand exists explicitly in form of customer orders or implicitly as expected customer need that have to be fulfilled by the semiconductor supply chain.

Demand Class: This concept is used for dividing the total forecast for a given product into several priority classes.

Firm Order Demand: This is a special demand class that is used for demand that is required to fulfill already committed/accepted orders.

Inventory Replenishment Demand: This concept refers to a special demand class that is used for replenishment of safety stock.

Forecasted Demand: This is a special demand class that is used for the projection of future demand.

Demand Priority: This concept is used to describe the different importance levels of a demand. The demand priority can be assigned independently from the demand class.

3.2.3 Order and Delivery

Order: An order contains at least one order position. An order has an order type and is associated to demand.

Order Position: An order position refers to a product specification, a quantity, and a requested delivery date. Each order position has a status and belongs to an order.

Replenishment Order: This is an order that is initiated by an internal request of the semiconductor manufacturer to produce the order according to the make to stock (MTS) strategy. A replenishment order can be divided into different sub order types, depending on the purpose of order creation.

Customer Order: This is an order that is initiated by a customer.

Delivery Concept: The deliver concept defines the terms and conditions for delivering an order to the customer. Especially partial and split delivery has to be taken into account.

Split Delivery: It can be allowed that order positions of an order are delivered in several portions.

Partial Delivery: It can be allowed that only parts of an order position of an order are delivered. Therefore, the customer is willing to waive parts of the quantity belonging to an order position.

3.2.4 Supply and ATP

Customer: A customer can place orders. He raises a demand for a specific product or service. Internal and external customer demand can be distinguished.

Customer Class: The set of all customers is divided into different priority classes or segments based on certain criteria like profitability or importance of customer.

Supply: This is the total amount of specific products that is available to customers. Supply has the dimensions quantity, time, location, product, including aggregations of all dimensions. Supply is defined as inventory or plan replenishment.

ATP: The part of the inventory and projected supply that can be used to fulfill customer orders is called ATP.

AATP: When scarce ATP quantities are allocated to different customer classes or customers, the resulting supply reservations are called allocated ATP (AATP) quantities.

Batching Interval: This is the time span for which arriving orders are collected to derive for all of them jointly a first promised delivery date.

3.2.5 Timing

Requested Delivery Date (RDD): The RDD is the point in time when the customer wants to get the order position.

Promised Delivery Date (PDD): This is the date for which eventually partial order position delivery is confirmed. The PDD date can be changed over time. Within the repromising process there are typically different PDDs available.

First Promised Delivery Date (FPD): Initially, the FPD is set for a delivery of an order position within the online order confirmation process.

Confirmed Delivery Date (CDD): The CDD is the committed date for a delivery of an order position that is communicated to the customer. It depends on the communication strategy between manufacturer and customer.

Delivery Date (DD): This is the point in time when the customer receives the requested order position.

3.2.6 Planning

Plan: A plan is an activity specification with an intended purpose. Planning is an activity with the purpose to determine a plan. Planning is associated with goals, in the present situation represented by objective functions to be optimized

Planning Window: Planning in supply chains is associated with a planning window which is formed by a set of consecutive planning periods.

Planning Period: A planning period is a specific DateTimeInterval from the time ontology (Time Ontology 2020). It belongs to a planning window. It has a temporal duration.

Planning Purpose: The planning purpose describes a set of criteria that influence other concepts, e.g. product aggregate.

Master Plan: A master plan is a specific plan which determines which quantity resulting from confirmed orders and from forecasted demand should be completed in which location in which period of the planning window. Moreover, outsourcing decisions have to be represented in master plans.

Allocation Plan: An allocation plan is a special plan which deals with assigning ATP quantities to a customer or a customer class.

Order Delivery Plan: This is the result of the order promising or repromising process for different sets of orders taking into account an allocation policy and the supply and allocation situation. Different order promising variants can be distinguished, for instance online order promising, batch order promising, and hybrid order promising. The same is true for order repromising.

3.3 Predicates

Examples for domain- and task-related predicates are collected in Table 1. We refer to Demand Fulfillment Ontology (2021) for the complete set of predicates. The first three predicates are domain-related, while the remaining ones are task-related.

Table 1: Important predicates for demand fulfillment.

Predicate	Description
SPLIT_POSSIBLE	determines whether an order split is possible for a customer or not
PARTIAL_DELIVERY_POS-SIBLE	determines whether a partial order delivery is possible for a customer or not
ALTERNATIVE_BOM_-AVAILABLE	determines whether an alternative BOM is available for a given product aggregate or not
ORDER_REPROMISING_POS-SIBLE	determines whether the start of the order repromising process is possible or not
ONLINE_ORDER_PRO-MISING_POSSIBLE	determines whether the start of the online order promising process is possible or not
REPROMISED_ORDERS_-AVAILABLE	determines whether repromised orders are available or not
PROMISED_ORDERS_-AVAILABLE	determines whether promised orders are available or not
ALLOCATION_PLAN_-AVAILABLE	determines whether a new allocation plan is available or not
MASTER_PLANNING_POSSIBLE	determines whether the start of the master planning process is possible or not
MASTER_PLAN_AVAILABLE	determines whether a master plan is available or not
ORDER_ARRIVED	determines whether a customer has placed a new order or not
ORDER_ACCEPTED	determines whether a customer order is accepted or not
ORDER_COMPLETED	determines whether a given order is completed or not

3.4 Activities

Examples for activities are given in Table 2. We refer to Demand Fulfillment Ontology (2021) for the complete set of activities. We distinguish decision-making agents (DMAs) and staff agents (SAs) in the S²CMAS prototype (Herding and Mönch 2016a) following the Product Resource Order Staff Architecture (PROSA) (Van Belle et al. 2012). Staff agents support decision-making agents, or more general decision-making entities, in course of solving their decision problems. Algorithms for decision-making are typically encapsulated by staff agents. Some of the identified predicates and activities for demand fulfillment are shown in Figure 2 by means of a UML class diagram. Predicates are models as attributes, whereas activities are represented by methods.

4 APPLICATION OF THE ONTOLOGY

The ontology has to support the communication of software agents. We illustrate the use of the proposed ontology by modeling the online order promising process in the S²CMAS prototype. The interaction between the online order promising DMA (OOP-DMA) and the corresponding online order promising SA (OOP-SA) is modeled. The OOP-DMA receives the information that a new order is arrived and asks the OOP-SA for initiating online order promising activities. Therefore, the OOP-DMA agent makes decisions with respect to the maximum amount of computing time, the length of the planning window, the length of a single planning period, and the promising strategies to configure the online order promising approach. When the DMA has received this information, it is able to gather the remaining data to make order acceptance decisions. In addition, based on the allowed computing time, a promising approach is chosen by the SA. The OOP-DMA asks then the OOP-SA to compute an order delivery plan for the order.

Finally, the OOP-DM asks for the result of the planning activities and informs other DMs that new order promising results are available. The interaction between the OOP-DMA and the OOP-SA is illustrated in Figure 3 by means of a specification and description language (SDL) diagram. Failure situations are not modeled. The messages in red color are from the OOP-DMA while the blue-colored messages are from the corresponding SA.

Table 2: Important activities for demand fulfillment.

Activity	Description
GET_LOCATION_INFOR-MATION	asks for location-specific information such as available products, machine groups, routes, and available capacity
GET_PRODUCT_STRUCTURE	requests the products, product aggregates and their hierarchical order for decomposition purposes
INITIATE_MASTER_PLANNING	initiates master planning activities through the master planning decision-making entity
COMPUTE_MASTER_PLAN	asks the staff entity of master planning to compute a master plan
GET_SUPPLY	determines the supply calculated by master planning
GET_FORCASTED_DEMAND	returns the part of the demand that is based on forecast
GET_AATP	asks for the AATP quantities for order promising
GET_PROMISED_ORDERS	asks for the already promised orders
INITIATE_ONLINE_ORDER_PROMISING	initiates online order promising by determining the relevant data to execute the online order promising approach
START_ONLINE_ORDER_PROMISING	asks for starting online order promising
INITIATE_ORDER_REPRO-MISING	initiates order repromising by determining the relevant data to execute the order repromising approach.
START_ORDER_REPROMISING	asks to start a specific order repromising approach
GET_UNPROMISED_ORDERS	asks for all orders which do not have a PDD
GET_PROMISED_ORDERS	asks for all already promised orders

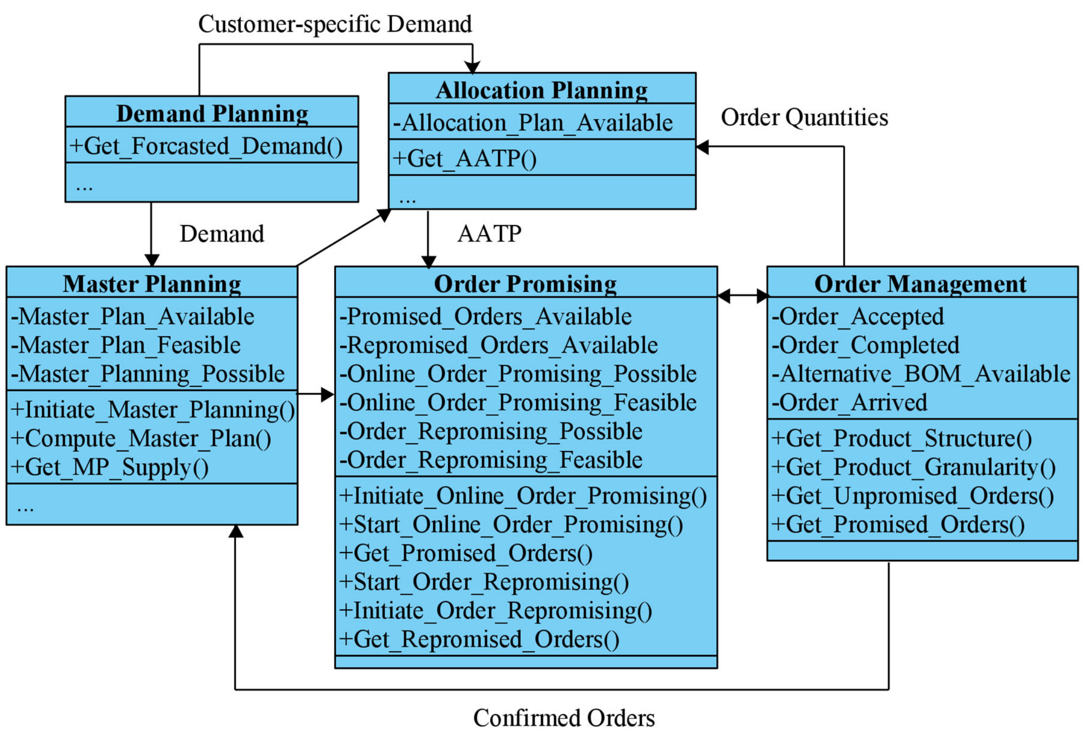

Figure 2: Demand fulfillment and its predicates and activities.

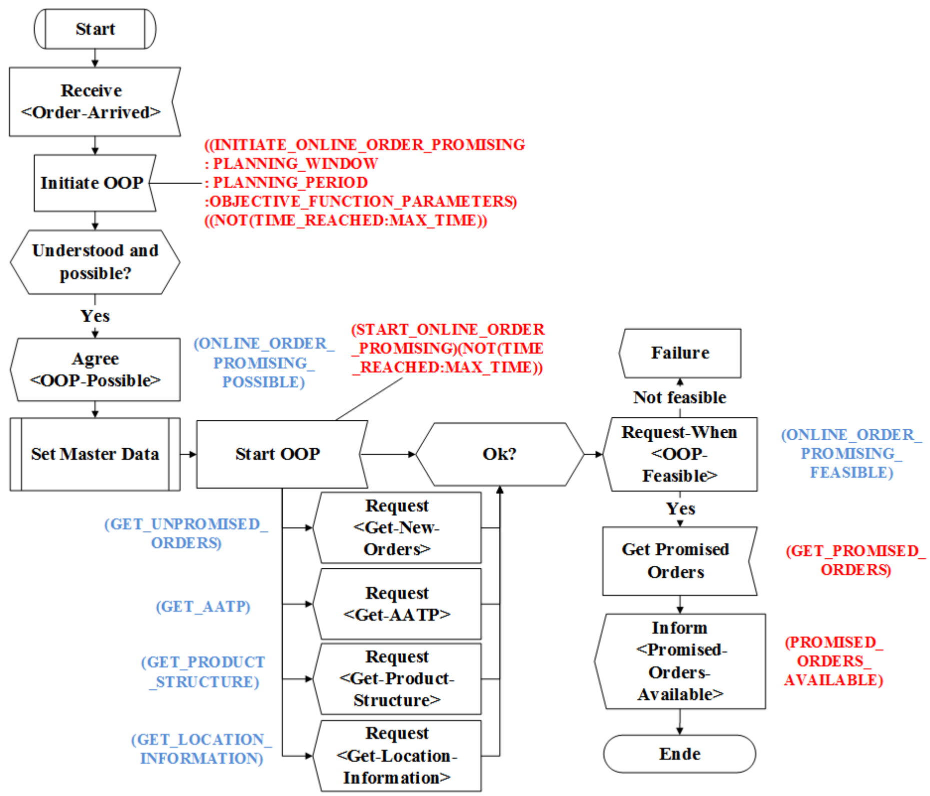

Figure 3: SDL diagram for online order promising.

Concepts, activities, and predicates of the proposed ontology are used. The red-colored messages from the DMA indicates that this agent asks the SA to initialize and start the promising activities and asks for the obtained results. The blue-colored messages from the SA indicate that the SA informs the DMA about the status as well as requests additional data from other agents required for the chosen OOP approach. The predicates of the ontology are used to communicate the success or failure of agent activities by the SA. We observe from Figure 3 that the agent activity INITIATE_ONLINE_ORDER_PROMISING is refined by a more detailed description including, for instance, the concept identifiers PLANNING_WINDOW and PLANNING PERIOD from the ontology.

5 CONCLUSIONS AND FUTURE RESEARCH

In this paper, we considered demand fulfillment activities in semiconductor supply chains. We designed a task- and domain ontology for demand fulfillment. A complete version of the ontology including an implementation based on Protégé is publicly available under Demand Fulfillment Ontology (2021). The proposed ontology was applied to model the interaction between software agents in course of the online order promising process in the S²CMAS prototype.

There are several directions for future research. First of all, we are interested in designing an appropriate content language for the S²CMAS prototype. Interaction protocols similar to one sketched in Figure 3 must be designed too. Moreover, we are interested in integrated the proposed ontology into the digital reference as a subontology. It seems also desirable and possible to generalize the proposed ontology to obtain an ontology for planning decisions in semiconductor supply chains. Only initial steps towards reaching this goal are reported in Scheuermann and Leukel (2014b).

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