# Planning Ontology for Semiconductor Supply Chains

## 1. Motivation

Planning a semiconductor supply chain is a complex endeavor. Even a single semiconductor wafer fabrication facility (wafer fab) may have hundreds of process steps to develop a chip. The planning work can be complicated by multiple facilities and suppliers and the bond, assembly, and test operations integrating the chips into modules and later finished products.

Planning is carried out at various levels of granularity (see Fordyce *et al.* 2011), for different purposes, with different time horizons, and with varying frequencies. Strategic planning may be conducted once or twice per year, for major product groups, and with a multiple-year planning horizon, e.g. five years. At the other end of the scale, detailed operational planning may be conducted daily at a lot level of detail with a planning horizon of only a few days. In between are one or more levels of tactical operational and aggregate planning. Some planning may be done at the enterprise level across all fabs, assembly plants, and vendors, while other planning may focus on a subset of an individual fab. Extensive surveys of semiconductor supply chain models may be found in Mönch *et al.* (2018a), (2018b), and Uzsoy *et al.* (2018). Enterprise planning is described, for instance, in Degbotse *et al.* (2013) while Bansal *et al.* (2019) introduce iterative combinatorial auctions to facilitate the integration of decentralized manufacturing units and their local models to achieve coordinated results for the enterprise in the introduction of product transitions.

The purpose of this ontology is to specify planning situations and the corresponding organization of data in semiconductor supply chains in a unified manner. While many semiconductor supply chain models and their specific applications are described in the literature, only occasionally does a single paper describe multiple integrated applications (see for instance the Heiney *et al.* 2021, Herding and Mönch 2022). Even these papers do not describe the detailed data structures used in support of these applications. It would be advantageous to have a single set of integrated data structures that can be used across a semiconductor manufacturing enterprise for its various supply chain planning applications.

This ontology facilitates the development of an integrated set of data and also a unified way of thinking about related business processes and applications. Ultimately, the ontology can be a fundamental building block of a well-run organization's business processes and the data, applications, and models that support them synergistically.

The rest of this document is organized as follows. In Section 2, we will briefly describe the design of the planning ontology. Concepts related to the planning system and process are discussed in Section 3. Concepts to describe the base system and process are presented in Section 5. In Section 4, concepts representing the control system and process are shown. Predicates and agent activities of the planning ontology are summarized in the Sections 6 and 7, respectively.

## 2. Overall Design of the Ontology

Taking a system theoretic point of view, we distinguish the base system from the control system and the planning system of an arbitrary manufacturing system (Mönch *et al.* 2013). The planning system supports planning decisions, whereas the planning process determines when and under which conditions these decisions are made. The control system supports production controlling decisions, i.e. scheduling decisions and decisions related to lot sizing and setting inventory control policies. The base system is formed by working objects and

We will use the decomposition into base system, control system, and planning system when we derive the concepts of the planning ontology.

## 3. Concepts to Represent the Planning System and Process

**Concept Definition:** A **PLANNING OBJECT** specifies what has to be planned as an atomic unit. A single PLANNING OBJECT typically represents a quantity of a certain product or product aggregate to be released or completed within a certain period in a certain node of the semiconductor supply chain. Other PLANNING OBJECTs can be orders or lots where lots refer to a group of production units that travel together through the wafer fab or backend facility.

Values are assigned to the attributes of a PLANNING OBJECT as a result of a planning decision.

**Properties.** A PLANNING OBJECT has several defining properties:

**IDENTIFIER:** Each PLANNING OBJECT has a unique identifier, abbreviated by ID.

**PRODUCT:** A PLANNING OBJECT is related to a PRODUCT/PRODUCT AGGREGATE. It specifies the type of good that is requested.

**(Optional) QUANTITY:** This property describes the size of a PLANNING OBJECT to be determined. The size can be measured, for instance, in wafers, number of items, number of lots, etc.

**TIME:** This property is required to manage timing aspects of a PLANNING OBJECT. It can be a release time, a finishing time, a single start time, or a set of start times for certain ACTIVITIES to be fulfilled.

**(Optional) LOCATION:** This property describes the place or places, for instance nodes of the semiconductor supply chain or specific machines of a work center where the ACTIVITIES associated with the PLANNING OBJECT have to be executed.

**(Optional) PRIORITY:** This property describes the relative importance of the PLANNING OBJECT. It provides the base for establishing a partial ordering of the importance of the set of planning objects.

**OWNER:** A PLANNING OBJECT is rarely considered in isolation. Usually it belongs to a set of PLANNING OBJECTS, for example, a planning instance.

**ACTIVITIES:** This property describes the set of activities that must be carried out to produce the goods that are associated with the PLANNING OBJECT.

Moreover, there are additional parameters for most types of PLANNING OBJECTS.

**EARLIEST RELEASE DATE:** This is the earliest time when the activities associated with a PLANNING OBJECT can start. Note that the parameter EARLIEST RELEASE DATE is exogenous, i.e. given, in contrast to the property TIME.

**DUE DATE:** This is the latest time when the activities associated with a PLANNING OBJECT have to be finished. Note that the parameter DUE DATE is exogenous, i.e. given, in contrast to the property TIME.

**(Optional) QUANTITY:** This property describes a given, i.e. fixed, size of a PLANNING OBJECT, for instance, the number of wafers that belong to a lot. Note that the parameter QUANTITY is exogenous, i.e. given, in contrast to the property QUANTITY where the amount of the quantity has to be decided.

Several examples for PLANNING OBJECTS are described.

1. In production planning, the quantities for all products have to be determined that must be released in a given period of the planning window (Kacar *et al.* 2013). These quantities form the PLANNING OBJECTS. Note that production planning activities are always related to a given frontend (FE) or backend (BE) facility.
2. In master planning, the quantities that have to be completed in a given period of the planning window for all facilities in a given semiconductor supply chain must be determined. (Ponsignon and Mönch 2012). These quantities form the PLANNING OBJECTS.
3. In lot planning, the start and completion dates of the macro-operations (Mönch *et al.* 2013) of a given lot form the PLANNING OBJECTS. Macro-operations are formed by consecutive operations, i.e. process steps of the route of a certain product.
4. IDemand fulfillment. Finished goods inventory is allocated to customer orders, the corresponding inventory is picked (i.e. withdrawn from inventory), and the orders are shipped to the customer. A similar allocation of supply to customer orders occurs during an Available To Promise (ATP) calculation. In both types of allocations, the PLANNING OBJECTS represent the inventory (whether in finished goods or anticipated to arrive in finished goods inventory) allocated to the customer orders. Moreover, the orders with a delivery date to be promised are also planning objects.

**Concept Definition:** A **PLANNING CONSTRAINT** restricts the action space. This space is formed by alternative actions that are a result of the planning decisions (Schneeweis 2003). In the planning domain, PLANNING CONSTRAINTS, often the capacity offered by resources, limit the quantities that are assigned to the PLANNING OBJECTS or impact the temporal properties of PLANNING OBJECTS.

Different types of **PLANNING CONSTRAINTS** are distinguished, namely:

1. **RESOURCE-AVAILABILITY-CONSTRAINT:** This type of constraint has an impact on the assignment of activities to RESOURCES and to START/END TIMES to ACTIVITIES.
2. **TEMPORAL-CONSTRAINT:** This type of constraint restricts the values of temporal attributes, modeled by the property TIME, that belong to PLANNING OBJECTS. For instance, there might be a minimum amount of time between two consecutive operations of a certain product in a given period. There are also situations in wafer fabs where a maximum amount of time between consecutive operations is possible (so-called queue time constraints).

3. **RESOURCE-COMPATIBILITY-CONSTRAINT:** This type of constraint ensures that only allowed activities are performed using a given RESOURCE.

**Properties.** A PLANNING CONSTRAINT has several defining properties:

**HARD:** PLANNING CONSTRAINTS with this property cannot be violated.

**SOFT:** PLANNING CONSTRAINTS with this property can be violated. This means that the degree of violation is typically penalized in a related criterion or performance measure.

Moreover, there are additional parameters for most types of PLANNING CONSTRAINTS.

**START-TIME:** This is the earliest point in time when the PLANNING CONSTRAINT is active.

**END-TIME:** This is the latest point in time when the PLANNING CONSTRAINT is active.

Several examples for PLANNING CONSTRAINTS are described.

1. In production planning, the most important PLANNING CONSTRAINTS are the capacities of the workcenters of the wafer fab (Kacar *et al.* 2013). Moreover, there are precedence constraints for the operations of the products that are constituted in the routes.
2. In master planning, the most important constraints are the capacities of the bottleneck workcenters (Ponsignon and Mönch 2012). We have again precedence constraints for the operations of the routes.
3. In lot planning, the capacity constraints for the bottleneck steps of a macro-operations are taken into account. Moreover, precedence constraints for the operations and macro-operations of the different products are respected (Mönch *et al.* 2013).

**Concept Definition:** The **PLANNING PURPOSE** specifies the objectives of a certain planning activity. It is given by a set of performance measures that are related to a set of PLANNING OBJECTS.

**Properties.** A PLANNING PURPOSE has several defining properties:

**PERFORMANCE MEASURES:** Each PLANNING PURPOSE is determined by a set of performance measures. Each measure is defined by a calculation procedure. Performance measures can be blended using weights to express the importance of the different measures.

**CRITERIA:** A criterion is assigned to each performance measure that belongs to a PLANNING PURPOSE. Typical criteria are maximization, minimization, i.e. if an optimization problem is considered, or larger or smaller than a prescribed value of the certain performance measure, a so-called target, i.e. if a satisfaction problem is solved. In a multi-criteria setting, the dominance concept for plans is of interest.

**(Optional) TARGETS:** Targets are prescribed values for the different performance measures.

**(Optional) PLANNING WINDOW:** A planning window describes for which amount of periods or which time span the performance measure values have to be calculated. In some situations, the planning window will determine the set of planning objects, for instance, lots completed within the planning window.

**PLANNING OBJECTS:** A set of planning objects is required to determine the performance measure values belonging to the PLANNING PURPOSE. The set of planning objects is often determined by the planning window.

**(Optional) WEIGHTS:** Weights can be used to express preferences of the decision makers among the different performance measures and related criteria.

Moreover, there are additional parameters for most types of PLANNING PURPOSES.

**COST:** Cost refers to the amount of money that is needed to do a certain action for a unit of a certain good, for instance, store or produce a unit of a product. Variable cost is distinguished from fixed cost.

**REVENUE:** Revenue refers to the amount of earnings generated by the sale of one unit of a certain good.

**PENALTY:** If CONSTRAINTS are violated by a plan penalties might be used to change the performance measure values to express that the violations are undesired.

Several examples for PLANNING PURPOSE are described.

1. In production planning, the PLANNING PURPOSE is cost minimization, i.e., the sum of work in progress (WIP), backlog, and inventory holding cost is minimized. Moreover, after the plans are executed under uncertainty, the mean profit, i.e., the difference of revenue and costs is used as performance measure (Kacar *et al*. 2013). Here, the profit is maximized, i.e. profit maximization is the PLANNING PURPOSE.
2. In master planning, the difference of revenue obtained from fulfilling additional forecasted demand and manufacturing, inventory holding, and backlog costs for confirmed orders is considered (Ponsignon and Mönch 2012). In this sense, profit maximization is the PLANNING PURPOSE.
3. In lot planning, the total weighted tardiness of all lots is minimized (Mönch *et al.* 2013). Total weighted tardiness minimization is the PLANNING PURPOSE.

**Concept Definition:** The **PLANNING PROCESS** specifies under which circumstances which (re)planning activities are performed by a DECISION-MAKING UNIT.

**Properties.** A PLANNING PROCESS has several defining properties:

**PERIODIC-TRIGGER:** This property defines after which amount of time a replanning activity is initiated in a periodic manner (Vieria *et al.* 2003). Rolling horizon approaches are triggered by such a periodic approach.

**EVENT-TRIGGER:** This property determines which events result in replanning (Vieria *et al.* 2003). For instance, replanning can be the result of the breakdown of a bottleneck resource.

**REPLANNING-DEGREE:** The degree distinguishes replanning from scratch and repair of existing plans (Vieria *et al.* 2003).

**FROZEN-FENCE:** This property specifies which planning decisions will remain unchanged in the case of replanning activities.

**PLANNING APPROACH:** This property defines which algorithm is used to make the required decisions.

**MAXIMUM COMPUTING TIME:** This property specifies the maximum time allowed to perform a certain planning activity.

**PLANNING PURPOSE:** The property specifies the objectives of the planning activities associated with the PLANNING PROCESS.

Moreover, there are additional parameters for most types of PLANNING PROCESS.

**PLANING INSTANCE:** Activities associated with PLANNING PROCESS require an instance of the concept PLANNING INSTANCE.

**PLAN:** Activities associated with a PLANNING PROCESS require an instance of the concept PLAN.

Several examples for PLANNING PROCESS are described.

1. In production planning, the PLANNING PROCESS is given by periodic replanning activities. A new plan is computed from scratch (Kacar *et al.* 2013). Initial WIP, backlog, and inventory are taken into account by means of initial values.
2. In master planning, the PLANNING PROCESS is given by periodic replanning activities (Ponsignon and Mönch 2014). A new plan is computed from scratch.
3. In lot planning, the capacity constraints for the bottleneck steps of a macro-operations are taken into account. Moreover, precedence constraints for the operations and macro-operations of the different products are respected (Mönch *et al.* 2013).

**Concept Definition:** The **DECISION-MAKING UNIT** specifies an entity that makes decisions.

Properties. A DECISION-MAKING UNIT has several defining properties (Schneeweiss 2003):

**SCOPE:** This property defines which planning function is addressed by the DECISION-MAKING UNIT (planning scope). It also describes to which part of the base system the DECISION-MAKING UNIT belongs (physical scope).

**DECISION TIME:** This property describes the point of time when a decision is made by the DECISION-MAKING UNIT.

**INFORMATION STATUS:** This property describes the internal and also the external situation of the DECISION-MAKING UNIT. At the same time, it describes information about the internal and external situation of other DECISION-MAKING UNITs and their information status (Schneeweiss 2003).

**DECISION-RIGHTS:** This property will allow a DECISION-MAKING UNIT to negotiate the instruction provided by other DECISION-MAKING UNITs. In a conventional or strict hierarchical setting, negotiations of instruction provided by superior DECISION-MAKING UNITs are impossible. In a distributed hierarchical setting in the sense of Schneeweiss (2003) reactions of the DECISION-MAKING UNIT which can lead to negotiations are possible (Schneeweiss 2003).

**(Optional) ANTICIPATION:** Anticipatory activities are used by a DECISION-MAKING UNIT to take into account the characteristics and the situation of other DECISION-MAKING UNITs in course of its own decision making (Schneeweiss 2003).

**PLANNING PROCESS**: This property specifies under which circumstances which (re)planning activities are performed by a DECISION-MAKING UNIT.

Moreover, there are additional parameters for most types of DECISION-MAKING UNITs.

**DECISION-MAKER TYPE:** We distinguish human decision-makers (human DECISION-MAKING UNITS) from fully automated DECISION-MAKING UNITs where computers make fully automated decisions. Between these two extremes there are semi-automated decisions, where a computer provides several decision alternatives and a human decision-maker chooses among them. Other variations of semi-automated decisions are possible, for instance, the computer recommends decisions in a fully automated manner. However, the human may over-ride those decisions. The computer recommends decisions in a fully automated manner. After viewing the output, the human realizes something is wrong, adjusts input data, and re-runs the computer calculations. Note that the decision-maker type can change over time.

**DECISION-MAKING INITIATIVE:** We distinguish fully autonomous DECISION-MAKING UNITs from DECISION-MAKING UNITs where the decision-making activities are triggered by other DECISION-MAKING UNITs. Note that the decision-making initiative can change over time in a situation-dependent manner.

Several examples of DECISION-MAKING UNITs are described.

1. In production planning, the DECISION-MAKING UNIT is given by a production planning system and optional human planners that belongs to a specific wafer fab.
2. In master planning, the DECISION-MAKING UNIT given by a master planning system and optional human planners that belongs to an entire semiconductor company. The DECISION-MAKING UNIT is related to several frontend- and backend facilities.
3. In lot planning, the DECISION-MAKING UNIT is given by a lot planning system, often a Manufacturing Execution System, and one or several human planners.

**Concept Definition:** The **PLANNING SITUATION** describes the organization of several DECISION-MAKING UNITS and also its environment.

Properties. A PLANNING SITUATION has several defining properties (Schneeweiss 2003):

**SET OF DECISION-MAKING UNITS:** This property describes the set of DECISION-MAKING UNITS that constitutes the planning situation. We refer to the elements of the set as vertices.

**SET OF CONNECTIONS:** If a vertex provides instruction or a reaction to another vertex then the two vertices are connected by a directed edge.

**LEVEL:** Each vertex has a level. The highest level is assigned to vertices that do not receive instructions from other vertices. The vertices belonging to the second highest level receive instructions only from vertices of the highest level. This definition can be repeated in a recursive manner. Reactions are only possible from vertices of level $k$ to vertices of level $k+1$ or level $k$.

**STRICT HIERARCHICAL SITUATION:** There are only edges between vertices of level $k$ and vertices of level $k-1$, where $k \geq 2$.

**DISTRIBUTED HIERARCHICAL SITUATION:** In this situation, edges referring to instructions and reactions are possible.

**HETERARCHICAL SITUATION:** All the vertices have level 1.

Moreover, there are additional parameters for most types of PLANNING SITUATIONs.

**CHARACTER OF THE INVOLVED DECISION-MAKING UNITS:** In an ANTAGONISTIC SETTING, the different DECISION-MAKING UNITS try to meet their own objectives which are in conflict. In a non-antagonistic setting, the DECISION-MAKING UNITS do not exploit their private knowledge in an opportunistic way.

Several examples for PLANNING SITUATIONs are described.

1. In supply chain planning, there is a single DECISION-MAKING UNIT for master planning which provides instructions for different DECISION-MAKING UNITs for production planning. There is a single DECISION-MAKING UNIT for each wafer fab.
2. In production planning and scheduling for a single wafer fab, there is a single DECISION-MAKING UNIT for production planning which provides instructions for a single DECISION-MAKING UNIT for lot planning.
3. In an overall planning system, the DECISION-MAKING UNIT for master planning is on the highest level, whereas the DECISION-MAKING UNITs for production planning are on the second highest level. The DECISION-MAKING UNITs for lot planning are on the third highest level.

**Concept Definition:** A **PLANNING INSTANCE** specifies the PLANNING OBJECTs and the values of related PLANNING CONSTRAINTS that form the basis for a planning decision.

Properties. A PLANNING INSTANCE has several defining properties:

**SET OF PLANNING OBJECTS:** This property specifies the involved PLANNING OBJECTS.

**SET OF PLANNING CONSTRAINTS:** This property specifies which constraints must be considered

SET OF PLANNING PARAMETERS: This property specifies which parameters are relevant for the current planning instance.

**(Optional) PLANNING WINDOW:** This property defines a time span that is divided into periods of a certain length.

**(Optional) PLANNING PERIOD:** This property defines a certain fraction of a planning window. Equidistant periods are common for many supply chain planning problems.

Several examples for PLANNING INSTANCE are described.

1. In production planning, the quantities for all products have to be determined that must be released in a given period of the planning window are the planning objects. The planning constraints are the values for the capacities of the work centers and the routes of the different products. Planning objects together with planning constraints form a planning instance.
2. In lot planning, the start and completion dates lots form the planning objects. The aggregated routes and the values of the capacities of the work centers serve as planning constraints. Planning objects together with planning constraints form a planning instance.

**Concept Definition: FROZEN FENCE** is used to set a frozen interval in which decision making is not allowed to change the previously determined values.

**Properties.** FROZEN FENCE has several defining properties:

**LOCATION**: It defines the location where the frozen fence applies.

**END DATE:** This is the latest point in time the frozen fence affects. The frozen fence typically starts at the beginning of the planning horizon.

**PLANNING OBJECT**: This defines to which planning object(s) the frozen fence is associated.

**Concept Definition:** A **PLAN** is an activity specification with an intended purpose.

Properties. A PLAN has several defining properties:

**SET OF PLANNING OBJECTS:** This property specifies a set of planning objects from a given planning instance where all attributes are supplied with values that are determined as the result of a planning decisions.

**FEASIBILIY STATUS:** A PLAN is feasible if all hard PLANNING CONSTRAINTS of the PLANNING INSTANCE on which the plan is based are fulfilled, otherwise, the plan is infeasible.

**Concept Definition:** A **PLANNING PARAMETER** is an object to which different values can be assigned to. A planning parameter can have different types such as numeric, string, arrays or others. Usually parameters will be used if values are not constant and they can be changes between different planning instances. Planning parameters are important ingredients of planning models.

Properties. A PLANNING PARAMETER has several defining properties:

**TYPE:** Defines the type of the value that is assigned to that planning parameter.

**(Optional) PLANNING PARAMETERS**: A planning parameter can have or consists of other planning parameters, e.g., a list or an array.

**Concept Definition:** A **PLAN EXECUTION** is related to performing the activities according to a PLAN either directly in the base system, for instance, releasing lots into a wafer fab, or as instructions for another DECISION-MAKING UNIT.

Properties. A PLAN EXECUTION has several defining properties:

**PERFORMANCE MEASURES:** Values for certain PERFORMANCE MEASURES can be computed after a plan is executed. This always requires that the consequences of a PLAN are assessed in the base system.

## 4. Concepts to Represent the Base System and Process

**Concept Definition:** A **PRODUCT** is a good provided by a system of interest. A product is manufactured by the execution of a certain set of activities. The manufacturing of a product is often subjected to demand. A PRODUCT can be a final product, raw material, or a semi-finished product.

Properties. A PRODUCT has several defining properties:

**ACTIVITIES:** This property specifies the set of activities (process steps) which are required to produce the product.

**RESOURCES:** This property describes the set of resources that execute the activities.

**LOCATION:** This is the facility where the product could be produced.

**PROCESS:** this refers to the process used to make a PRODUCT. There can be multiple processes (multiple ways of making a particular PRODUCT) at a given LOCATION.

**(Optional) BILL OF MATERIAL (BOM):** A set of potentially alternative BOMs can be used to meet the demand of a certain product.

This concept can be taken from the Enterprise ontology (Uschold *et al.* 1998) or the OZONE ontology (Smith and Becker 1997).

**Concept Definition:** A **PRODUCT HIERARCHY** characterizes the top-down and bottom-up relationship between different product aggregates. It organizes the PRODUCT AGGREGATES according to defined criteria. A PRODUCT AGGREGATE is used to group different products based on certain criteria. The grouping criteria depends on the planning purpose (e.g. controlling, production). It is a certain view on a set of products.

**Properties.** A PRODUCT HIERARCHY has several defining properties:

**PARENT AGGREGATE:** Each parent aggregate may be associated with several child aggregates.

**CHILD AGGEGATE:** Each child aggregate belongs to exactly one parent aggregate.

Both the PARENT AGGREGATE and CHILD AGGREATE are PRODUCT AGGREGATES.

Several examples for PRODUCT HIERARCHY are described.

1. In production planning at IBM (Fordyce *et al.* 2011), a product is the lowest level of the hierarchy. Each product can belong to exactly one product group. A product group is formed by at least one product. A product group can belong to exactly one product cluster. A product cluster is formed by at least one product group. A product group can belong to exactly one product super cluster. A product super cluster is formed by at least one product group. To reduce human effort, data is maintained at the highest level of the product hierarchy desired by the user. For instance, when a particular data item is the same for all products within a given product super cluster, that data would be stored and maintained only at the product super cluster level without it being necessary to maintain that data at the product, product group, or product cluster level of detail.
2. The product structure is divided into a production view, a marketing, and a sales view at Infineon (Seitz 2021). In addition, each view consists of several product aggregation levels. Some aggregation levels are shared between the views. In general, the production view contains all relevant information required to produce/manufacture a product such as route information, facility dedications, quality information and more. The marketing and sales view in is used to sell products to customers and contains information such as form, function and its technical datasheet specific specifications. Both views contain several product aggregation levels which are mainly used for the different planning functions. As higher the aggregation level, as more general are the product information. From the product data perspective, each lower level inherits the information from the higher levels. The highest (most aggregated) level of the product aggregation consists of the Plan Position (PPOS). The PPOS level is shared between the production, the marketing, and the sales view. It contains the product master data such as its form and its function. The PPOS level is mainly used for long-term capacity planning as well as marketing and sales strategy development. The second highest level of aggregation on the marketing and sales view consists of the Rhythm Forecast Plan Product (RFP). One RFP can belong to exactly one PPOS while one PPOS can consists of at least one RFP. RFP is used for demand planning purposes. The third highest level on the marketing and sales view consists of the Sales Product (SP). The SP represents the external view of a product and can be ordered by the customer. One SP can

belong to exactly one RFP while one RFP can consist of at least one SP. The SP is disaggregated to the Finish Product (FP) aggregation level. The FP contains information of the products route from the start of its production until it leaves the production sites and where it is tested. One FP belongs to exactly one SP while one SP consists of at least one FP. The finest product aggregation level is called Stock Keeping Unit (SKU). Besides information of the production from upper levels, it also contains information about its storage location. The SKU is used for stock-related planning functionalities. The SKU links the marketing and sales view with the production view. On the production view, the highest aggregation level consists of the Fabrication Position (FPOS). It contains information of the manufacturing route on a high degree of abstraction. Since the manufacturing route is set, the FPOS is mainly used for short-term network-wide capacity planning. One FPOS belongs to exactly one PPOS while one PPOS consist of at least one FPOS. The second highest aggregation level on the production view consists of the Die-Bank Representative (DREP). The DREP contains information of the assembly and test activities and in which facility they should be performed. DREP is used when the production site of a product is set but the assembly and test facilities are not defined yet. It is called DREP because the products on this aggregation level are typically stored in the Die-Bank before they will be assembled and tested. On the upper level, one DREP belongs to exactly one FPOS while one FPOS consists of at least one DREP. On the lower level, one DREP consists of at least one SKU while one SKU is associated to exactly one DREP. SKU and PPOS are both shared between the production and marketing and sales views.

**Concept Definition:** A **PRODUCT AGGREGATE** combines individual products into a few logical products groups. This results in a reduction of complexity, which enables a better overview.

**Concept Definition:** A **PART** represents a physical instance of a product in the manufacturing process. It therefore realizes a product. A part moves through the system and is manufactured according to its product specification. A part is associated with exactly one product. The binning rules of the associated product specification can be applied to the respective part.

Properties. A PART has several defining properties:

**PRODUCT:** This property specifies the product which is realized by the part.

**LOCATION:** This property specifies the location (e.g. fab) where the PRODUCT is built.

**PLANNING OBJECT**: This property refers to the planning object where the part belongs to.

**EARLIEST RELEASE DATE:** This is the earliest time when the activities associated with the PRODUCT of the PART can start.

**DUE DATE:** This is the latest time when the activities associated with the PRODUCT have to be finished.

**Concept Definition:** A **PROCESS** specifies a method of making a product at a location. The process is expressed at a coarse level of granularity suitable for use in production planning.

Properties. A **PROCESS** has several defining properties:

**PRODUCT:** This property describes the product which is manufactured using the process.

**LOCATION:** This property describes in which facility where the process is performed.

**CAPACITY:** A process consumes available capacity that is offered in the location by resources.

SUB**PROCESS**ES**:** This property refers to a process being potentially composed of a set of processes, which we call subprocesses. Thus, processes are recursive in that they may consist of other (shorter) processes.

**LEADTIME:** This property defines the time between the release of a product (its start) and its completion.

**YIELD:** Yield is the fraction of a product's release quantity that results in completed products following their original specification.

**BILL OF MATERIAL:** This is the set of components needed to assemble the PRODUCT at the LOCATION using the PROCESS(es).

**(Optional) BINNING:** This contains the distribution percentages of tested PRODUCT resulting from testing of the untested PRODUCT (see the BINNING concept for details of the the applicable information).

**Concept Definition:** A **BILL OF MATERIALS (BOM)** describes the component products used to make another product.

Properties. A BOM has several defining properties:

**PRODUCT:** This property specifies the product in terms of a final product, a component, or a semi-finished product.

**LOCATION:** This property describes the place, typically a node of a semiconductor supply chain where the assembly takes place.

**PROCESS:** This property describes how the product is manufactured at a location. There may be multiple (alternative) processes that may be used in manufacturing the part at a location.

**COMPONENT PRODUCT** This property describes the component product that is used (consumed) when the product is assembled. The fact that a component is itself a product reflects the recursive nature of a BOM.

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

Properties. A DEMAND has several defining properties:

**DEMAND CLASS:** This property describes the priority of fulfilling the demand by the REQUESTED DATE. For instance, customer orders tend to be the highest priority class, replenishment to target inventory levels may be the second most important class, followed by sales forecasts discounted by historical forecast errors, and the rest of the sales forecast, i.e. the risky portion, forms the least important demand class.

**PRODUCT:** A product is a good that fulfills a prescribed set of requirements.

**ORIGIN:** This is the geographical region where the demand occurs, its destination.

**QUANTITY:** This is the requested amount of the product or service that is triggered.

**REQUESTED DATE:** This is the date which is requested by the customer.

**(Optional) COMMIT DATE:** This is the delivery date which is committed to the customer. It is no earlier than the **REQUESTED DATE**.

**(Optional) COMMIT DEMAND CLASS:** This describes the priority of fulfilling the demand by the COMMIT DATE. When the **REQUESTED DATE** is earlier than the **COMMIT DATE**, the **COMMIT DEMAND CLASS** will be of higher priority than the **DEMAND CLASS** indicative of the importance of the supplying organization meeting its commitments.

**Concept Definition:** The **AVAILABLE CAPACITY** describes the ability of a resource within a period of time to perform activities or processes. Elmaghraby (2011) refers to this as operational capacity, i.e. the productive capacity that is obtained from the nominal capacity by subtracting the anticipated and unavoidable loss in productivity, for instance, due to machine breakdowns in a wafer fab.

Properties. The AVAILABLE CAPACITY has several defining properties

**LOCATION:** This property specifies the facility where the resource is located that offers capacity.

**RESOURCE:** This property describes something which has capacity available. It can be, for instance, a single machine, a set of machines, a work center, a work area, or a single wafer fab.

**UNIT:** This property describes how the capacity is measured, for instance, in time or in wafers to be released.

**EFFECTIVE START DATE:** This is the date when the resource that offers the capacity gets available.

**MAXIMUM CAPACITY:** This property specifies the maximum number of units of capacity available per period to support new manufacturing releases, i.e. processing of operations on the resource.

**MINIMUM CAPACITY:** This property specifies the minimum number of units of capacity required to be consumed per period. For instance, this property might be used to model a vendor contract which calls to order at minimum a specified rate.

Several examples for AVAILABLE CAPACITY are described.

1. The available capacity of a work center in a wafer fab, i.e. a machine group, can be specified by the availability time of a single machine multiplied by the number of identical machines within the same work center.
2. The available capacity of an entire wafer fab can be described by specifying the number of wafers that can be released in a period.

**Concept Definition:** The **REQUIRED CAPACITY** describes which capacity is required to perform a certain manufacturing activity or process.

Properties. The REQUIRED CAPACITY has several defining properties:

**PRODUCT:** This property is used to specify the product which is associated with the activity or process that consumes the capacity.

**LOCATION:** This property specifies the facility where the resource is located that offers the required capacity.

**(Optional) ACTIVITY:** This property refers to the activity which uses the capacity.

**PROCESS:** This property refers to the process which consumes the capacity.

**RESOURCE:** This property describes something which has capacity available. It can be, for instance, a single machine, a set of machine, a work center, a work area, or a single wafer fab. The resource is required to perform the activity or the process.

**UNIT:** This property describes how the capacity is measured, for instance, in time or in wafers to be released.

**EFFECTIVE START DATE:** This is the date when the CONSUME QUANTITY or OFFSET PERIODS becomes effective for this REQUIRED CAPACITY.

**CONSUME QUANTITY:** This property specifies the number of units of capacity that is consumed by the activity or process per piece of product released.

**OFFSET PERIODS:** This property specifies the number of periods between the release of the Product and when it will consume capacity.

Several examples for REQUIRED CAPACITY are described.

1. Performing a certain process step on a machine of a work center requires a certain amount of time, the processing time.
2. Performing a process requires a certain amount of processing time on the bottleneck machines of a wafer fab.

**Concept Definition:** The **INVENTORY** describes the quantity of a certain product that is available in stock to be used to meet demand.

Properties. The INVENTORY has several defining properties:

**PRODUCT**: The property refers to the product which is in stock.

**LOCATION**: This property refers to the location of the facility where the inventory is available.

**CURRENT STOCK**: This is the currently useable inventory.

**Concept Definition:** The **PROJECTED WIP** describes the quantity of a certain product that is anticipated to be received into inventory at a particular location at a particular time.

Properties. The PROJECTED WIP has several defining properties:

**PRODUCT**: The property refers to the product which is anticipated to be received into inventory.

**LOCATION**: This property refers to the location of the facility where the inventory resulting from the completed WIP will be received and stored.

**PROJECTED QUANTITY**: This is the amount of a certain product that is anticipated to be in inventory at the projected date.

**PROJECTED DATE**: This is the period in which the projected amount of a certain product is anticipated to be arrive into inventory.

**PRODUCT**: This property describes which product is associated with the WIP.

**Concept Definition: The IN-TRANSIT INVENTORY** describes the quantity of a certain product that has been shipped from one location to another. This quantity has left the inventory of one location, but has not yet been received into the inventory of the receiving location.

Properties. The **IN-TRANSIT INVENTORY** has several defining properties:

**PRODUCT**: The property refers to the product which is anticipated to be received into inventory.

**SUPPLYING LOCATION**: This property refers to the supplying plant or vendor.

**RECEIVING LOCATION**: This property refers to the receiving plant location.

**PROJECTED QUANTITY**: This is the amount of a certain product that is anticipated to be in inventory at the projected date.

**PROJECTED DATE**: This is the period in which the projected amount of a certain product is anticipated to arrive into inventory.

**Concept Definition: RESOURCE**

This concept can be taken from the Enterprise ontology (Uschold *et al.* 1998) or the OZONE ontology (Smith and Becker 1997).

**Concept Definition: ACTIVITY**

This concept can be taken from the Enterprise ontology (Uschold *et al.* 1998) or the OZONE ontology (Smith and Becker 1997).

**Concept Definition: SUBSTITUTION** refers to using alternative products. Depending on the product, each one could be replaced by using specific alternatives at the same stage of production, e.g. final product, raw material, or semi-finished products (Degbotse et al. 2013) to complete a manufacturing step or fulfill a customer order.

**Properties.** SUBSTITUTION has several defining properties:

**PRODUCT**: It defines the product where substitution could be applied to.

**LOCATION**: It defines the location where substitution is allowed.

**START DATE:** This is the earliest point in time when substitution is active.

**END DATE:** This is the latest point in time when substitution is active.

**SUBSTITUTE**: This defines a products which can be used to substitute for the defined PRODUCT.

**SUBSTITUTION QUANTITY**: Defines the quantity of SUBSTITUTE required to substitute the defined product, for instance, replace 1GB memory by two substitutes of 500MB.

**COST**: This is the cost which occurs if the product is substituted by its SUBSTITUTE.

**Concept Definition: BINNING** refers to the process of testing and categorizing products against defined measures and sort them into different bins (Degbotse 2013). Each bin belongs to certain levels of defined measures (e.g. chip speed, current, voltage, energy consumption). Binning is often combined with SUBSTITUTION.

**Properties.** BINNING has several defining properties:

**COMPONENT PRODUCT**: It defines the untested product where the test result indicates which tested PRODUCT results from the binning process.

**Tested PRODUCT**: It defines the output bin that results from the binning process.

**LOCATION**: It defines the location where binning is allowed.

**START DATE:** This is the earliest point in time when the binning DISTRIBUTION is active. The distribution can change over time because of the product lifecycle.

**END DATE:** This is the latest point in time when the binning DISTRIBUTION is active.

**PROCESS**: It defines the process which is associated with the binning rule.

**DISTRIBUTION**: This property specifies the distribution of the tested PRODUCT resulting in a specific BIN, for instance, 50% high-quality product, 25% medium-quality product and 25% low-quality product.

**Concept Definition: YIELD** is the percentage of released product that results in good product. For example, yield could be the fraction (percentage) of good dies resulting from total dies released.

**Properties.** Yield has several defining properties:

**PRODUCT**: It defines the part where the given yield belongs to.

**LOCATION**: This defines the location where the yield belongs to.

**PROCESS**: This defines a process where yield should be calculated for.

**EFFECTIVE DATE:** This describes the time at which time the yield becomes effective.

**Concept Definition: SUPPLY INFORMATION** provides information of the used and unused supply of a supply chain.

**Properties.** SUPPLY INFORMATION has several defining properties:

**PRODUCT**: This defines the product where the information belongs to.

**LOCATION**: This defines the location where the supply will become available.

**TYPE/CLASS**: The class can be used to group different supply types such as forecasted supply, reserved supply or promised supply.

**AVAILABILITY DATE**: This is the point in time when the supply is expected to become available.

**DUE DATE:** This is the point in time when the supply should be available to meet demand on time.

**MINIMUM SUPPLY**: This is the minimum supply which is required to be fulfilled at the due date.

**MAXIMUM SUPPLY**: This is the maximum supply which could be fulfilled at the due date.

## 5. Concepts to Represent the Control System and Process

**Concept Definition:** A **LOT SIZING RULE** defines a rule to specify the lot size for a specific product. The lot size defines the number of pieces belonging to a product. The lot size is the result of applying lot sizing rules.

**Properties.** A LOT SIZING RULE has several defining properties:

**MINIMUM LOT SIZE**: It sets the minimum size of a lot.

**MAXIMUM LOT SIZE**: It sets the maximum size of a lot.

**PRODUCT**: It defines the product where the lot sizing rule applies.

**LOCATION**: It defines the location where this applies.

**START DATE:** This is the earliest point in time when the rule is active.

**END DATE:** This is the latest point in time when the rule is active.

**Concept Definition:** An **INVENTORY POLICY** indicates how much earlier or how much more (safety stock) needs to be built than that required to satisfy demand on time. Inventory Policies define the rules which have to be implemented at a specific inventory location such as safety stock or product mix for supporting the production process flow as well as fulfilling customer demand.

**Properties.** An INVENTORY POLICY has several defining properties:

**PRODUCT**: It defines the product where the inventory policy could be applied to.

**LOCATION**: It defines the inventory location where this rule can be used.

**START DATE:** This is the earliest point in time when the policy is active.

**END DATE:** This is the latest point in time when the policy is active.

**SAFETY STOCK**: This is the planned minimum inventory level available to provide protection against future uncertainty and volatility.

**SAFETY TIME**: The number of periods worth of demand that should be available in inventory to protect against cycle time variability.

**TYPE**: A policy could be static or dynamic. Static refers to a fixed and constant value. Dynamic policies allow to take the current status of the supply chain network into account.

The different concepts and their relationships are visualized in Figure 1a and Figure 1b.

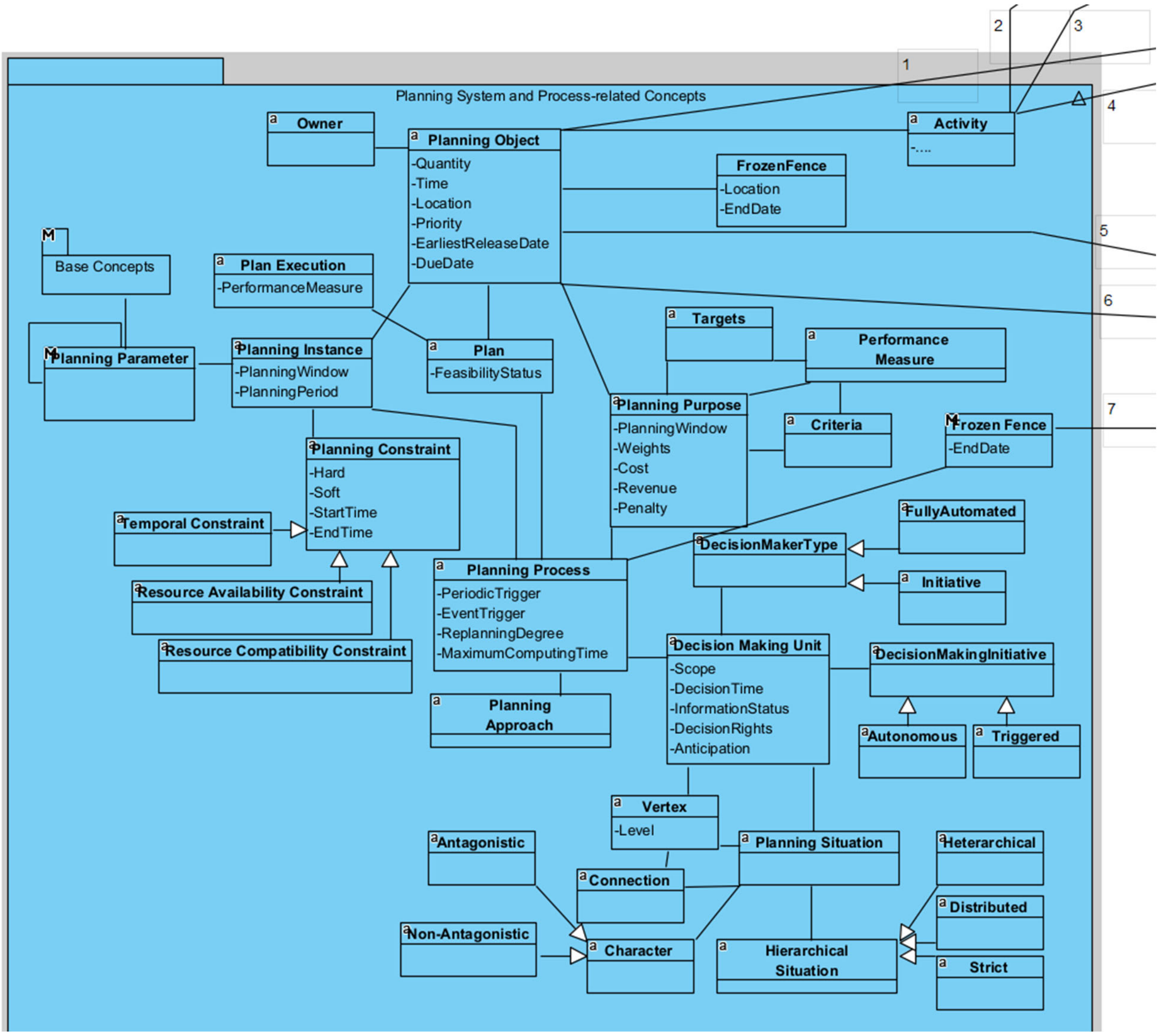


**Figure 1a:** UML Class Diagram of the Concepts of the Planning Ontology

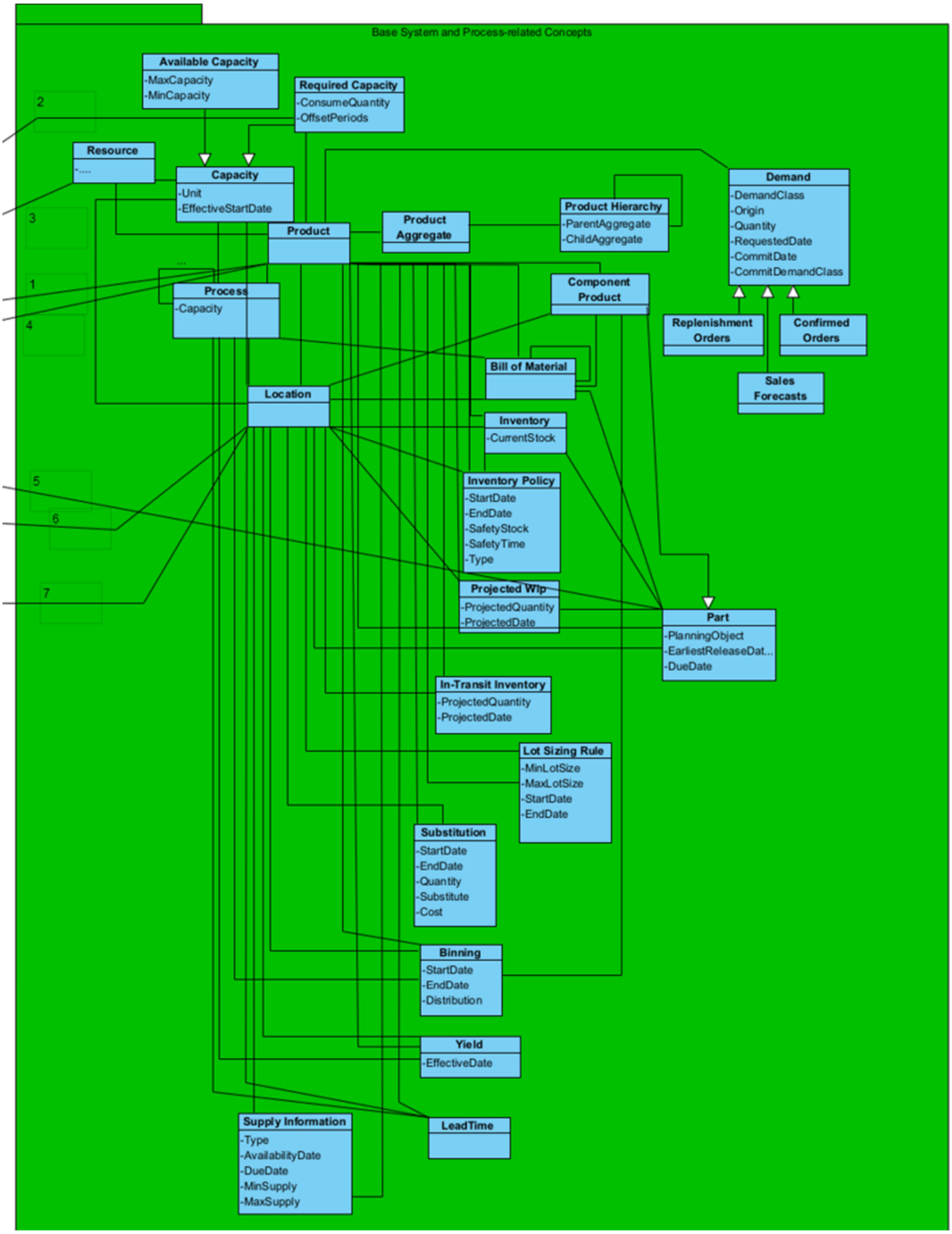


**Figure 1b:** UML Class Diagram of the Concepts of the Planning Ontology

## 6. Predicates of the Planning Ontology

The predicates belonging to the planning ontology are summarized in Table 1.

Table 1: Predicates of the Planning Ontology

| Predicate | Scope | Description |
|---|---|---|
| VALID_FACILITY | D | determines whether a given facility (wafer fab or backend) is able to produce a certain product or not |
| VALID_SUBCONTRACTOR | D | determines whether a given subcontractor can be used for manufacturing a certain product or not |
| PLAN_COMPUTED | T | determines whether a given plan is available for execution |
| PLAN_FEASIBLE | T | determines whether a given plan is feasible with respect to some or all constraints |
| CAPACIY_ EXPANSION_REQUIRED | T | determines whether a capacity expansion for a given resource is required |
| INVENTORY_ POLICY_CHANGE_ REQUIRED | T | determines whether the used inventory policy should be changed |
| REPLANNING_REQUIRED | T | determines whether a replanning activity is required |
| PLANNING_INSTANCE_ AVAILABLE | T | Checks whether a certain planning instance is available or not |
| INVENTORY_LEVEL_APPRO-PRIATE | D | Checks whether an inventory level is high enough, for instance, to provide enough safety stock |
| PLAN_EXECUTED | T | Checks whether a certain plan is executed or not |
| DECISION_NEEDED | T | Provides that a planning decision is immediately needed |
| DEMAND_DATA_ AVAILABLE | T | Checks whether demand data is available or not |
| WIP_DATA_AVAILABLE | T | Checks whether WIP data is available or not |
| INVENTORY_LEVEL_ AVAILABLE | T | Checks whether inventory data is available or not |
| FROZEN_FENCE_ACTIVE | T | Checks whether a frozen fence is part of the planning process or not |
| SUPPLY_AVAILABLE | | Checks whether supply is available or not |

## 7. Agent Activities of the Planning Ontology

The different agent activities together with the corresponding description that belong to the planning ontology are gathered in Table 2.

Table 2: Agent Activities in the Planning Ontology

| Activity | Description |
|---|---|
| ADD_DMU | Add an additional decision-making unit to a given planning situation |
| INITIATE_PLANNING | Initiates to execute a planning activity |
| INITIATE_RE_ PLANNING | Initiates to execute a replanning activity |
| PARAMERIZE_ PLANNING_ APPROACH | Set the parameters of a given planning approach |
| PROVIDE_ALL_ DMU(k) | Provides the set of DMUs of a planning situation found level $k$ |
| GET_PLAN | Provides the computed plan |
| GENERATE_PLAN-NING-MODEL | Generates a planning model for a given instance of a planning problem and a planning purpose, e.g. constraints and objective function for an LP are generated |
| SET_MAXIMUM_COMPUTING_ TIME | It provides the amount of allowed time for decision making |
| COMPUTE_PLAN | Computes a plan based on request |
| GET_ADJACENT_TOP_ LEVEL_DMU(k) | Provides the set of DMUs of a planning situation found level $k + 1$ |
| GET_ADJACENT_BASE_ LEVEL_DMU(k) | Provides the set of DMUs of a planning situation found level $k - 1$ |
| EXECUTE_PLAN | Initiates the execution of a given plan |
| GET_INVENTORY_LEVEL | Provides the inventory level of a given storage |
| GET_PROBLEM_INSTANCE | Provides a problem instance |
| UPDATE_PLANNING_OBJECT | Updates the properties of a given planning object |
| GET_PLANNING_SITUATION_TYPE | Determines the type of a certain planning situation |
| SET_MAXIMUM_COMPUTING_TIME | Sets the amount of computing time that is possible to make a planning decision |
| SET_PLANNING_APPROACH | Sets the planning approach within a given planning process |

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