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FIRST STEPS TOWARDS BRIDGING SIMULATION AND ONTOLOGY TO EASE THE MODEL CREATION ON THE EXAMPLE OF SEMICONDUCTOR INDUSTRY

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ABSTRACT

With diverse product mixes in fabs, high demand volatility, and numerous manufacturing steps spread across different facilities, it is impossible to analyze the combined impacts of multiple operations in semiconductor supply chains without a modeling tool like simulation. This paper explains how ontologies can be used to develop and deploy simulation applications, with interoperability and knowledge sharing at the semantic level. This paper proposes a concept to automatically build simulations using ontologies and its preliminary results. The proposed approach seeks to save time and effort expended in recreating the information for different use cases that already exists elsewhere. The use case provides first indications that with an enhancement of a so-called Digital Reference with Semantic Web Technologies, modeling and simulation of semiconductor supply chains will not only become much faster but also require less modeling efforts because of the reusability property.

1 INTRODUCTION

The semiconductor industry is characterized by having complex and extensive supply chains due to its wide range of customers with varied demands for products. On the one hand, product specificity implies long and sophisticated manufacturing processes, and on the other hand, the environment comprises unpredictable demand due to the volatility of the electronics market. Furthermore, the semiconductor industry is known to be capital-intensive due to expensive equipment and the presence of rapid innovation cycles. As a result, companies in the semiconductor industry need to fiercely adapt their operations to such an evolving environment, and in turn, require their supply chains to be highly resilient and agile.

In order to overcome such challenges, simulation models are often used to analyze prospective scenarios, as well as to evaluate proposed changes or new concepts. With simulation, system behavior can be better understood, and its performance can be better assessed with ‘what-if’ scenarios (Chien et al. 2011). However, simulation requires the acquisition, application, storage as well as maintenance of vast amounts of data. Besides, every new research requires efforts to be expended for retrieving information and recreating models that might already exist elsewhere (Benjamin et al. 2006).

Furthermore, with data being generated and processed at each step of the manufacturing cycle, efficient data and knowledge management frameworks are essential. Semantic Web Technologies serve as a promising approach to integrate data from heterogeneous sources and also make it machine-readable. Ontologies, being one of the essential building blocks of the Semantic Web Technologies, provide a consistent and standardized way of information retrieval for both humans and machines (Moder et al. 2019). An ontology is an inventory of all entities existing in a domain, along with their properties and relationships.

Ontologies are used as a methodology to establish common naming for concepts and relationships between concepts of a particular domain. This is accomplished by linking information on data level using Resource Description Framework (RDF), which is the standard encoding for Semantic Web. Thus, defining and maintaining a controlled vocabulary of processes, roles, objects and interactions serves as a reusable framework for data management and collaboration of diverse teams especially across the semiconductor supply chain domain (Moder et al. 2019).

The main steps for developing a simulation include: formulating the problem, model creation, data preparation, verification, optimization, interpretation, and documentation. Out of these steps, data preparation accounts for the largest proportion of time spent by modelers when building a simulation (Wolfgang 1994). The proposed approach would benefit the modeler by saving time, particularly in the data preparation phase, consequently shortening the overall process timeline. In order to save redundant efforts spent on retrieving information and building models from scratch, ontologies as a resource for creating reusable simulation models within semiconductor supply chains are proposed in this paper. With the proposed concept, ontologies once created for a supply chain simulation model can be reused further for other models to extract required supply chain elements, implying less time and effort to create a new model from scratch. This paper also describes a proposed use case, limited to illustrating the concept and not its implementation.

In Section 2, we provide background information about the main concepts addressed in this paper. In Section 3, we describe the methodology followed to develop an ontology-based simulation model and its required building blocks. In Section 4, we further explain the methodology with an example use case, followed by a discussion, where we evaluate the capabilities of the proposed system. In Section 5, we discuss the limitations and the future scope of the proposed concept.

2 BACKGROUND

2.1 Simulation

Simulation makes it possible to mimic the real environment by offering a risk-free and flexible virtual world, with which we can bridge expensive and implausible changes in the real world. (Mönch et al. 2018) highlight the increasing importance of simulation for semiconductor supply chains over the last two decades, with production facilities being globally distributed and with firms specializing in specific production stages. Moreover, semiconductor supply chain simulations also drive research in areas like production planning as they provide testbeds to evaluate various models and algorithms.

The motivation for extensive efforts in simulating models of semiconductor supply chains has been seen after the success of discrete-event simulation (DES), which was established as a tool to analyze wafer fabs and assembly and test facilities (Fowler et al. 2015). However, the modelling and analysis of larger semiconductor supply chains prove to be computationally intensive and require large amounts of data to output statistically valid results (Mönch et al. 2018). A common approach to mitigate the computational burden of DES-based simulation replications is the use of meta-models. (Li et al. 2016) propose a meta-model-based Monte Carlo simulation to replace the DES model for production planning. Research has also been undertaken to develop simulation object libraries, allowing rapid development of a reduced simulation model for semiconductor supply chains (Yuan and Ponsignon 2014). Moreover, recent testbeds related to semiconductor operations have been published that can be used both by researchers and practitioners to evaluate their respective approaches with a common playground while avoiding the modeling effort (Ewen et al. 2017; Laipple et al. 2018; Hassoun et al. 2019).

Nevertheless, research has not resulted in a broadly reusable model accommodating to a varied range of research questions. It is very often that for each new simulation, the modeler analyzes the process and starts from scratch in the given simulation software, owing to a number of reasons such as - difficulty to build robust models with standardized interfaces and allowing interconnectivity with other models; evolving technology making it effort-intensive to maintain the operation of such models in updated conditions; research projects focusing on limited aspects of supply chain problems (Mönch et al. 2018).

2.2 Ontology

Ontologies are descriptions of concepts and relationships among those concepts for a specific domain. They surpass traditional taxonomies as they allow entities to have properties and relationships. They also allow concepts within a domain to be defined as classes and the meaning of particular classes is defined by its position in comparison to other classes, as well as its properties, relationships, and restrictions. Ontologies can be defined as standard vocabularies that consolidate knowledge in a wide community in specific domains (Silver et al. 2011).

(Noy and Mcguinness 2001) define ontology as a description of concepts in a domain (called classes), properties of those concepts defining distinct features or attributes (called roles or properties), and restrictions on those roles (called facets or role restrictions). An ontology with a set of classes forms a knowledge base. Classes are the most important part of ontologies, as they describe concepts in a specific domain. For example, if we consider the semiconductor domain, the class semiconductor product represents all products and a specific product is an instance of that class. XMC4800 is an instance of the semiconductor product class. A class can have subclasses representing more specific concepts than the superclass. Instances of the class *semiconductor product* can have roles describing their *qualifications, price,* etc. All instances in the class *semiconductor product* have a role hasProduct*Qualification* and its value is an instance of the class *IndustrialQualification*. All instances in the class *IndustrialQualification* have a role *productQualificationOf* referring to all semiconductor products. Figure 1 depicts this example by showing some classes, instances and their relationships within the semiconductor domain.

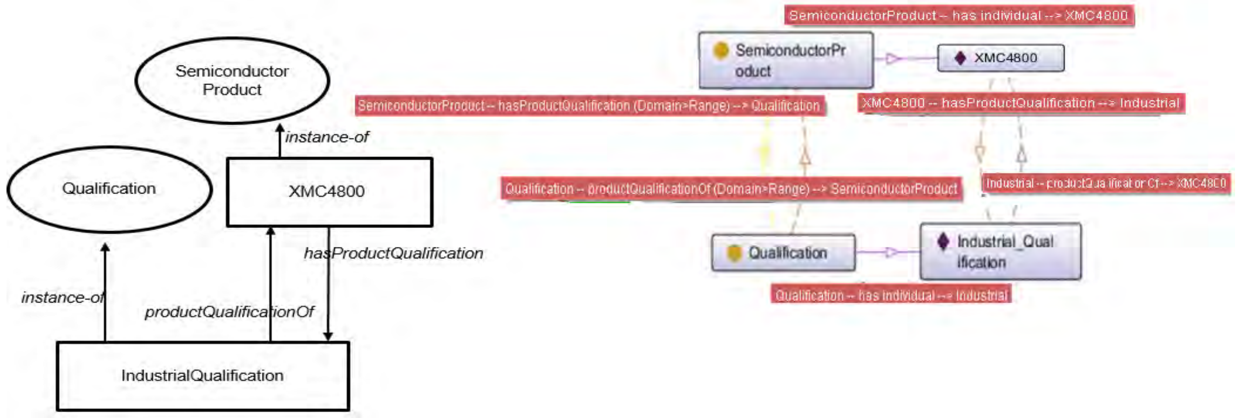

Figure 1: (left) Representation of semiconductor domain; (right) An ontology of same domain

Conclusively, an ontology development includes the definition of classes, the arrangement of classes hierarchically (subclass-superclass), the definition of roles with admissible values for those roles, and adding values of the roles for all instances (Noy and Mcguinness 2001).

2.3 Digital Reference: An Ontology for Semiconductor Supply Chains

In our approach, bridging simulation and Semantic Web Technologies will facilitate the model building by leveraging the distributed knowledge that is captured in the ontology of the semiconductor domain spanning from the execution level up to supply chain operations. Depending on the goal and the scope of the simulation, relevant elements are applied. The division of scope follows the four standard simulation levels (Fowler et al. 2015), with each level represented by an ontology and then the sub-ontologies or levels merging into a more abstract, higher-level ontology – the so called Digital Reference (Ehm et al. 2019).

Figure 2 depicts the four simulation levels at the top left corner. Level one, the most granular, includes the interactions across materials and resources at the equipment level. Level two represents the manufacturing site with the major classes of work area, demand, lot and route. Level three depicts a broader view of the production network, including the internal supply chain (frontend, backend, distribution centers, and production partners) but without customers. Level four depicts the end-to-end supply chain. It is the broader and higher vision of the entire supply chain, including all other ontologies from all levels and represents the Digital Reference ontology at the top right corner (Ehm et al. 2019).

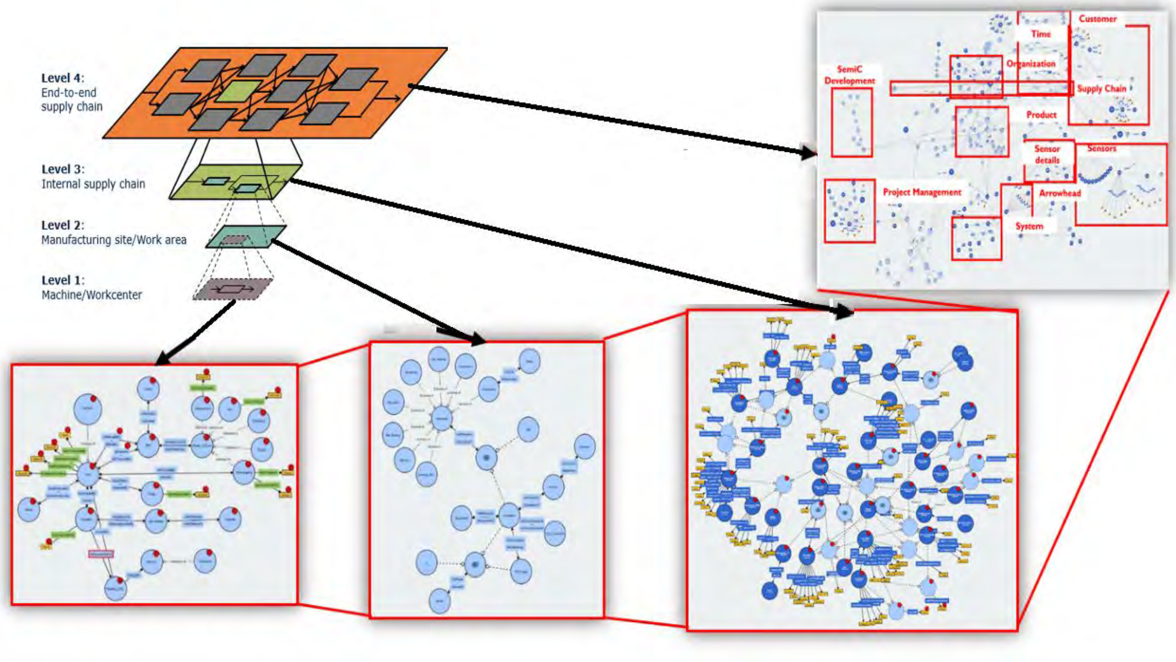

Figure 2: Four Levels of Semiconductor Operations and ontologies

This overarching ontology provides an understandable and common knowledge structure for semiconductor supply chains, also making it easier for partner companies to interact within the mutual vocabulary of terms and functions used (Ehm et al. 2019). The Digital Reference ontology is currently only available on requested access, but is planned to be made publicly available in a follow-up project. The interested reader might contact the corresponding author of this paper to enquire about access right.

The Digital Reference is an ontology which represents semiconductor supply chains. It is an amalgamation of different supply chain pillars and semiconductor production concepts such as Digital Production, Supply Chain Networks and Product Lifecycle Management. The Digital Reference, that enables the creation of a digital twin for semiconductor supply chains, has the potential to support simulation models built upon already existing ontologies and models. The Digital Reference, developed within the Productive 4.0 initiative (Productive 4.0 Consortium 2020), comprises different domains representing a combination of different ontologies. The domains have classes and subclasses that are defined by properties as well as descriptions and are connected to other classes in different domains, enabling a consistent representation across all taxonomies.

These domains represent all stages of the supply chain with several sub-ontologies that currently represent concepts, hierarchies and organizations, e.g. product ontology, sensor ontology, organization ontology and business process ontology. Other relevant ontologies can be integrated to further expand its scale to more areas of semiconductor supply chain processes (Ehm et al. 2019). A visualization of the

Digital Reference with its domains is presented in Figure 3, and an overview on some of its domains is presented in Table 1.

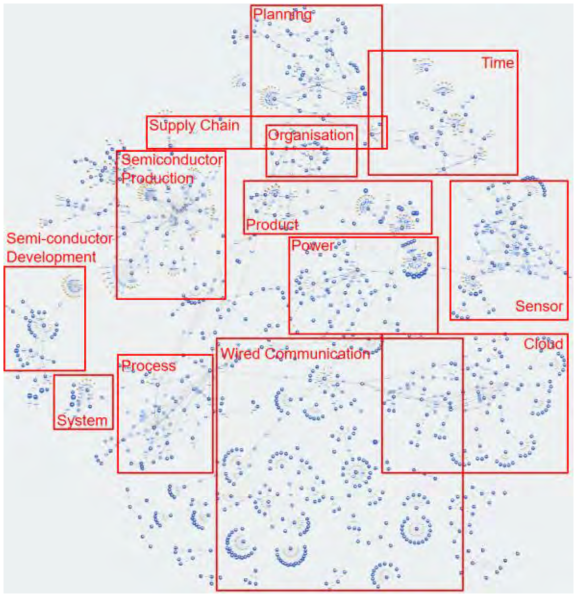

Figure 3: The Digital Reference

Table 1: Overview of some domains in the Digital Reference

Ontology	**Description**
Process Model Version	Defines the mechanisms and elements used in a process
Sensor	Defines the different actions, parameters, and states that a sensor can be or perform in
Semiconductor Operations	Defines the steps and entities involved in semiconductor production operations
Supply Chain Planning	Defines the different parameters, actions, and entities involved in supply chain planning
Power	Describes in detail the states and components that a chip needs to manage its power
Product	Defines the states an Infineon product can be in and its information
Time	Defines temporal entities and the parameters that can influence them

2.4 Previous Works on Ontology-based Simulation

(Benjamin et al. 2006) presents an Ontology-driven Simulation Modeling Framework (OSMF) providing a visual programming interface to build, compose and maintain distributed simulations readily. The key motivation is to facilitate simulation composability, integration and interoperability. The OSMF concept is based on model libraries - comprising ontology and process templates with structural and behavioral information of reusable components, as well as reference libraries – containing scalable domain models with reference process ontologies and reference information meta-models. Ontology libraries serve as a well-structured, revisable knowledge database that can be used for multiple use cases.

(Silver et al. 2006) discuss the development of Process Interaction (PI) Discrete Event Simulation (DES) ontologies named Process Interaction Modeling Ontology for Discrete Event Simulations (PIMODES) and Discrete Event Model Ontology (DeMO). Both ontologies were developed using Web Ontology Language (OWL) but with different approaches. PIMODES intends to support the interchange of simulation models as an ontology focusing on process interaction world view, while DeMO is developed as a DES Ontology focusing on DES world views.

(Sarli et al. 2016) introduces an ontology network conceptualizing the Supply Chain (SC) simulation domain into a distributed environment. The preliminary network ontology, named SC Federation High-Level Architecture (SCFHLA) network, adopts the semantic model of SC domain and maps concepts from SC domain to simulation domains using meta-relations and axioms in order to reduce efforts to build the Federation Object Model (FOM). The ontology was developed using Protégé and employs SC Knowledge (SCK) ontology to propose a reusable SC simulation development.

(Soares et al. 2000) describe the requirements analysis and system specification for an order promising module. The core elements of an ontology for planning tasks in the context of semiconductor supply chains are derived.

(Sprock and Mcginnis 2015) propose a formal domain modeling methodology to create domain specific methods and robust interfaces between those methods. For the DES domain, this methodology suggests the use of a domain-specific language that supports the specification of the structural, behavioral, and control aspects of each system. This approach is demonstrated through a distribution supply chain use case that integrates CPLEX, a multi-objective genetic algorithm, and a DES tool named SimEvents.

(Herding and Mönch 2017) introduce an ontology to allow for a supply chain-wide interoperability of software agents that support planning and control decisions in semiconductor supply chains by means of a domain- and task-specific ontology. A prototype named S2CMAS is demonstrated that is a hierarchically organized agent-based system that allows for decisions ranging from long-term capacity planning for the entire network to detailed scheduling decisions for single wafer fabrication facilities. The ontology for the S²CMAS system is designed based on a domain analysis.

3 METHODOLOGY

3.1 Overall Concept

Figure 4 shows the overall concept that incudes domain ontology, rule-based engine, and simulation ontology. The different buildings blocks are explained in more detail in the remainder of this section.

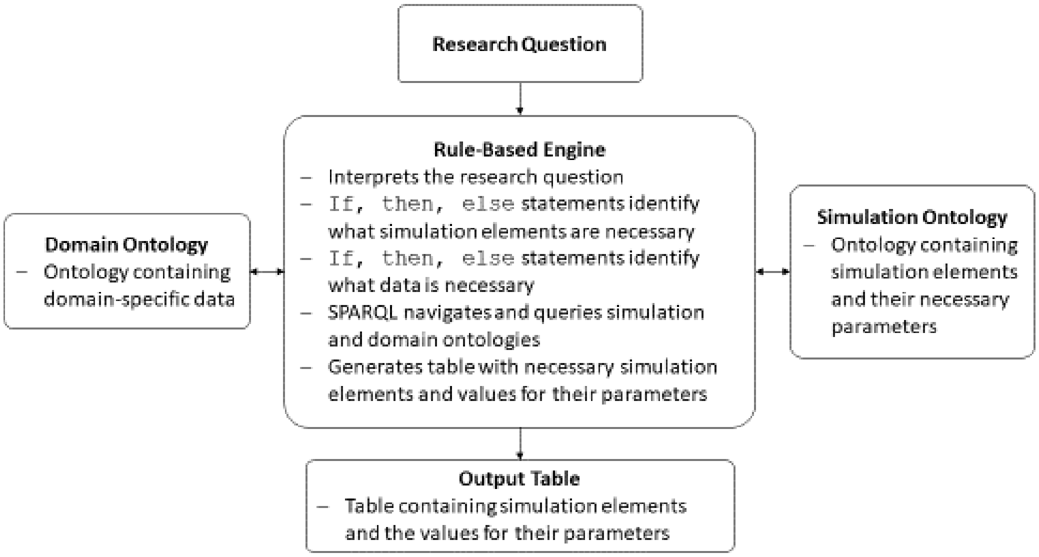

Figure 4: Overall concept

3.2 Related Works on Simulation Ontology

(Benjamin et al. 2006) explain that ontologies can help with the unambiguous interpretation of the problem statements and in precisely conveying information about the problem to the simulation modeler. Moreover, ontologies contribute in harmonizing the statements of objects involved by providing explicit, uniform semantic descriptions of terms and concepts. Additionally, Ontologies play an important role in identifying inconsistencies and incompleteness in a domain system description. They can be used to analyze and validate system descriptions. Authors explain that ontologies play an essential role in unambiguously interpreting the information contained within the system descriptions in order to correctly understand the flow logic and decision logic within the real world processes being modeled. They add that in the detailed analysis of information about objects and constraints. This involves mapping the simulation model constraints to specifications of real world constraints that are found within the domain system descriptions.

(Silver et al. 2011) presents DeMo, a general Modeling and Simulation ontology that represents the domain of discrete-event modeling. DeMO describes the classic DES world views, their formalisms and modeling techniques. The models within this ontology capture discrete state changes via events. Through explicit descriptions of the concepts assumed in each of the DES world views, as well as the relationship between these concepts, DeMO attempts to enable the sharing of this descriptions in an understandable language both by humans and machines. DeMO's rationale considers that all discrete-event models have basic components, as well as mechanisms of how the models should run. Therefore, its structure begins with a base class DeModel (discrete-event model). The sub-classes that follow are state-oriented, event-oriented, activity-oriented and process-oriented models, which describe modeling formalisms. Subsequently these particular formalisms serve as the base for a hierarchy of modeling techniques. DeMO is available on the Web, both for modelers and computer applications, facilitating the evolution of Web-based Modeling and Simulation and enabling the combined efforts from its community.

(Teo and Szabo 2008) developed CODES, a hierarchical framework to support component-based modeling and simulation. The basic idea of the framework is the *component-connector paradigm*, where *connectors* link the *components* – considered as black box with input and output channels – allowing the exchange of data and messages. The framework allows the users to look for customized components, reuse the existing ones and check the semantic and syntactic composition of the system built. All this functionalities make use of an ontology called COSMO. The hierarchies of the ontology go in two main directions: since the ontology wants to be as general as possible and at the same time, it wants to fit even the most specific domain requirements, the ontology describes a set of components shared among all the domains and components specific to each application domain. Moreover, it also outlines the attributes and behavior of each component.

3.3 Rule-Based Engine

The rule-based engine is the bridge between the domain and simulation ontologies and the user. The purpose of the rule-based engine is to interpret a research question entered by the user, determine what simulation elements are required to investigate the question, and to determine what data should be used in the simulation study. The scope of questions that the rule-based engine can address must be pre-defined. If further questions beyond this scope are to be investigated, the rules in the engine will need to be extended.

The rule-based engine prompts the user with a series of questions using underlying if-then-else statement to narrow down the initial research question into a more precise one and identifies the information necessary to start building a simulation. This information includes the objective of the simulation, the necessary level of detail for the study, and the relevant KPIs.

Once the research question has been deconstructed, the engine determines what needs to be simulated (i.e. tool, work center, factory, and supply chain). This is achieved by analyzing the objective, level of detail, and KPIs of the research question. Next, the engine determines what simulation elements (i.e. queue, delay, split) are required to model the system via the simulation ontology. The simulation ontology also allows the engine to determine what parameters need to be defined using data from the domain ontology to build an accurate simulation. Through the interpretation of the research question and the information extracted from the simulation ontology, the engine builds a table showing what simulation elements are necessary and what parameters they will require for the simulation.

The values of the parameters are determined through the domain ontology. Based on the details of the research question, the engine uses the domain ontology to identify values for the necessary parameters (i.e. capacities, throughputs, maintenance schedules) for each of the simulation elements. The values are then entered into the table of simulation elements and parameters for the user to build the simulation. After the engine finishes running, the user has a simple list of simulation elements and their parameters based on actual data to enable the quick and accurate assembly of a simulation model.

3.4 Domain Ontology

According to (Kaiya and Saeki 2006), a domain ontology provides a semantic basis for requirements descriptions and to achieve “lightweight semantic processing” in order to detect properties of requirements descriptions.

(Wang et al. 2004) elaborate that in a domain ontology the structure of a domain is described in terms of classes and properties. In fact, in case of an ontology-based simulation, the domain ontology in question is an ontology describing entities, agents, data, inputs, outputs, sub-processes involved in the processes to be simulated. It describes also how these components relate to each other and interact within the domain.

The four planning levels, presented in Figure 2 can be the domain ontologies. In the following section we define a use case with a focal point a tool, belonging to level 1 Machine/work center. We use the lowest granularity level to highlight the aspects of our methodology, yet it is scalable to higher level i.e. End to End supply chain. In the semiconductor domain, the Digital Reference depicts the highest level (fourth level) of the framework, hence represents the holistic supply chain with all involved stakeholders. Here one can see that ontologies can provide both a very detailed view on complex data sets as well as a well-structured overview.

4 ILLUSTRATIVE USE CASE

4.1 Use Case Description

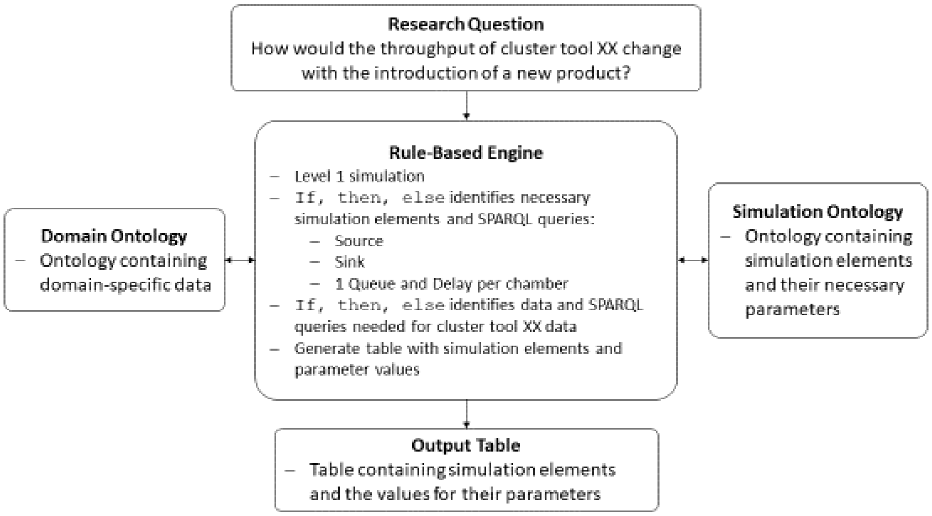

Figure 5: Overall concept for the example case

We present an example of how such a system would work via the case of throughput analysis on a piece of semiconductor manufacturing equipment with the introduction of a new product. The specific piece of equipment being analyzed is known as a cluster tool which processes wafers.

A cluster tool has several process bays that perform different steps in the manufacturing process, and, depending on the specific product being produced, will have many repeated steps with different durations. The wafers arrive to the tool in lots, are loaded into the machine via a load port (which operates under vacuum pressure), and then the wafers proceed through the machine according to their recipe one by one. Once all wafers are processed, the lot is removed from the machine through an exit port (cf. Figure 5).

Additionally, before lots of a given product can be produced on the equipment, usually a qualification step needs to be performed. For qualification, one wafer is processed by the machine and then examined to ensure that the electrical and physical characteristics are still correct. Once the machine has been qualified, it is considered qualified for a certain period of time, and production can proceed as normal.

The research question the user would pose to the engine would be formulated as follows: "How would the throughput of cluster tool XX change with the introduction of a new product?" By asking the user a series of questions with underlying if-then-else-statements, the engine determines that a level 1 simulation is needed, the relevant KPI is throughput, and the data will need to be pulled for cluster tool XX. These statements also allow the engine to determine that a simulation would require a source, a sink, and that each chamber of the tool should be modeled as a queue followed by a delay. Using SPARQL, the engine queries the simulation ontology to generate a list of parameters necessary for each of the elements. Also using SPARQL, the engine then queries the domain ontology to determine the number of elements required, and the proper values for their parameters. The engine compiles all of the information and outputs it to a table to aid the user in the creation of the simulation model.

4.2 Domain Ontology

Using the domain ontology, the engine needs to determine the number of chambers cluster tool XX has, the current products being produced on it, the proportional loading of each product, and their production recipes (which process bays are used and for how long). Additionally, the domain ontology needs to provide information regarding the frequency of lot arrivals, lot size, the frequency of required qualifications, and the probability of a failed qualification. The Figure 6 is an ontology depiction of the cluster tool as part of Digital Reference. This ontology belongs to level 1 represented in Figure 2.

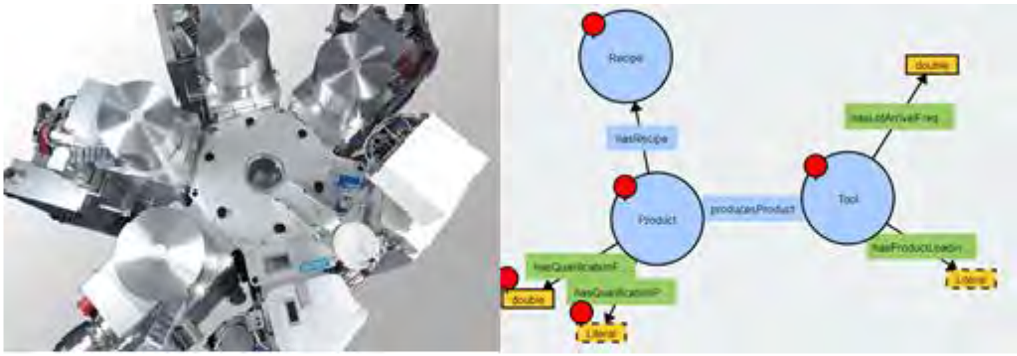

Figure 6: (left) Cluster Tool (SENTECH 2016); (right) ontology representation of the tool

4.3 Simulation Ontology

The simulation ontology would build off of DeMO, except it would extend the ontology to support agent-based simulation. DeMO describes the classic DES world views as well as a variety of DES formalisms and modeling techniques that conform to the world views. It consists of four subclasses, each describing a top-level modeling formalism: state-oriented model; event-oriented model; activity-oriented model; process-oriented model.

Similarly, for agent-based simulation, there would be an Agent-Based class with subclasses for different modeling formalisms. The subclass which would be of greatest interest for the example case would be the process-oriented model. The process activities of relevance for the example case would be the simulation elements source, queue, delay and sink. Table 2 summarizes the Simulation Ontology.

Table 2: Simulation Ontology

Subject	Predicate	Object
Source	hasInterarrivalTime	InterarrivalTime
Source	hasAgentsPerArrival	AgentsPerArrival
Source	hasAgentType	Agent
Queue	hasAgentType	Agent
Queue	hasCapacity	Capacity
Delay	hasDelayTime	DelayTime
Delay	hasCapacity	Capacity
Delay	hasAgentType	Agent
Sink	hasAgentType	Agent

4.4 Discussion

The system presented relies on ontologies to enable the automation of the building process of a simulation model. The rule–based engine parses a research question entered by the user, using ontologies and pre-defined rules, to determine what data should be used in the simulation study and what simulation elements are required to investigate the question. This entails enhancements in terms of performance and facilitates the expansion of the domain in question by merging ontologies representing other domains. In fact, in the given example, the ontology can be expanded by adding other machines and tools, afterwards we can add details about a manufacturing site or a working are (level 2). Consequently, we may expand the scope to successively include further levels of simulation from manufacturing to supply chain operations. Moreover, ontologies serve as a standard that allows portability and reusability of a simulation model. Thus, interconnection of models can be done after relying on ontologies. Additionally, the solution provided allows deepening of the model, as more details can be smoothly added to the ontology, thus leading to a more thorough simulation process. The granularity levels within the model can also be swapped when it is built primarily using ontologies.

5 CONCLUSION AND NEXT STEPS

Semantic Web enables quantifiable enhancement to the process of building a simulation model. It allows the expansion and the deepening of a domain by interconnection of models. However, the overall improvement in performance is hardly quantifiable. Future work focuses on measuring performance enhancement and the change in efficiency after introducing Semantic Web. This can be measured by the time taken to construct a simulation model using legacy techniques as opposed to using the rule-based engine. This is challenging as the time taken to reach a simulation model can only be roughly estimated as the time take by the simulation engineer to come to the model in terms of design and creating it using a suitable tool.

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