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SYSTEMS ENGINEERING AND DESIGN OF HIGH-TECH FACTORIES

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ABSTRACT

Contemporary technology for Product Lifecycle Management (PLM) integrates computer aided design (CAD) and engineering analysis (CAE) to support rapid, distributed, team-oriented product data development and management, including high fidelity simulation on demand. . This technology potentially provides a platform for creating a new generation of factory design tools which enable "on demand" simulation and analytic model results to be used by factory designers. This paper describes the opportunity, and provides an illustration in the context of semiconductor wafer fab design.

1 INTRODUCTION

High tech factories in industries such as semiconductor devices, automobiles, or biotechnology are expensive, with investment requirements ranging into several billions of dollars. They also are complex, requiring the integration of many functions, technologies, and diverse material flows with stringent requirements for speed, reliability, and efficiency.

In the case of semiconductor manufacturing, it is very instructive to examine the published literature related to factory design. In that literature, one finds papers addressing the broad impact of technology or economics on factory design (see, e.g., Bottoms and Wenstrand 1983, Hunter and Humphreys 2003, Kiser 1998, VanLeeuwen 1996, or Weiss 1996). One finds papers on design concepts (see, e.g., Binder and Honold 1999, Castrucci 1995, Colvin, Jones et al. 1998, Weiss 1999, and Yen 1996). One finds papers that propose broad approaches to design or specific analyses to support various design decisions (see, e.g., Benavides et al. 1999, Chen et al. 1997, Colvin et al. 1998, Colvin et al. 1999a, Colvin et al. 1999b, Hopp et al. 2002, Plata 1997, Schroeder 1997, or Weiss 1997). Naturally, one finds papers addressing simulation in fabs, since simulation is the ultimate analytical tool for evaluating fab designs (e.g., a search of the Inspec and Compendex databases for "semiconductor" and "Winter Simulation Conference" returns almost 200 unique citations).

What one does not find in this search of the literature are papers addressing engineering tools for factory design, especially tools that make simulation (or any other analysis tool) readily available to the engineers charged with factory design decisions. It is this gap in the literature that we address.

Today, factory design is largely an application of expert knowledge, with very limited computer-aided engineering support, a situation that stands in stark contrast to the design of the products produced in these factories. CAD tools, such as AutoCAD™, often are used to document proposed factory arrangement, including the placement of tools, and there is at least one software solution (FactoryCAD™ from UGS) that enhances AutoCAD to provide a number of functions for specifying tools, material handling systems, and physical arrangement, as well as testing for clearances. In addition, FactoryCAD can export data to a simulation package using a standard data exchange protocol.

However, even FactoryCAD is not integrated with systems engineering tools or with engineering models of the factory systems or processes. In fact, a case could be made that it is not good system design practice to try to force a CAD tool to embed all the data, knowledge, or methods needed to support detailed factory analysis. After all, CAD models, like all models, are fundamentally a limited view of the artifact being modeled.

The work reported in this paper is an attempt to exploit contemporary PLM technology to develop a superior approach to factory design and analysis, by integrating tools that are specialized for particular design related functions. These tools would allow factory designers to work with the concepts they already understand—products, process equipment, material handling, space, labor, and control systems—and would give them access to a variety of analytical models to estimate relevant factory performance metrics without requiring technical modeling expertise.

In the following discussion, we will focus on simulation as the analytic model, although it should be clear that more abstract models, such as queuing network models or deterministic optimization just as easily could be integrated. Also, our discussion will focus on semiconductor fabs as the specific example of high tech factories, although the concepts presented clearly generalize to other types of factories.

2 THE SOFTWARE TOOLS TO BE INTEGRATED

There are a range of contemporary IT-based tools that are relevant for developing a factory CAD, or F-CAD, system. Obviously CAD capability is important because the physical arrangement of tools in the fab is important, as is the configuration of automated material handling systems (AMHS). There are a number of commercial off-the-shelf (COTS) CAD systems that would be appropriate. Other COTS tools include simulation (such as Automod™, eM-Plant™, etc.), and database management (such as Access™, MySQL™, etc.).

In addition, there are two other categories of COTS tools that are key elements of any future F-CAD system. The first is the kind of collaboration tools now available from the leading PLM software vendors, such as TeamCenter™ from UGS or SmartTeam™ from Dassault Systemes.

When appropriately integrated, these tools support multiple engineering and management functions by providing a unified environment for authoring, editing, versioning, maintaining, and sharing the technical data, product and production requirements data, and other relevant data for a design project, along with design decisions, and supporting analyses. In the context of factory design, such an environment is key, since the various contributors to the factory design are likely to come from different disciplines (strategic planning, product design, manufacturing engineering, architecture-engineering-construction, etc), are likely to be globally distributed, and may include third parties such as equipment or systems vendors.

The second category of COTS tools essential in F-CAD is those emerging from the SysML™ development process. SysML is an extension of UML™ to support systems engineering. Essentially, SysML modifies three UML diagrams (activity diagram, block definition diagram, and internal block diagram), and adds a new diagram type called the "parametric diagram."

A tool like SysML will provide a common language for specifying factory design requirements, and for the systems engineering design of the factory. While we will use SysML in our presentation, we refer the reader to a variety of on-line resources for details about SysML (see, e.g., OMG 2006 or Anonymous 2006).

3 THE ISSUE OF DESIGN WORKFLOW

Factory design is a lengthy process, starting with broad goals and constraints, proceeding through interacting and iterative decision making by a number of often independent discipline – based groups. We take as axiomatic the equivalence between the collection of all design decisions and a description of the factory design.

Our goal is to support the fab design process, including capacity planning, AMHS design, physical configuration, and detailed performance analysis. We anticipate the involvement of a variety of strategic planners, factory planners, engineers, system architects, and designers, each providing particular elements of the design data related either to requirements/constraints or to design decisions. We also anticipate a shared design data repository, where decisions and analyses can be archived, and where version control can be enforced.

In an environment where multiple actors are involved in authoring and editing information related either to requirements or design decisions, the issue of design process workflow—i.e., the sequence in which design decisions are made--becomes critical. If each actor can freely edit the data for which he is responsible, then there is no "reference" data that can be used reliably by other actors for decision making. The result would be a chaotic design process requiring much iteration. A more disciplined process in which the sequence of decisions (and corresponding edits to the design database) is constrained would be preferred, however, there is no generally-accepted or standard design workflow. Thus, we face a dilemma, namely, how to present the concept of F-CAD tools without addressing the issue of design workflow which such tools are intended to support.

We propose a simple solution to this dilemma. We shall assume a fixed design workflow, consisting of the following steps:

1. define the operation types, i.e., the conversion steps that must be performed on a product instance by a production tool instance
2. define products, and their required manufacturing operations sequences, and throughputs
3. define the tool set, and the operational capabilities of each, including operational parameters
4. determine the number of each type of tool needed to meet throughput requirements
5. specify the physical arrangement of tools in the factory
6. specify the AMHS, including any necessary control policies
7. specify lot sizes, lot release and scheduling rules
8. simulate to determine throughput and cycle time

According to this workflow, an operation type must be defined before it can be designated for use by a product, or assigned to a tool; a portfolio of tools must be defined before the layout can be created; the tools must be located in the layout before the AMHS can be specified; and the AMHS and job control policies must be specified before factory performance analysis or simulation can be done.

This workflow enforces an arbitrary design discipline. However, it does not exclude any potential designs. In addition, it supports experimentation with different design decisions, i.e., different toolset or configurations, as well as different control rules, such as lot dispatch or scheduling.

Of course, at any step in the workflow sequence, one can iterate to an earlier step, or a step can be skipped if all the required data from that step are already available (e.g., in the case of modifying an existing factory). While this is a very simplistic approach to managing the design data authoring/editing process, it will allow us to demonstrate the capabilities one would want in an F-CAD system without becoming bogged down in the details of data synchronization or version control.

4 F-CAD REQUIREMENTS

The remainder of this paper addresses the specific scenario of semiconductor fab deign, although the concepts prevented generalize to other factories. Comprehensive F-CAD requires mechanisms to execute each of the eight steps outlined in the design workflow description. This, in itself, does not represent a major undertaking. For example, steps 1, 2, and 3 could be done readily using a spreadsheet based tool. Step 4 involves a difficult decision, but a model such as the one proposed by (Hopp, Spearman et al. 2002) might be deployed as a custom-coded application. Steps 5 and 6 could be done using AutoCAD to represent the process tools and AMHS elements in the layout, and selection from predefined alternatives for the AMHS control policies. Step 7 could be done, again, using a spreadsheet for lot sizes and release rules, and selecting from predefined alternatives for the scheduling rules. Step 8 can be accomplished using any reasonably functional COTS simulation package.

There are two fundamental problems, however:

1. In every case where data is captured, there must be an agreed upon data schema that will enable the data to be shared effectively across the design workflow, and
2. There must be a comprehensive factory *reference model* that will support the algorithmic translation of data captured in steps 1 through 7 into a simulation model for use in step 8.

These two problems must be solved in any F-CAD realization.

A generic wafer fab simulation model is described in (Kim, Park et al. 2001) and a corresponding reference model is described in (Kim 2004). We believe emerging SysML tools will allow the development of a generic wafer fab reference model in a form that is immediately sharable and transferable, and moreover, defines a schema enabling instance data capture and management. This generic model and the associated schema will be the basis for the spreadsheet applications to capture data in steps 1-3 of the proposed design workflow. It will enable the creation of template libraries to support the layout functions of steps 5 and 6.

5 F-CAD ARCHITECTURE

We believe that a practical and highly functional F-CAD system can be created using available commercial-off the-shelf (COTS) technology, In realizing a truly useful F-CAD system, COTS tools must be integrated with a standard reference model and with standards for data exchange. The basic concept is illustrated in Figure 1, below. Clearly, this is a conceptual rendering of the proposed architecture, and many details remain to he specified for a specific implementation. Our purpose here is to describe the architecture and devious trade through a small case that it is a feasible approach to F-CAD.

The meta-model layer in Figure 1 is the initial development of a generic factory model using SysML, e.g., the SysML IDE from Artisan. The resulting metamodel is used in both the modeler layer and the data collection and simulation layer tools.

In the modeler layer, SysML-based tools can be used to describe the basic fab entities and their logical relationships. The SysML extensions to UML allow the creation of SysML diagrams which reference external data or software. For example, a parametric block might describe a process tool, and some of the essential data for that process tool might come from an AutoCAD model.

In the data collection and simulation layer, the detailed data for the factory instance is developed, and integrated. As needed, the simulation model is automatically generated and executed.

6 SMALL SCALE EXAMPLE

To demonstrate the concepts described, we have implemented the key functionality identified in Figure 1, and exercised it for a small scale example. Our example problem is a single bay from the Sematech 300 mm wafer fab example (Anonymous 2005).

We present three specific results in implementing the architecture of Figure 1: (1) the results from using SysML to specify a reference model; (2) the process used to integrate design functions, based on the reference mode.; and

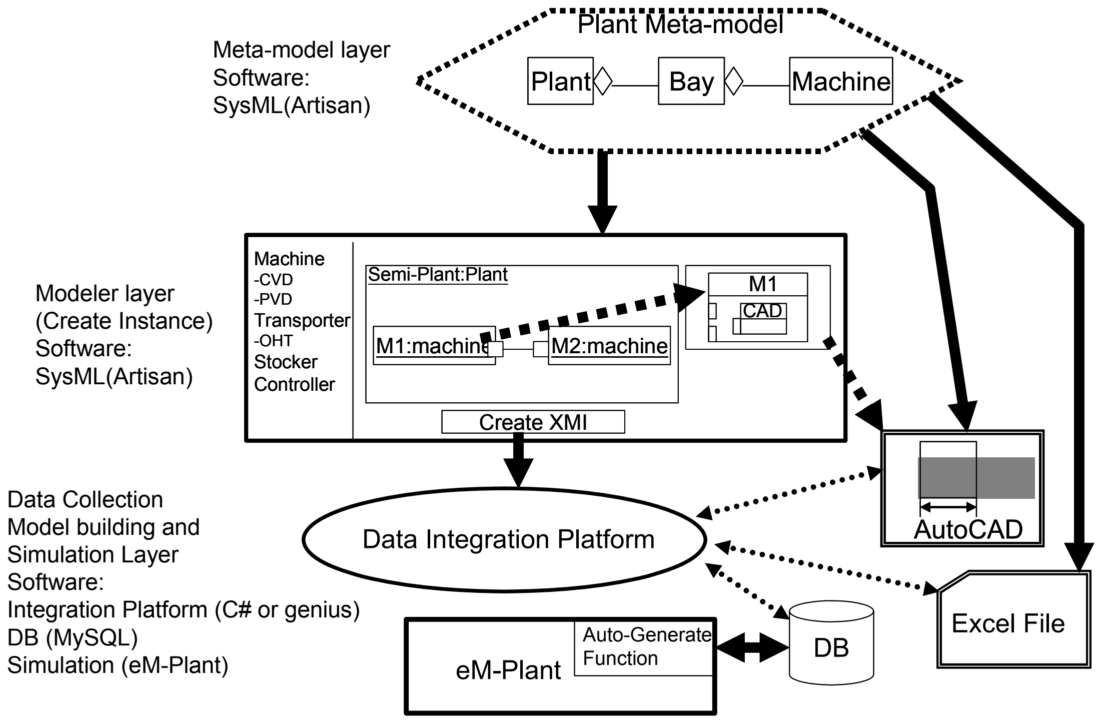

Figure 1. Proposed F-CAD Architecture

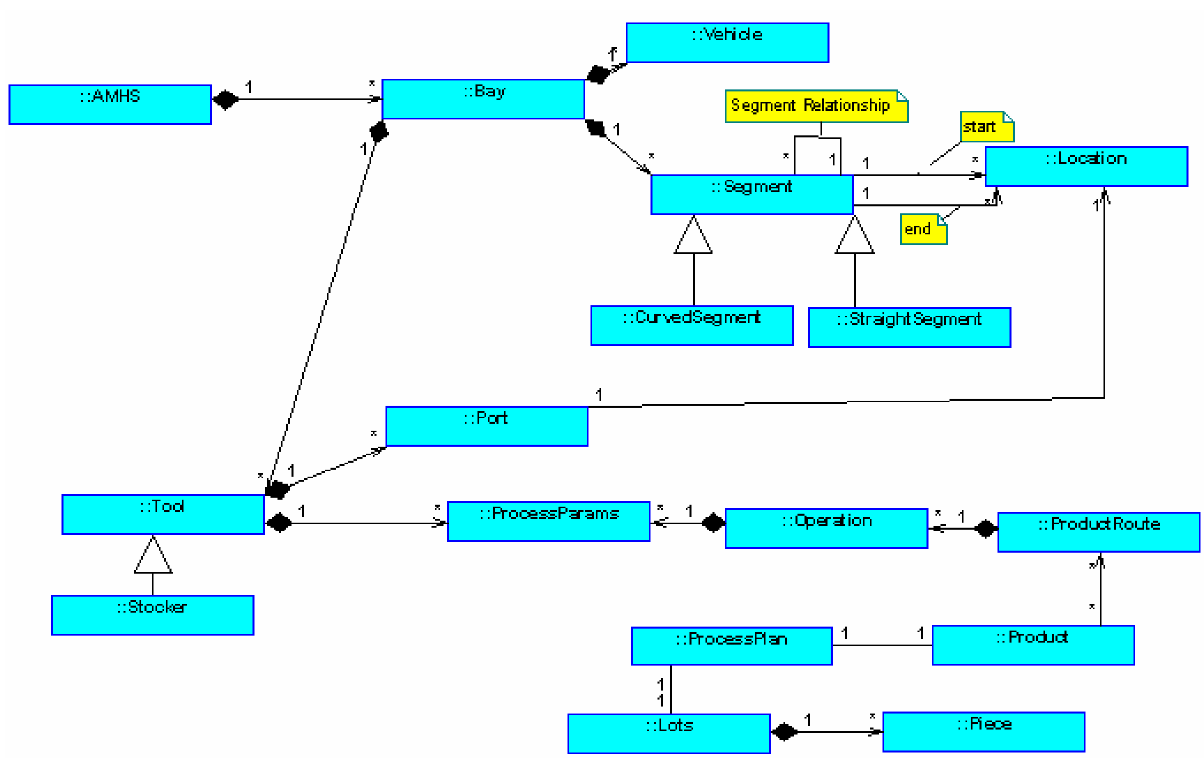

Figure 2. SysML Diagram for Semiconductor Fab

(3) how to translate design data to generate the simulation model.

Figure 2 presents a structure diagram in SysML which describes the physical entities in the fab and their relationships. The elements of the structure diagram in figure 2 are self-explanatory, perhaps with the exception of "port". Ports represent the interface points at which lots are exchanged between vehicles and tools. Note that "stocker" is a subclass of "tool."

The SysML parametric diagram can be used to model the detailed structure of the entities, but is not shown here. The attributes of the entities relevant for design decision-making are identified in Figure 3, which displays a specific data schema used for our example. Note that, for this simple demonstration, production requirements are given in the schema as a constant rate for each product, modeled as a specific start time, end time, and lot release frequency.

In a fully-implemented F-CAD tool, the design database would be populated by using a variety of specific authoring tools. For example, the specific catalog of tools land their properties) might be authored in Access, while the portfolio of tools, their locations, and the AMH5 configuration might be authored using AutoCAD. For the purposes of this concept demonstration, we implemented the design database in Access, and directly authored the relevant design data, rather than constructing the linkages to automatically extract the parameter values from other tools. For our demonstration, the specific data values are taken from the Sematech model (Anonymous 2005).

The final step in our demonstration is the automated generation of a detailed simulation model. Our simulation modeling tool is eM-Plant from UGS. Most of the information needed to construct the model is contained in the structure diagram in Figure 2 and the DB schema in Figure 3.

What remains to be specified are the control rules to be used. We believe it is possible to specify these control rules using SysML tools, and automate the generation of corresponding simulation models, although we do not present such a specification here. The specific control rules required for our demonstration are lot scheduling (where to send a lot when it completes an operation, and what waiting lot to select when a tool becomes available) and vehicle dispatching (whereto send a vehicle when it completes a move task). For the purposes of this demonstration, we have implemented only one alternative for each control rule, and these simple control rules effectively behave as first-come- first-serve (FCFS) and first-in first-out (FIFO) in queues.

The auto-generation function which builds the simulation model automatically is implemented in eM-Plant itself. eM-Plant provides functions for reading from a database (in our case, the design database) and creating model elements. Figure 4 presents a screen shot showing both the

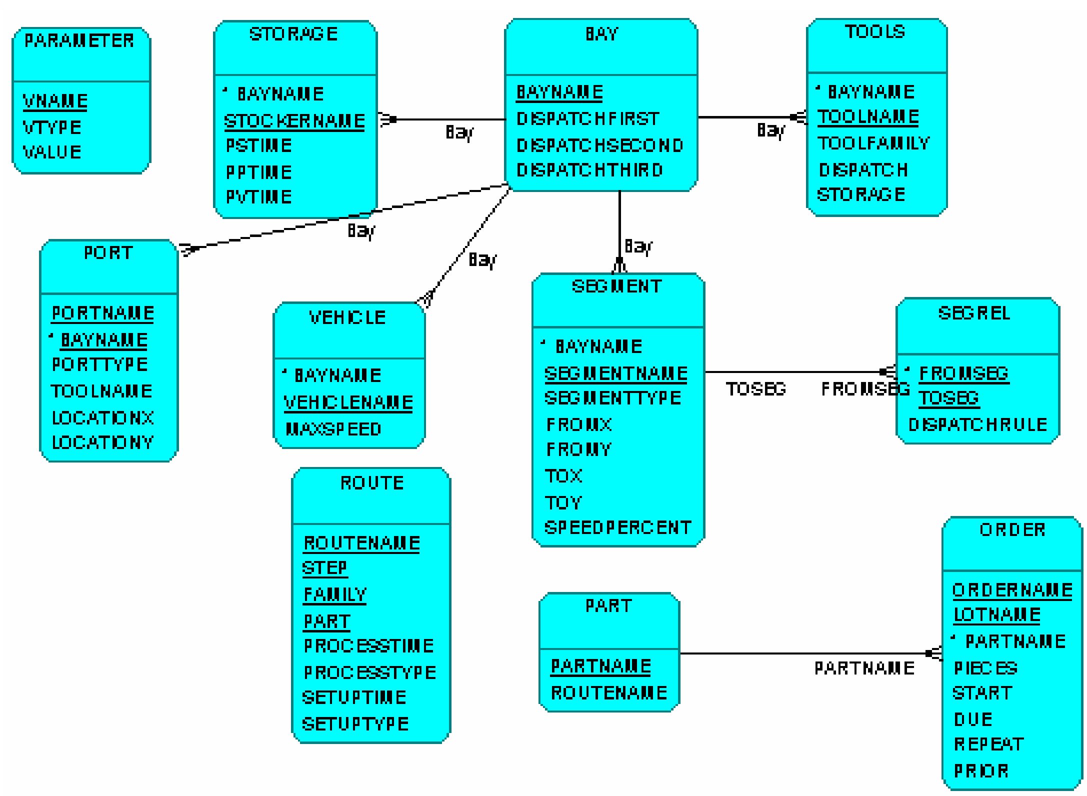

Figure 3. DB Schema for Semiconductor Industry

functions used and the resulting animated display. Based on the instance data, the auto-generate function will create the bays, segments, stockers, tools, AMHS, and schedule rules respectively.

7 CONCLUSIONS

Simulation should play a major role in all phases of the design of high tech factories, but to do so it must be made readily accessible to factory design teams. Factory simulation should be as accessible to the factory designer as finite element methods are to the mechanical designer, or as circuit simulations are to the electronics designer. Such is not the case today, but the factory CAD concept we have described is one way to achieve that state. We have argued that COTS PLM software provides the technology platform to make this a reality, and we have provided a small scale example to demonstrate the feasibility.

The next step in this research is to deploy the concepts demonstrated in a full scale prototype, and demonstrate the feasibility for supporting design of a real wafer fab.

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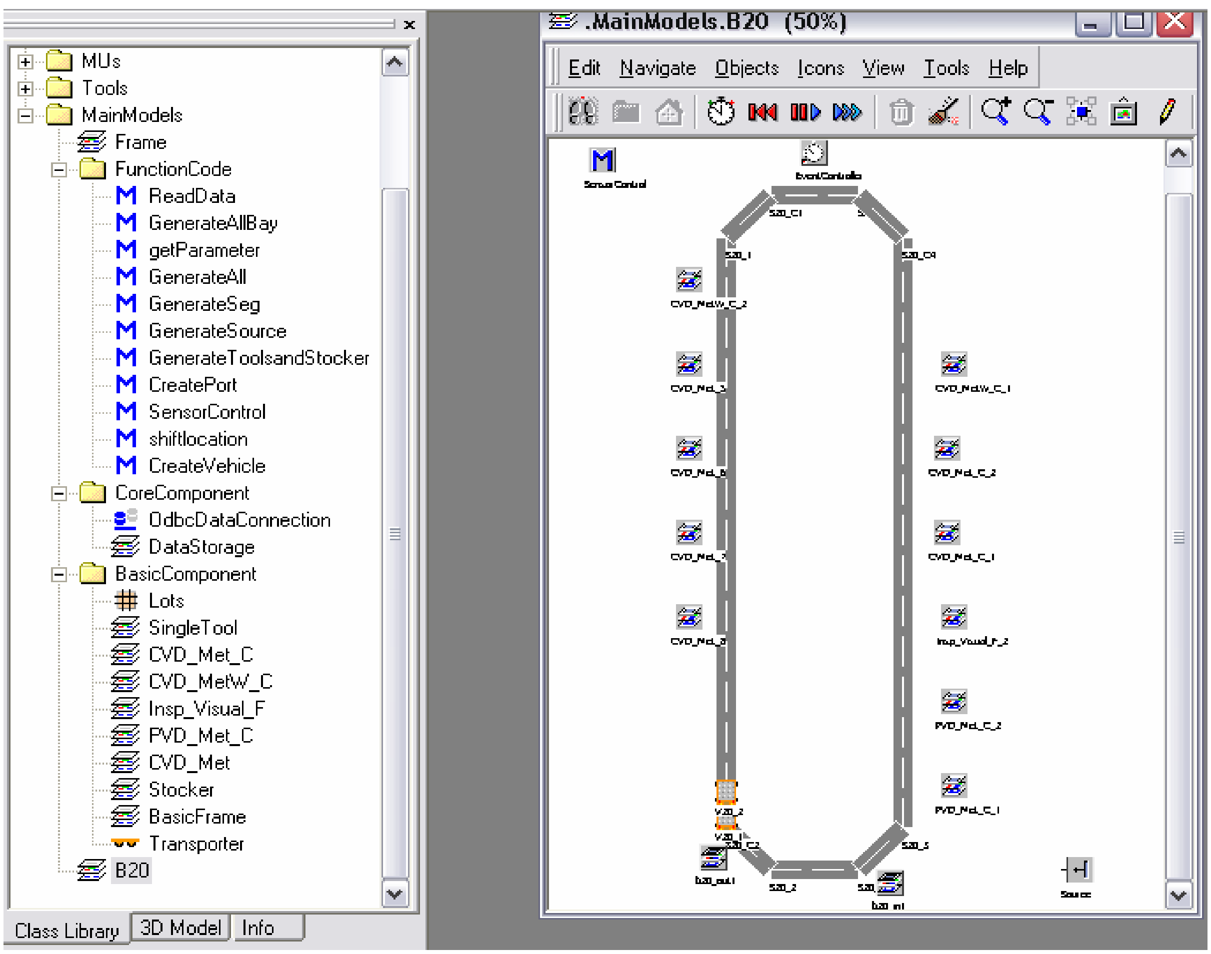

Figure 4. Auto-Generation Function and Simulation Model

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