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Technote: Applications of MBE for Healthcare

Introduction

Healthcare, in the US and globally, faces a challenge: how to offer a broader range of preventative, diagnostic and therapeutic services to a greater number of consumers without a proportionate increase in cost or decline in quality. As healthcare costs in the US approach a fifth of the US GDP, it makes sense to apply the best technical innovations to the issues, though this is not a substitute for addressing other structural issues in the healthcare delivery system. Localized successes in applying classic systems engineering approaches like lean techniques and simulation offer motivation for applying the full range of modern modeling and simulation.

Model-Based Systems Engineering (MBSE) arose from the idea of capturing a system's specification as a single, unified computer model, rather than a series of static disconnected documents. As the idea developed, it became clear that a single model in a single tool, for example, a SysML system architecture model, was insufficient for the purpose. While such a model is useful as a high-level roadmap for the system, it requires mechanisms to link it to all the other engineering models and data repositories where most of the detailed system data is created and stored. The goal now was better described as Model-based Engineering (MBE) as all the disciplines and tools in the engineering process were engaged in an ongoing network.

MBE offers a number of powerful advantages in addressing the challenges of healthcare. The area is a clear example of a system of systems. As Figure 1 indicates, we must recognize the interaction between multiple systems. The human body is a complex system of systems in its own right, composed of multiple interacting subsystems. It is subject to a range of environmental factors, including the physical

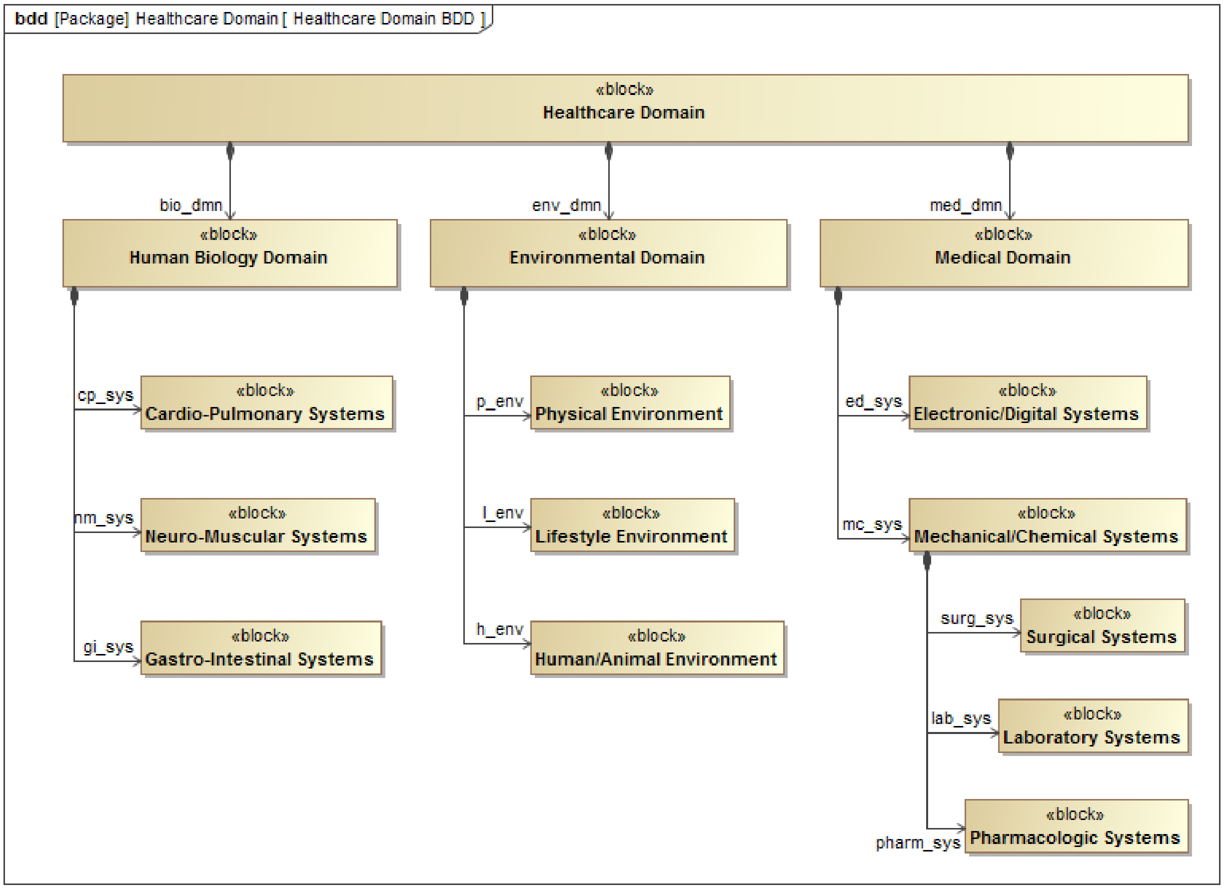


Figure 1 Healthcare Domain System of Systems

environment, lifestyle factors like work, diet and exercise, and contact with other humans and animals (the epidemiological environment). When a problem is recognized, the human body may also become subject to the medical care domain, what we often myopically think of as the healthcare system. Each of these systems is a separate discipline, studied by specialists with specialist tools. MBE recognizes the connections between them as critical to understanding human health outcomes, a concept widely accepted, but infrequently put into practice.

In this whitepaper, we will explore how MBE can serve modeling and simulation in the healthcare domain. We present four examples showing a range of healthcare applications and specific use cases for connecting SysML models with the other engineering software tools these domains use.

- A simplified cardiovascular system SysML connectivity model transformed into a Simulink block structure for biological simulation
- A healthcare delivery SysML parametrics model solved using an external mathematical solver and data from a MySQL database for resource planning
- A medical device SysML model connected to PLM and MCAD tools for engineering development.
- An HL7 messaging development system connected with JIRA issue tracking for project management

All of these models use Syndeia™, a standard software platform from InterCAX for creating and managing a unified system model with a network of persistent connections to models in different tools and repositories. Syndeia 2.0, released July 2015, is used for all examples except the JIRA interface, which will be available in Syndeia 3.0, planned for release in May 2016. It should be noted that the range of products available for MBE connectivity is increasing and Syndeia is not exclusive of other products supporting other use cases.

Cardiovascular System Model and Simulation

The human cardiovascular system is extremely complex. The heart pumps blood into arteries, which subdivide into a finer and finer network of capillaries that supply oxygen and fuel and carry away waste products from the body's tissues, and recombine into veins that return the blood to the heart. A second loop sends blood through the lungs for oxygenation.

SysML internal block diagrams (IBDs) provide an efficient way to model this network, using multiple levels of diagram to drill down to finer detail. Figure 2 shows Level 1 of this model, dividing the system into three main subsystems. Each of the ports shown is a proxy port typed by the interface block Blood, although the stereotype and type information has been hidden to reduce diagram clutter.

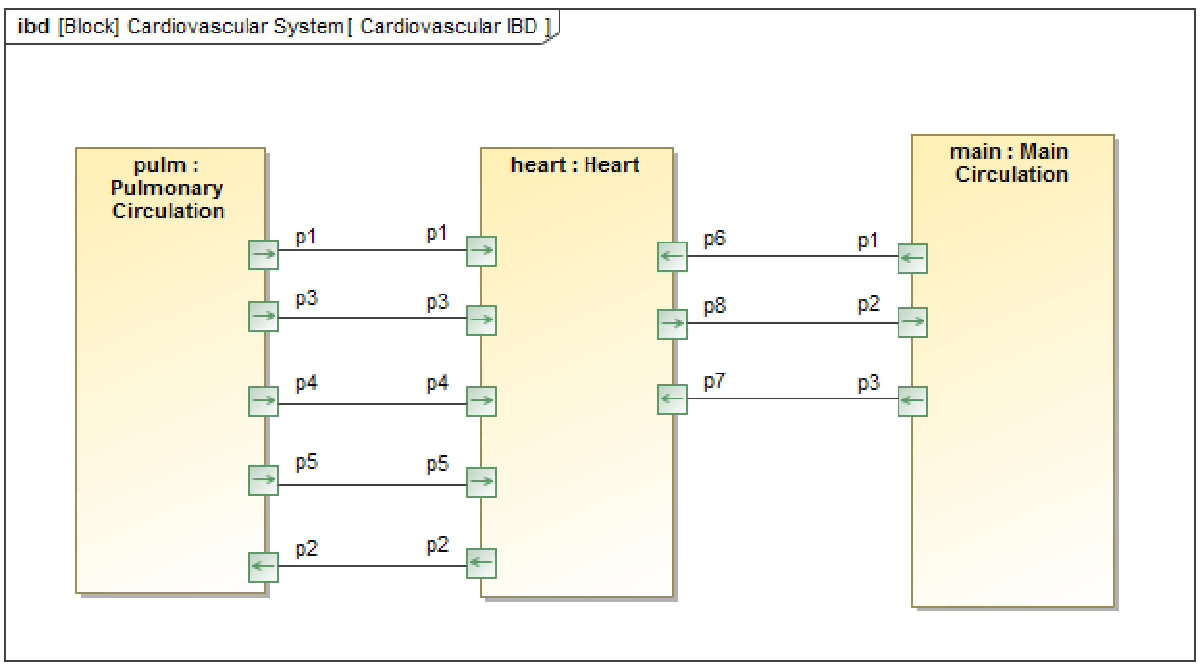


Figure 2 Cardiovascular System SysML IBD (Level 1)

Using Syndeia, we can use the SysML model to generate an equivalent Simulink model (Figure 3). The block structure created becomes the basis for the Simulink analyst's work, adding MATLAB code to the block to create an executable simulation. This is not a one-time export-import process; the models remain linked through a fine-grained network of persistent connections that allow them to be compared and reconciled as the two models evolve and diverge.

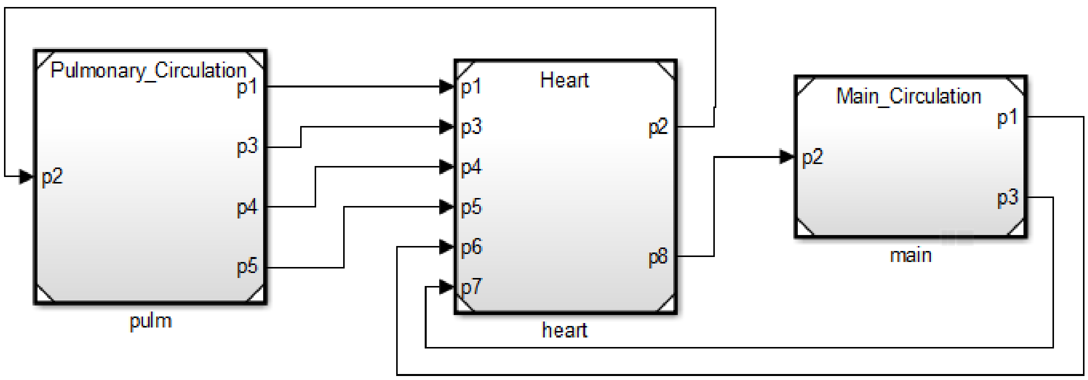


Figure 3 Cardiovascular System Simulink Block Diagram (Level 1)

The subsystems in Figure 2 have their own Level 2 IBDs; for example, Figure 4 represents connectivity inside the Main Circulation block. It shows several of the main veins and arteries, including the aorta and superior vena cava, as well as major subsystems, e.g. Head and Neck Circulation. The Syndeia transformation has brought over all levels under the Cardiovascular System block to Simulink in one step, including the Main Circulation block in Figure 5.

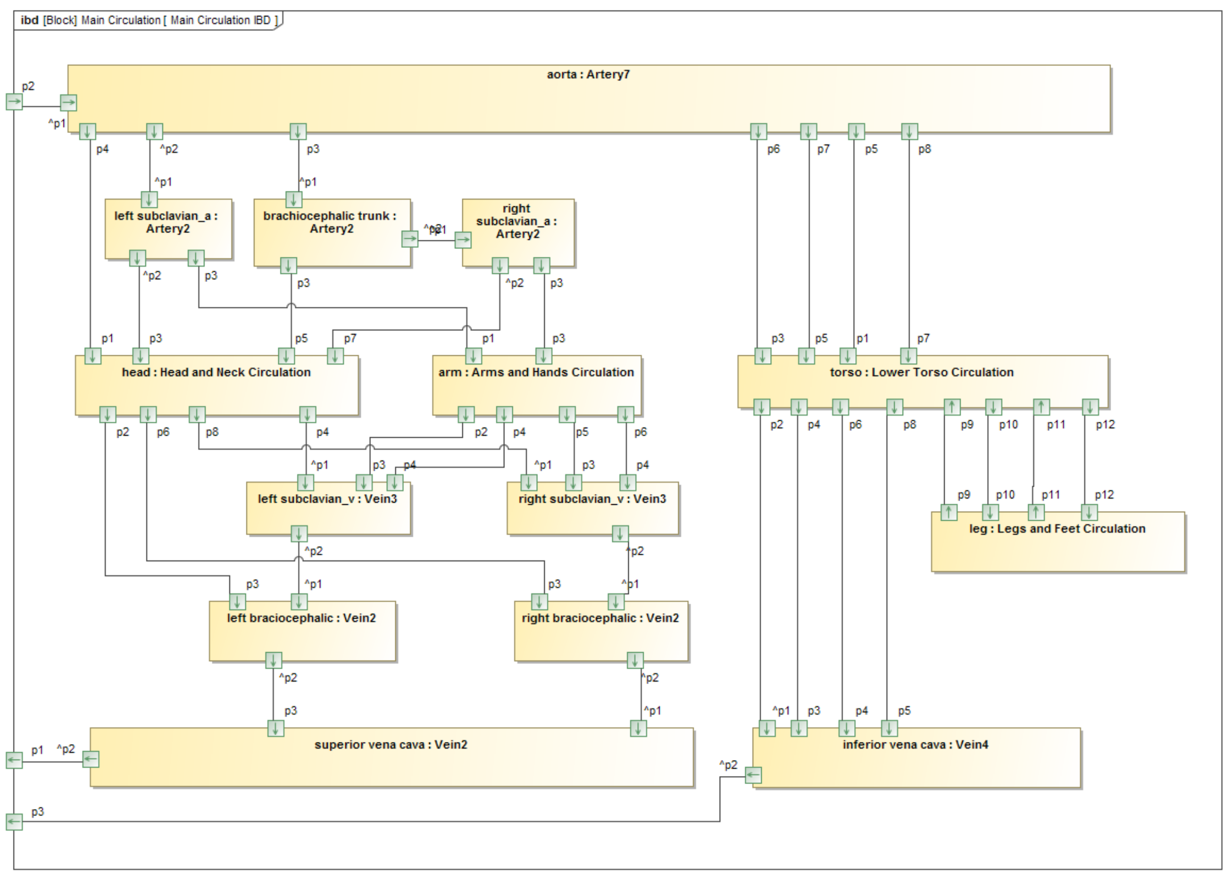


Figure 4 Main Circulation SysML IBD (Level 2)

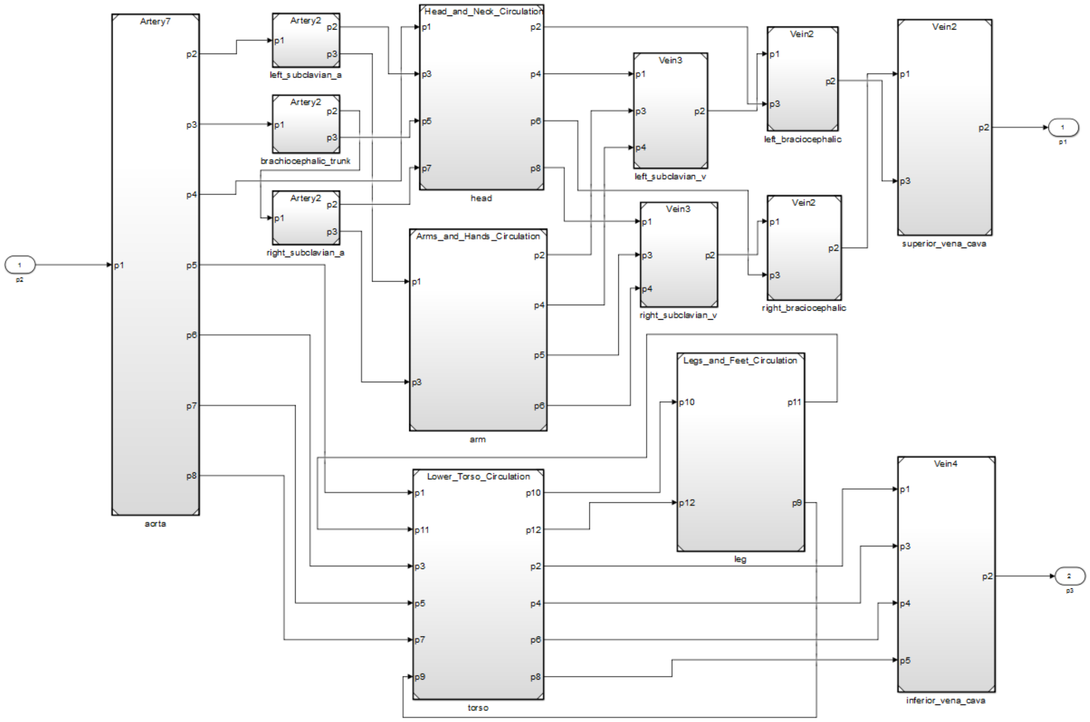


Figure 5 Main Circulation Simulink Block Diagram (Level 2)

Any number of levels can be brought over in a single Syndeia operation. Figure 6 shows the IBD for the Head and Neck Circulation block, which becomes the Simulink block structure in Figure 7.

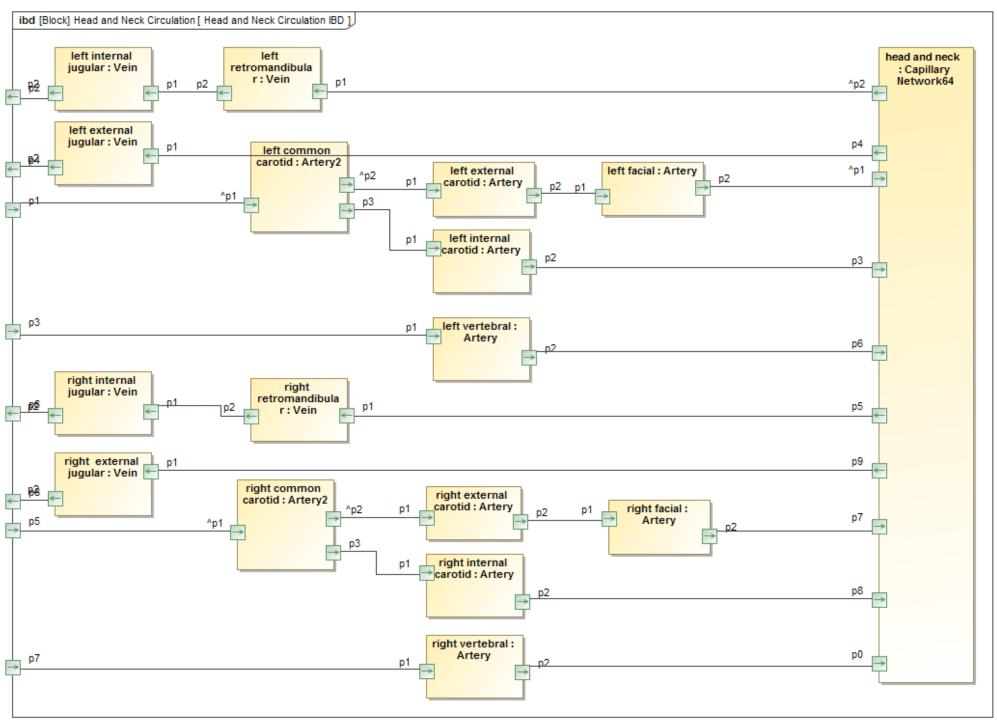


Figure 6 Head and Neck Circulation SysML IBD (Level 3)

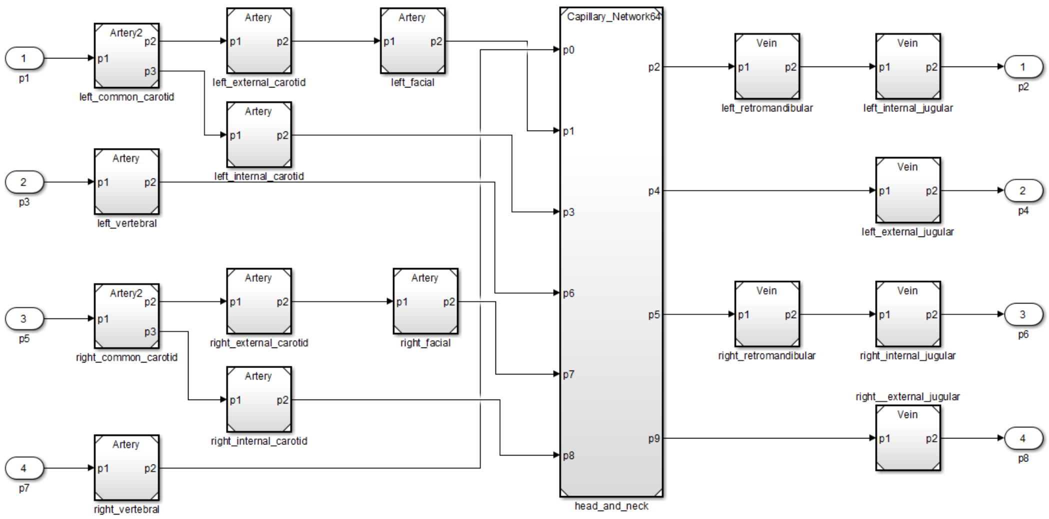


Figure 7 Head and Neck Circulation Simulink Block Diagram (Level 3)

All the subsystems shown in the Level 1 and 2 diagrams were further decomposed in our model, but the effort stopped at the Level 3 subsystems, the Capillary Networks. These could be further decomposed as well to any level of detail required. Filtering the number of levels and the content brought over between models is an important capability being added to Syndeia with both modeling and access/security import. It needs to be tailored to the model's needs, their conceptual domains, and concerns about releasing proprietary or classified information.

Healthcare Delivery Analysis

Efficiency in healthcare delivery has long been a target of systems engineering and operations analysis effort. Improvements in emergency room care, for example, can lead to better outcomes and better patient experience while reducing the cost of care. Much of this work has been done with specialized simulation tools, with the drawback that the models must be created, validated and updated in each tool separately. MBE calls for a single model with both architectural and analysis aspects. SysML supports analysis through parametric diagrams.

In this section, we apply simple parametric analysis to testing medical facility staffing and supply against requirements, all captured in a SysML model, but linked to mathematical solvers, databases and potentially other models in other tools. Figure 8 shows the system structure of a chemotherapy facility, a domain consisting of one-to-many drug delivery stations, nurses and patients, as well as a drug supply of several available chemotherapy drugs. The architectural elements are shown in gray. The green blocks represent analysis models that reference the system elements to carry out specific analyses.

Figure 9, a SysML requirements diagram, shows three requirements that the facility is expected to meet, for example, that nurse utilization in managing the drug treatments should not exceed 50% of their time (in order that they have adequate time for record keeping and other activities). Each requirement is refined by a constraint block that tests that requirement as a conditional, returning 1 for pass and 0 for fail. Figure 10 shows these tests incorporated in the Drug Delivery Analysis block. The remainder of the Drug Delivery Analysis parametric model is shown in Figure 11. It calculates the total time per month

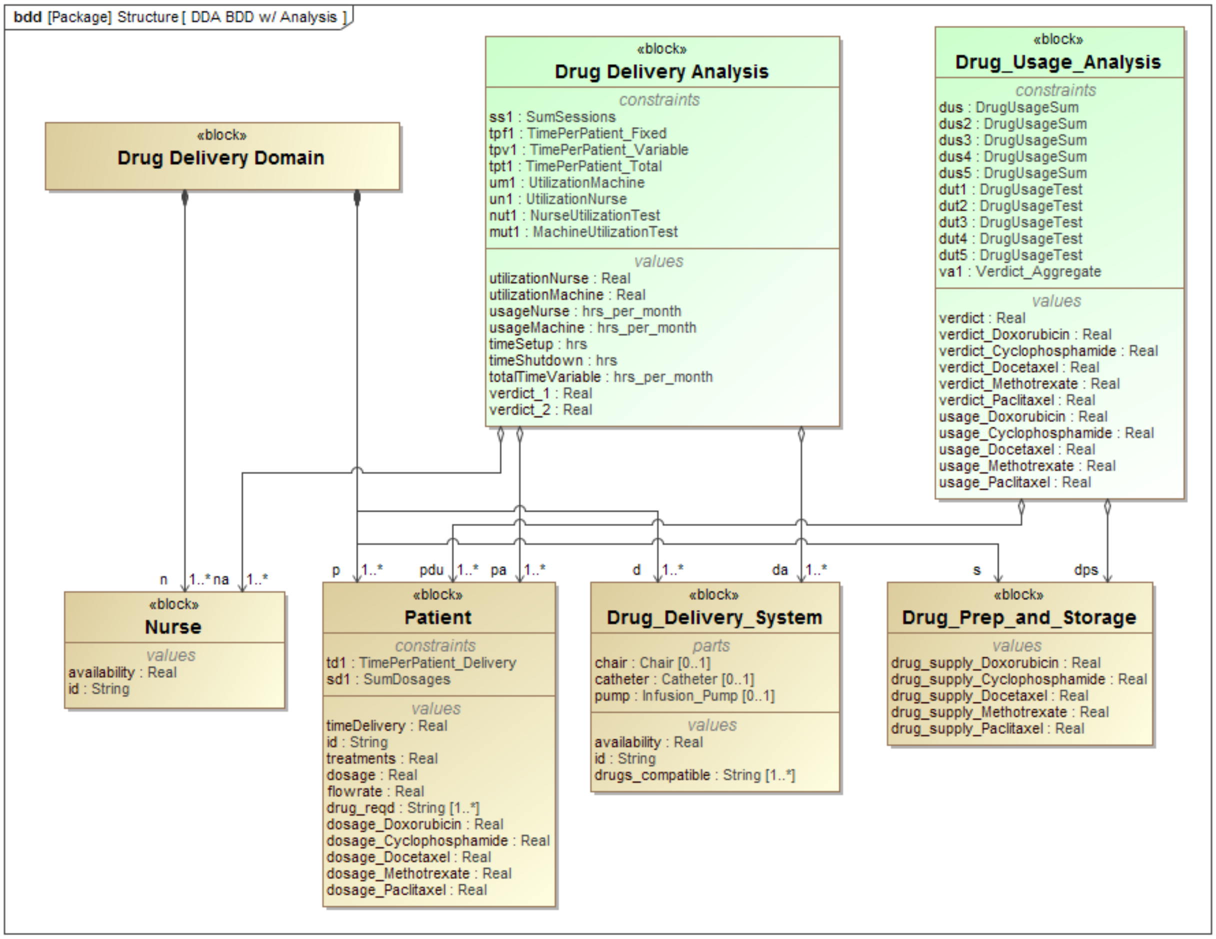


Figure 8 Drug Delivery Facility Structure – SysML Block Definition Diagram

required to treat all patients, including both their individual treatment times and standard set-up and shutdown times per patient, and how this compares with nurse and drug delivery station availability. A parallel analysis for drug usage keeps track of the stocks and uses of five chemotherapy drugs. Keeping these analyses in separate blocks allows them to be developed without affecting the base system elements.

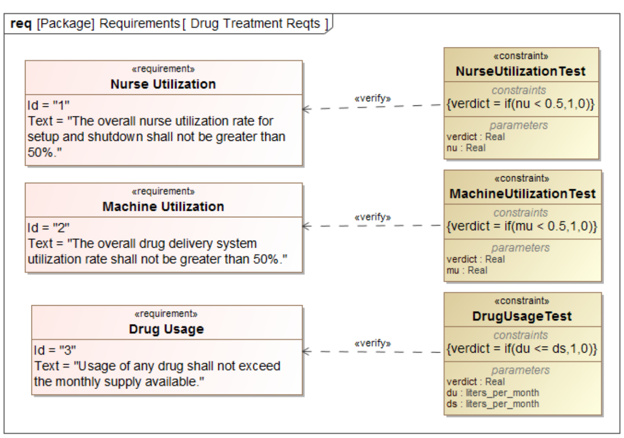


Figure 9 Delivery Requirements

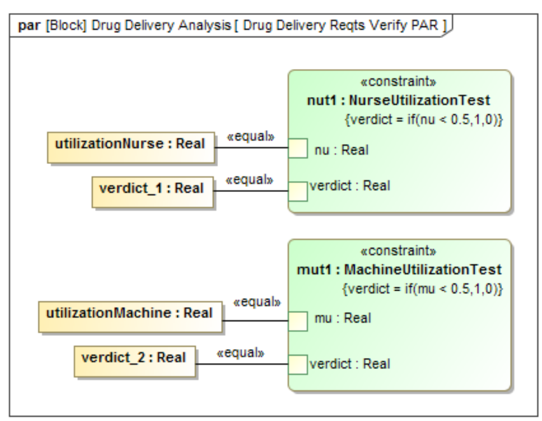


Figure 10 Delivery Requirements Verification

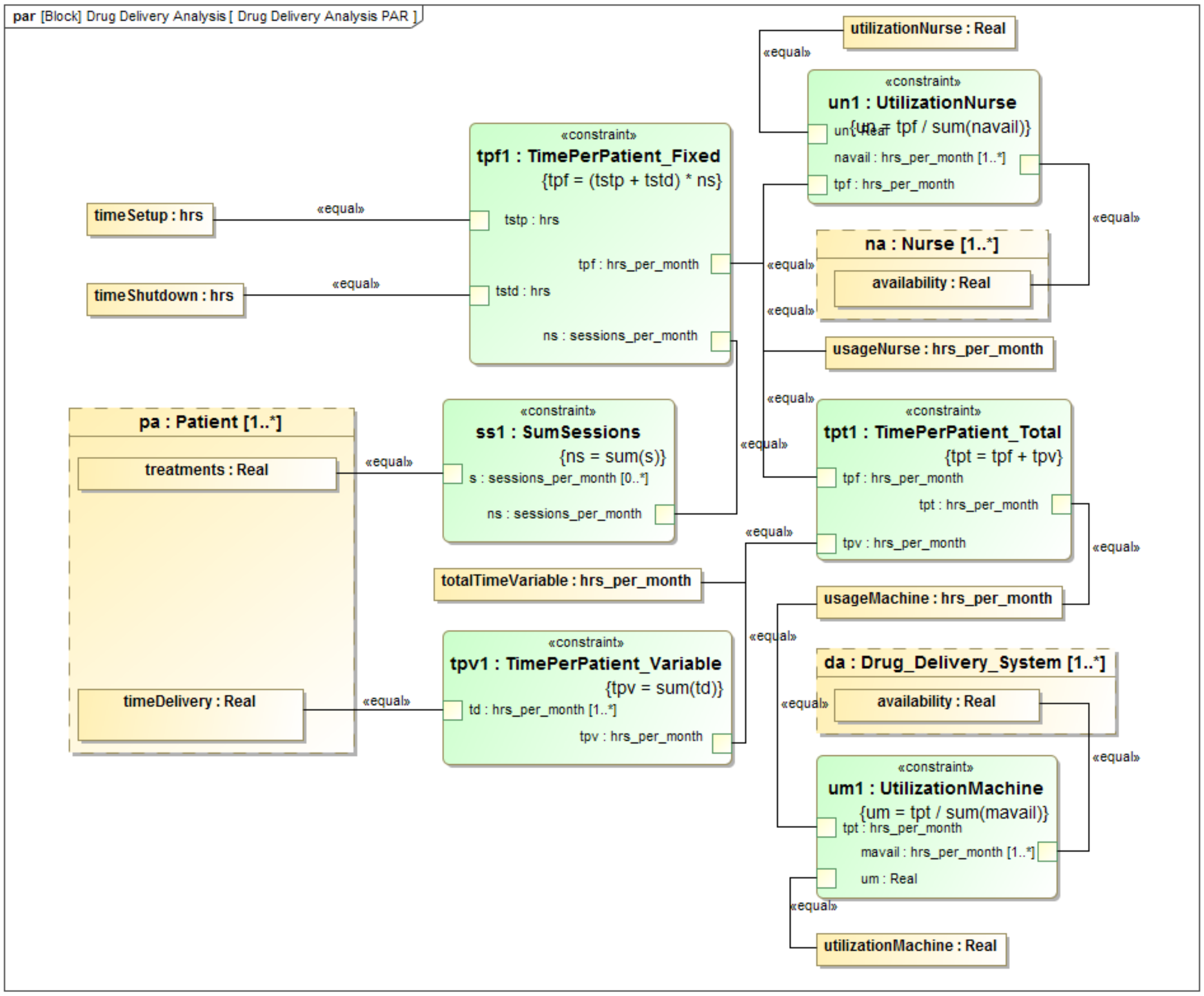


Figure 11 Drug Delivery Facility Analysis – SysML Parametrics Diagram

Having developed the parametric model, we need to create one or more instances of the model with patient, drug, nurse and drug delivery system data. Ordinarily, this data would be stored in a database and brought into the parametric model as necessary. In our example, we use a MySQL database holding a series of tables. In Figure 12, the Syndeia dashboard shows the contents of the MySQL tables on the right and the instances of the table rows that Syndeia has generated in the SysML model on the left, biomed_Drug_Delivery_System_301, biomed_Nurse_201, and so forth. The SysML instances and the database remain linked, so changes in database data over time may be recognized and be used to update the SysML model whenever the user wants.

Each type of system element has different parameters. In our example, nurses are only characterized by ID number and availability in hours per month, drug delivery systems by ID, availability and drug types compatible. Patient data includes treatment profile information, including drugs needed, dosage and flowrate, and treatment frequency.

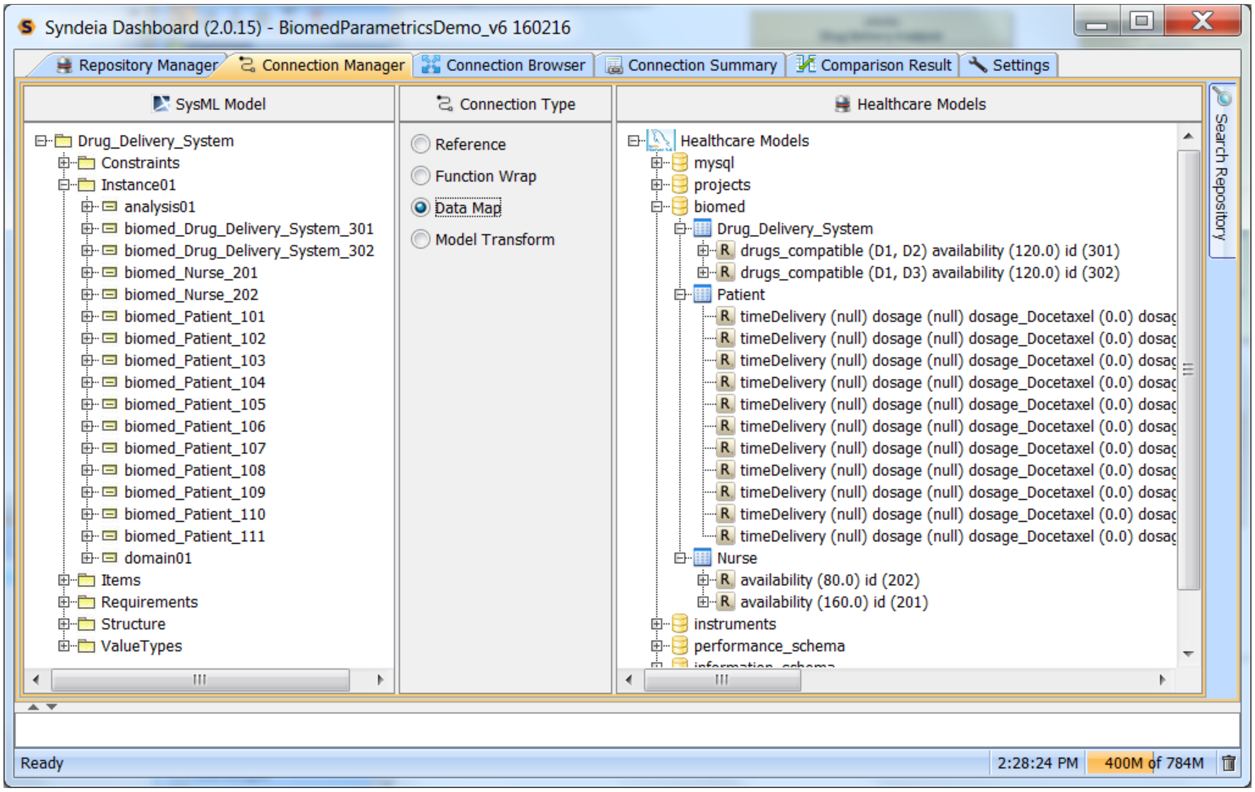


Figure 12 Patient, Nurse and Machine Data Connections to MySQL Database via Syndeia

While Syndeia is used to create the instances and keep them linked to the database, a second InterCAX software tool, ParaMagic™, is used to carry out the availability calculations and requirements verification. ParaMagic is launched from an instance of the Drug_Delivery_Analysis block. The ParaMagic browser is shown in Figure 13, where the instances of nurse, patient and drug delivery system referenced by the analysis have been selectively expanded to show the input data. The constraints inside the analysis block are shown at the bottom.

On execution, the network of constraints and parameter values is sent to an external symbolic math solver (PlayerPro from Wolfram Research) which returns the calculated results to the ParaMagic browser. In Figure 14, we show the results for the first instance, with two nurses and two drug delivery stations. Nurse utilization – the fraction of the nurse's time on duty spent on patient treatment – is only 0.21 and verdict_1, the verification of the Nurse Utilization requirement in Figure 9, is 1, pass. Machine utilization – the fraction of time, on average, the drug delivery stations are used – is 0.63, so verdict_2 is 0, fail on the Machine Utilization requirement. The difference comes from our model, where nurses are only fully engaged in treatment during set-up and shutdown for each patient session, an assumption that might need to be modified in a more realistic model.

In Figure 15, a second instance is created, adding an additional drug delivery station. In this case, both requirements are verified as passed. In this way, we have shown that a model linking the system architecture, databases of patient and facility data, and a powerful math solver allows us to explore alternative treatment scenarios and improve healthcare resource utilization.

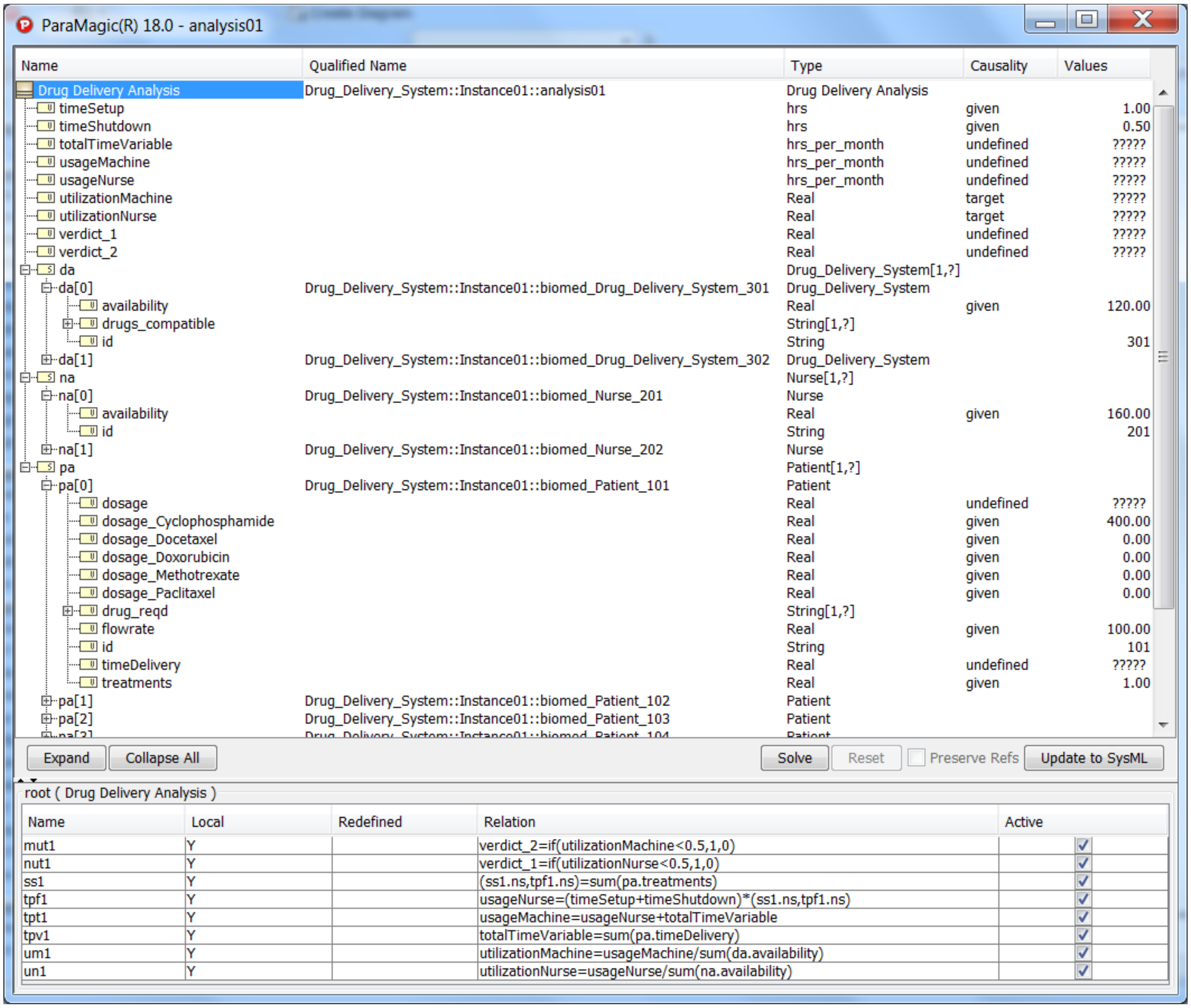


Figure 13 ParaMagic browser before solving, showing representative patient, nurse and machine instances

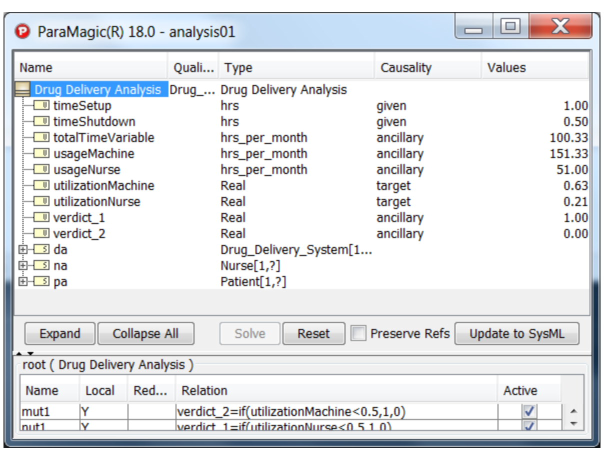


Figure 14 Instance01 – Solution for two machines

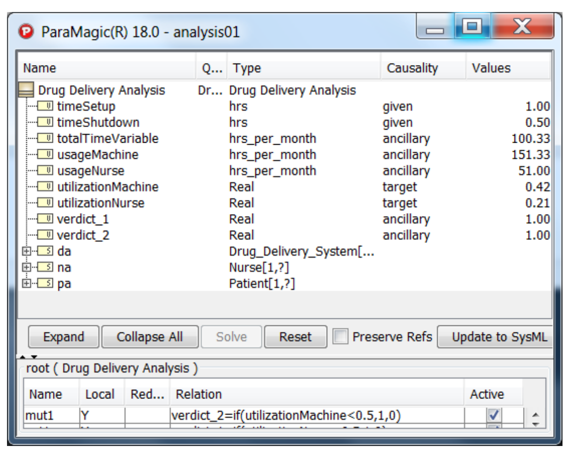


Figure 15 Instance02 – Solution for three machines

Medical Device Design and Manufacture

One area in the biomedical and healthcare domain where MBSE has made significant progress is in medical device design and manufacture. At the same time, device suppliers use modern PLM (product lifecycle management) and CAD (computer-aided design) like other organizations engaged in complex engineering problems.

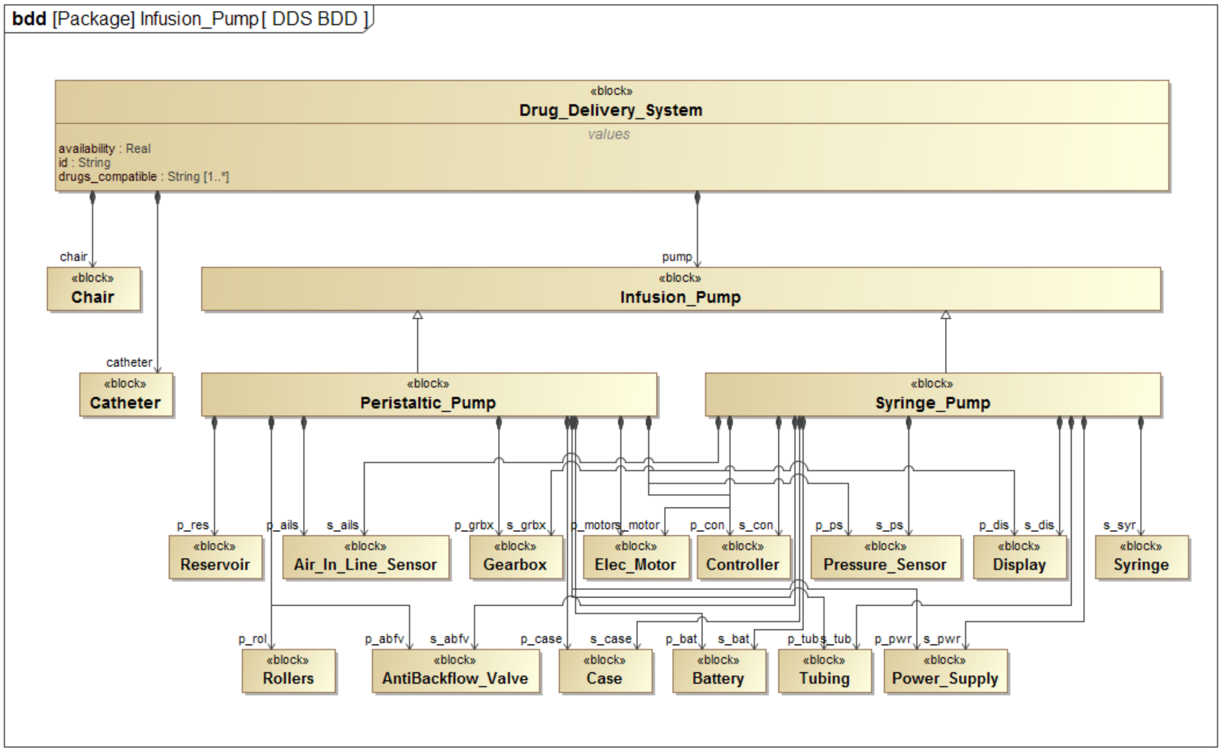


Figure 16 Decomposition of Infusion Pump Variants within the Drug Delivery System domain

Figure 16 shows the structural decomposition of the Drug Delivery block shown earlier in Figure 8, with specific focus on the Infusion Pump, a medical device that meters out the drug into the patient catheter. In this SysML BDD, two infusion pump variants, peristaltic and syringe pumps, are specified with their subsystems, some of which are common to both. Figure 17 shows the interfaces for the syringe pump variant in a SysML IBD. In this way, the conceptual design of a medical device, including functions and requirements, is captured within a larger context model.

As the product enters detailed design, focus turns to engineering models which are configuration-managed in a PLM system, although the need for the architecture model does not disappear. In Figure 18, Syndeia has been used to generate a PLM BOM (bill of materials) in Siemens Teamcenter for the peristaltic pump variant. As with the previous Syndeia examples, the two models remain connected for comparison and updating as the project develops. The same transformation could be used in reverse, taking subsystem data managed in PLM for sensors, motors, etc. and using it to create new SysML blocks to be used in next generation system development.

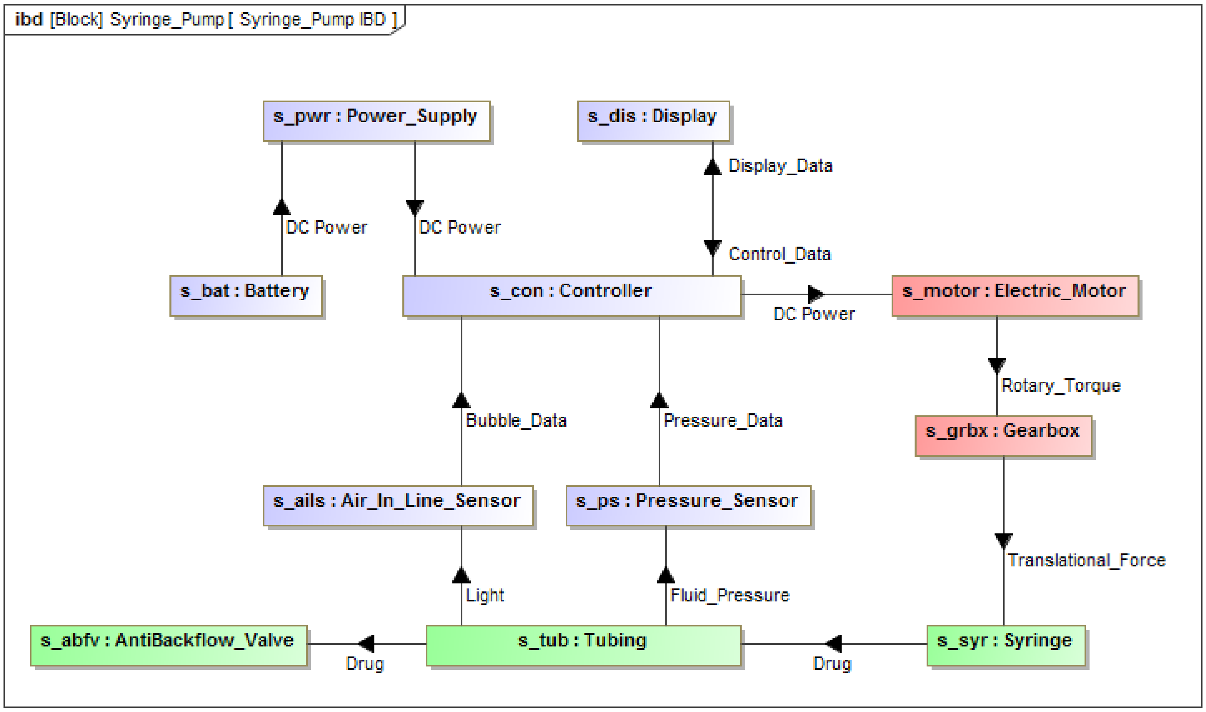


Figure 17 Syringe Pump IBD (color coding identifies electronic, electromechanical and chemical contact subsystems)

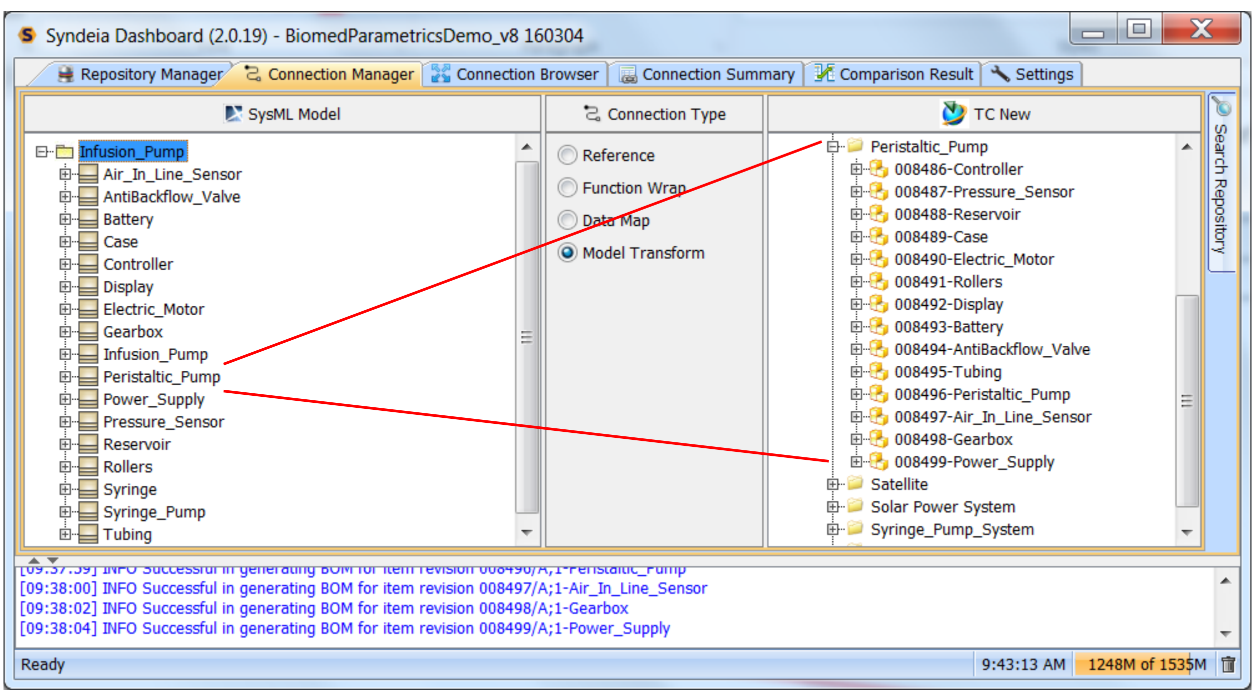


Figure 18 Syndeia used to seed Teamcenter PLM Bill-of-Materials for Peristaltic Pump variant

Syndeia can also facilitate the connection between the system engineer and the CAD designer. There are multiple potential use cases. A simple reference link between the Syringe SysML block and the Syringe CAD model in Siemens NX (Figure 19) allows the system engineer to open and view the CAD model (Figure 20).

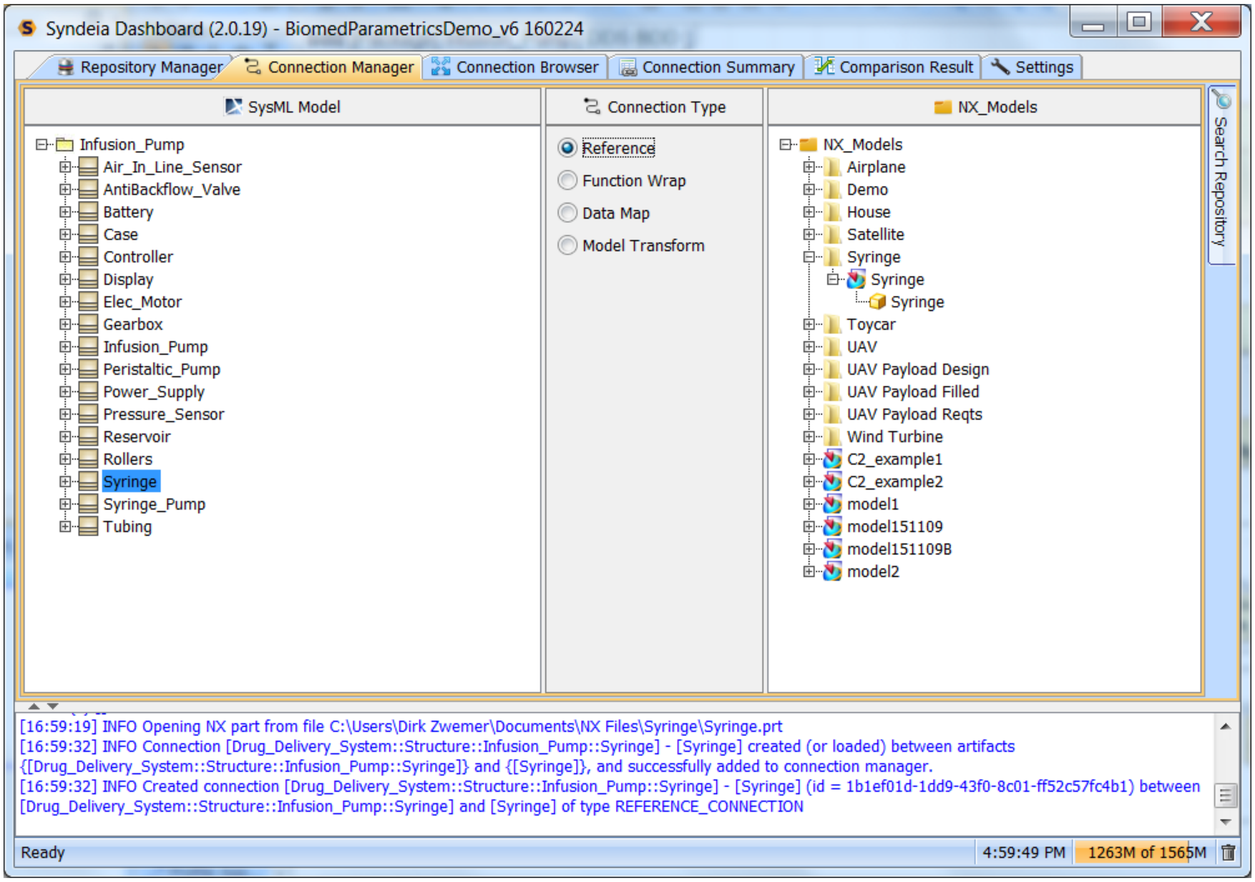


Figure 19 Syndeia dashboard showing SysML model on left and CAD files on right

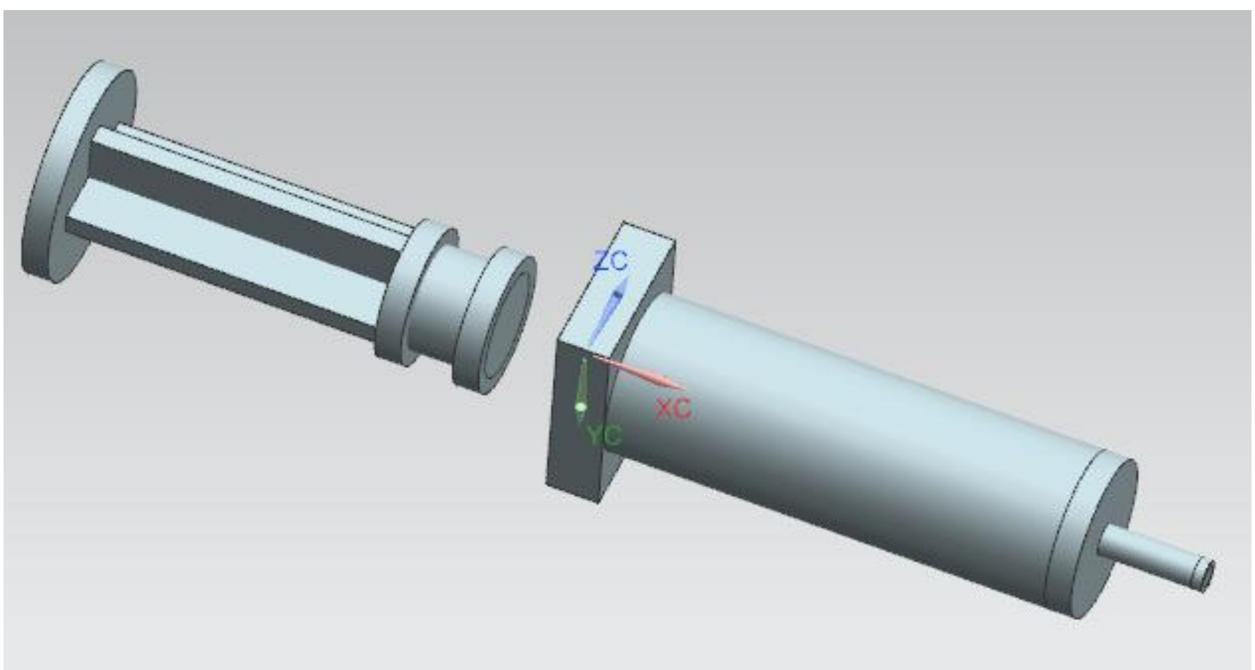


Figure 20 Syringe CAD model in Siemens NX

A more sophisticated use case connects geometry values in the 3D parametric CAD model to value properties in SysML, allowing changes in CAD design to update the SysML model for evaluating their impact on meeting system requirements. In Figure 21, the CAD model (right inset) is used to generate a linked SysML model of the syringe. Values of the innerBarrel part property are used to calculate syringe volume in a parametric model (lower right inset), which includes a constraint to verify the Inner Barrel Volume requirement, similar to the verification processes in the previous section.

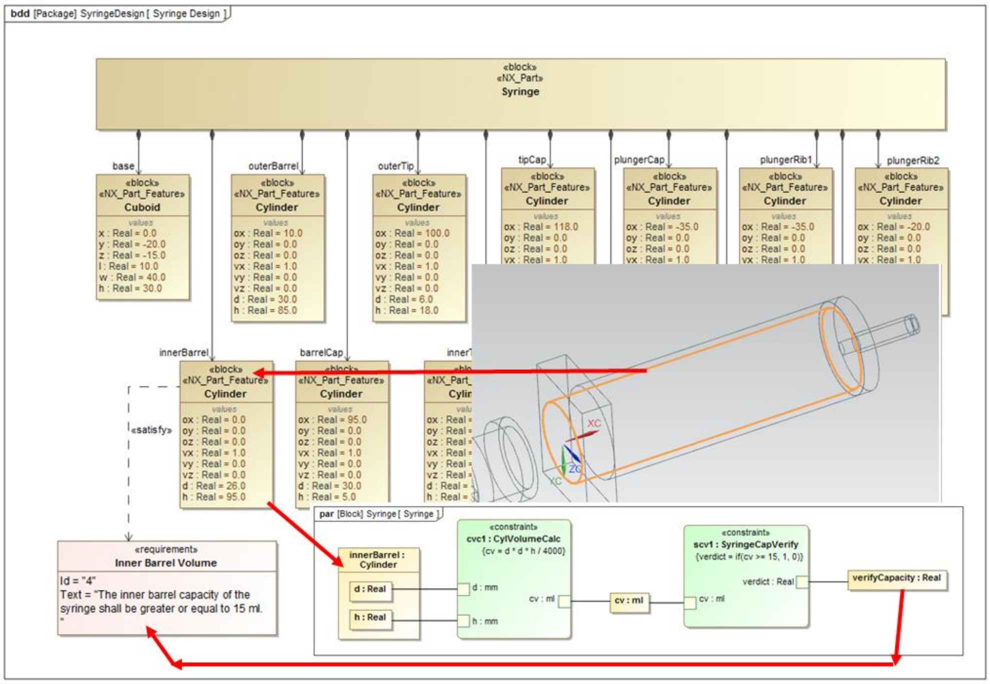
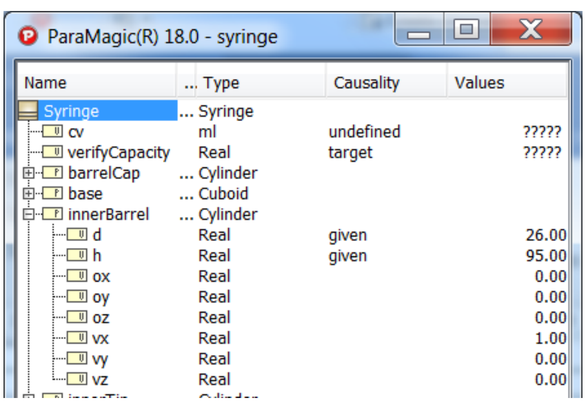


Figure 21 CAD model (right) is linked to SysML model of Syringe.

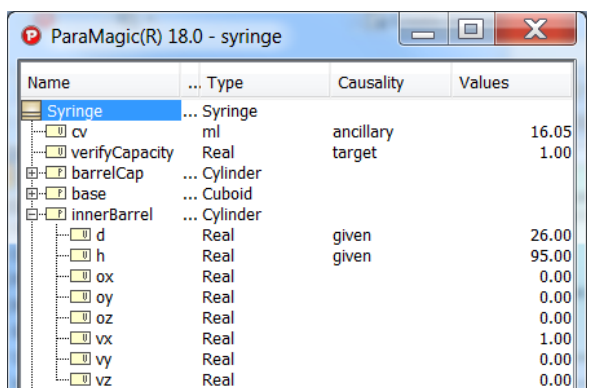
Using ParaMagic (Figure 22 and Figure 23), the syringe capacity is calculated and compared to the 15 ml minimum requirement. The current design passes the requirement, but changes of the CAD design would need to be transmitted via Syndeia to the SysML model and re-verified .



ParaMagic(R) 18.0 - syringe

Name	... Type	Causality	Values
Syringe	... Syringe		
cv	ml	undefined	?????
verifyCapacity	Real	target	?????
barrelCap	... Cylinder		
base	... Cuboid		
innerBarrel	... Cylinder		
d	Real	given	26.00
h	Real	given	95.00
ox	Real		0.00
oy	Real		0.00
oz	Real		0.00
vx	Real		1.00
vy	Real		0.00
vz	Real		0.00

Figure 22 ParaMagic, Syringe volume verification, before solving



ParaMagic(R) 18.0 - syringe

Name	... Type	Causality	Values
Syringe	... Syringe		
cv	ml	ancillary	16.05
verifyCapacity	Real	target	1.00
barrelCap	... Cylinder		
base	... Cuboid		
innerBarrel	... Cylinder		
d	Real	given	26.00
h	Real	given	95.00
ox	Real		0.00
oy	Real		0.00
oz	Real		0.00
vx	Real		1.00
vy	Real		0.00
vz	Real		0.00

Figure 23 ParaMagic, Syringe volume verification, after solving

Electronic Records Information System Modeling

Our previous examples have focused on primarily physical systems. Software and cyberphysical systems are equally important in the healthcare domain. The system engineer developing an electronic information system (EIS) for a healthcare facility needs to interact with ALM (application lifecycle management) systems like Git and issue tracking project management tools like JIRA.

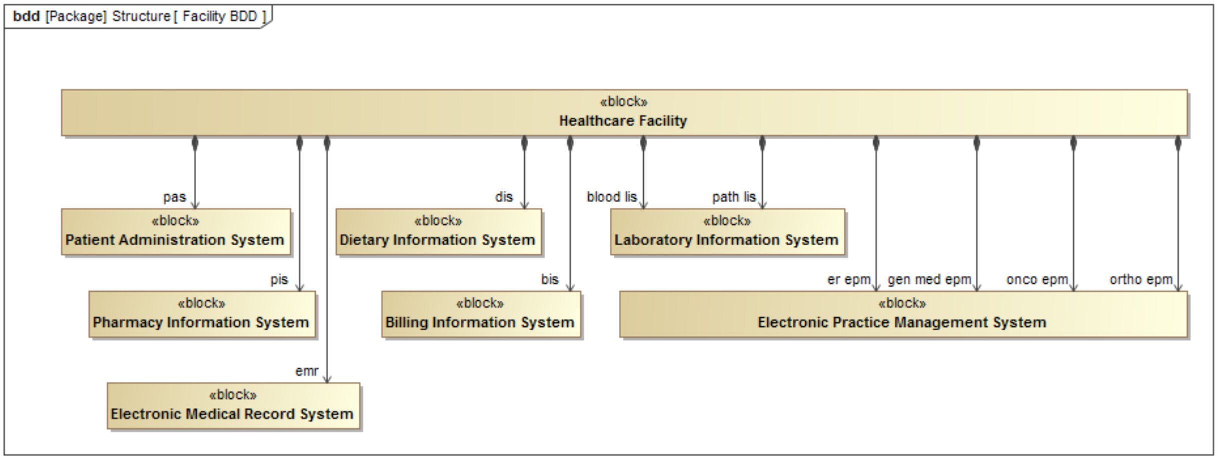


Figure 24 SysML model of a Healthcare Facility for which a electronic information system is being developed

In this example, we consider a healthcare facility with independent software systems for each department, as shown in Figure 24. A system engineer is tasked with developing a message exchange system between these elements based on the HL7 Version 2 standards. She begins by describing the interfaces and content exchanged between departments based on SysML interface blocks, such as those shown in Figure 25. The flow properties of these interface blocks are typed by HL7 message types as well as a direction. Figure 25

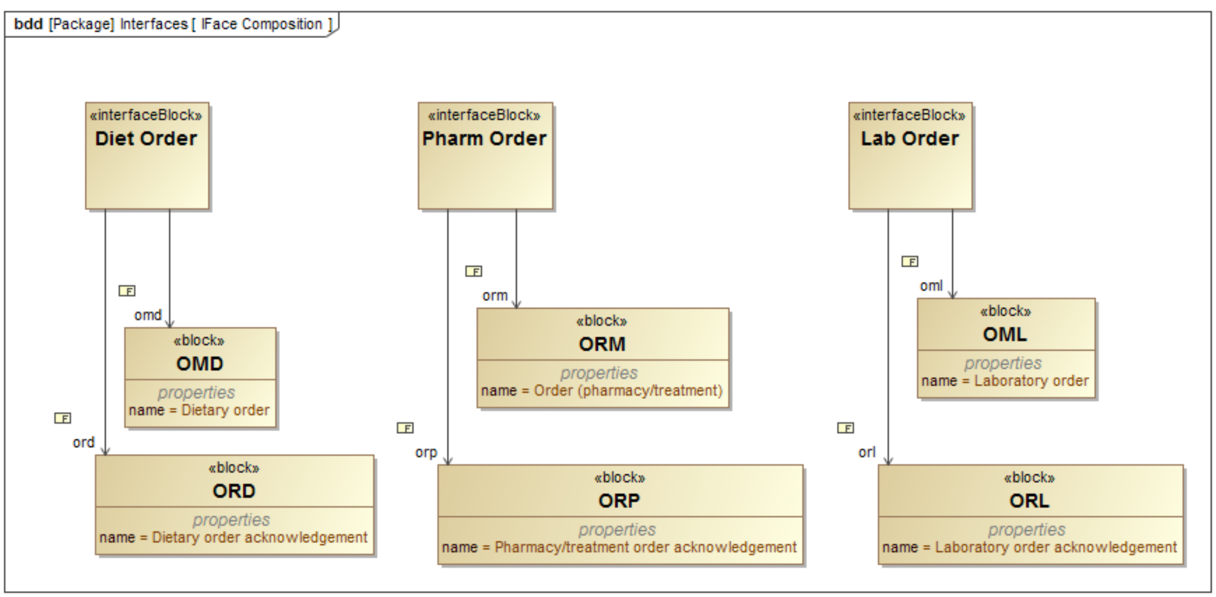


Figure 25 Examples of EIS interface blocks based on HL7 messages

With these defined, IBDs of the system to be developed describe the interfaces between departments in IBDs using proxy ports and item flows, as illustrated in Figure 26. Medical practice departments are shown on the right, support departments on the left. All ports are proxy ports. On highlighted connectors, the item flows show HL7 messages that are compatible with those ports.

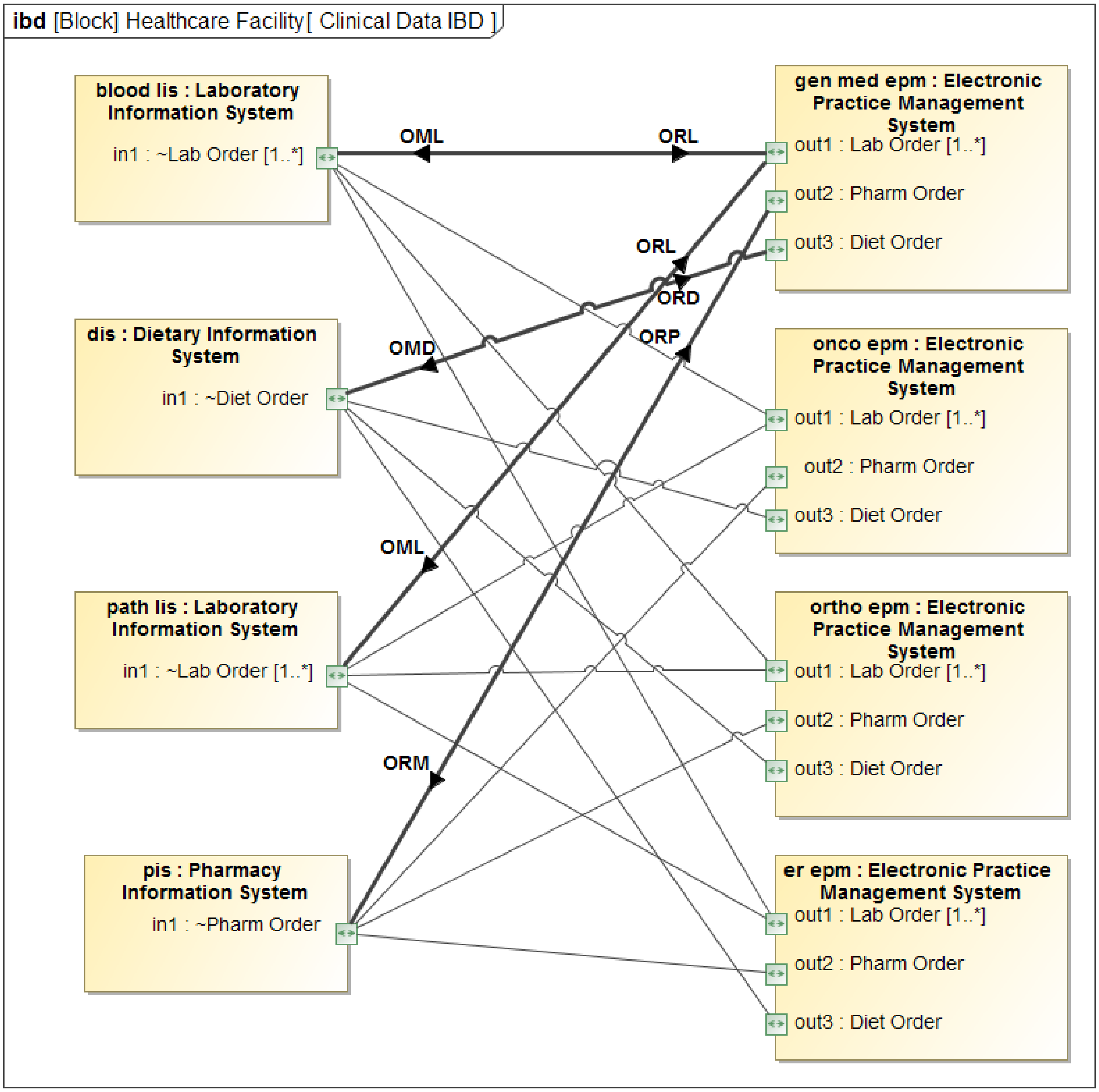


Figure 26 IBD (partial) of electronic information system connecting healthcare facility departments, selected connectors with their item flows highlighted

SysML can be used to model the HL7 messages in greater detail. In HL7 Version 2, messages are composed of standard segment types. Many segments are used by multiple message types and a message may contain more than one instances of a segment type. Figure 27 uses a BDD to illustrate the composition of two messages, where SysML features like inheritance and multiplicity capture important information about the message structure.

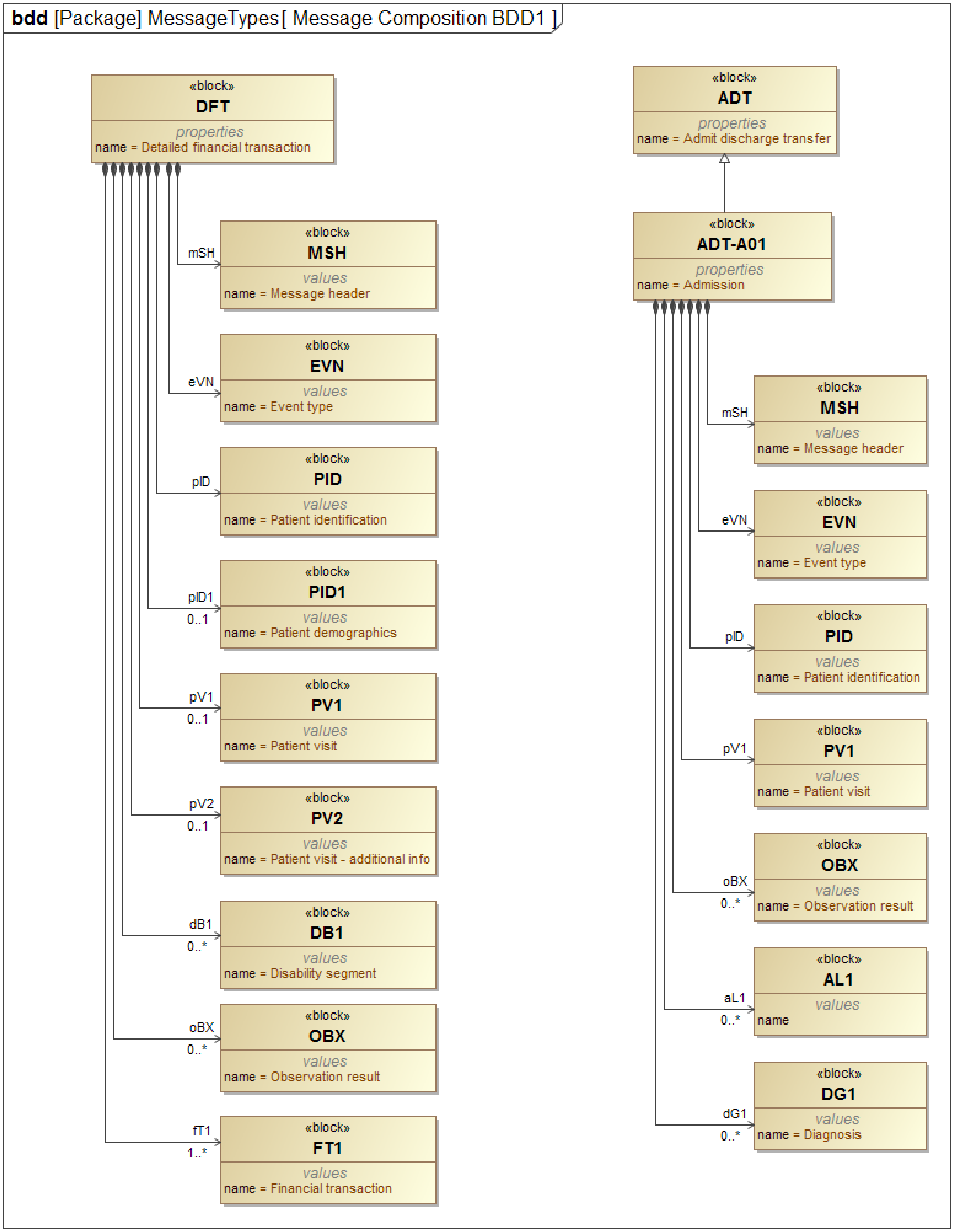


Figure 27 Representative HL7 Version 2 message structure using segments as part properties.

While developing and testing the EIS, the system engineer will need to keep track of issues and problems that arise. JIRA is an online tool widely used for this purpose. With access to the JIRA project, the system engineer can use Syndeia to create reference links between the SysML model and the JIRA project. For example, if she wishes to track issues by message type, she can create a reference link from the message type in SysML (left side of Figure 28) to a new issue in the JIRA project.

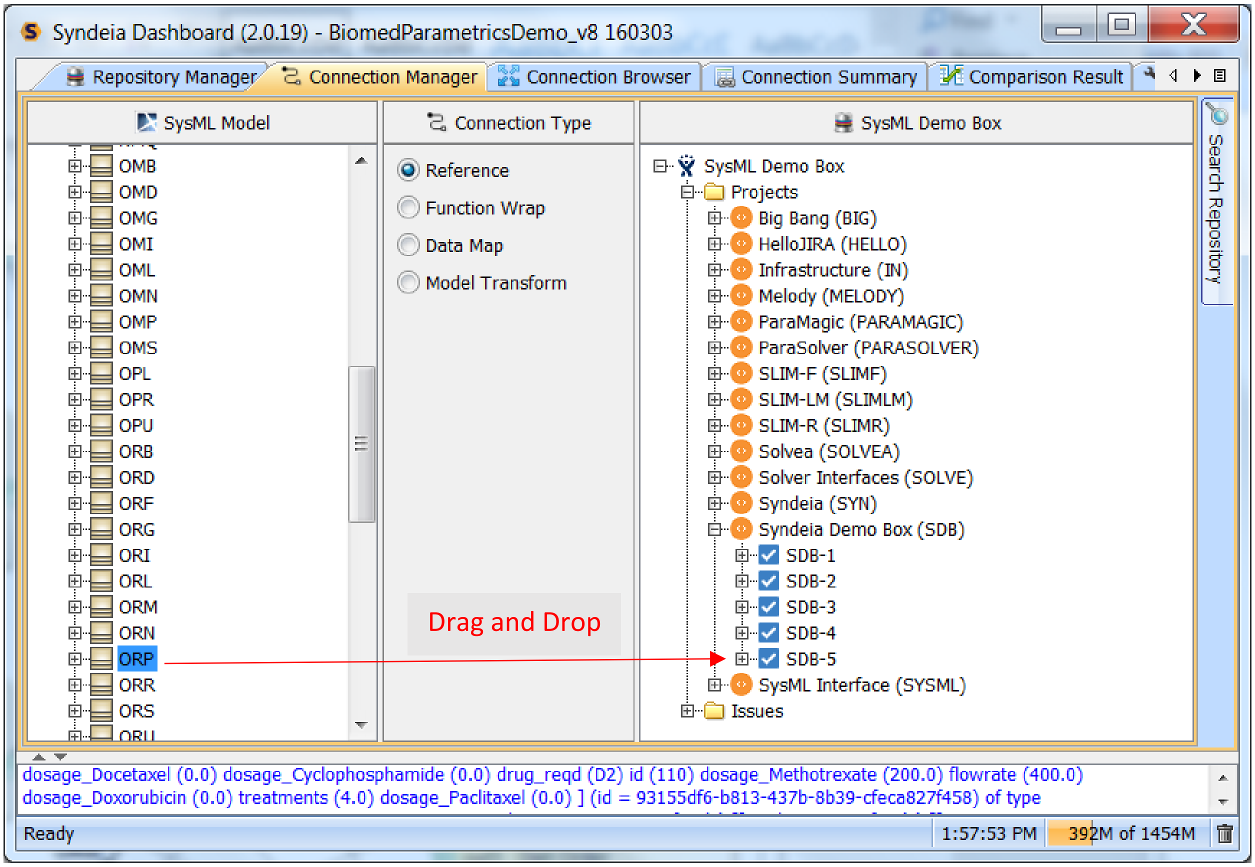


Figure 28 Creating a reference link between SysML and JIRA using Syndeia

Once these reference links are now created, the system engineer can go to any element in the SysML model and see and open the related JIRA issue. In Figure 29, the user has right-clicked on the ORM block in the SysML diagram. Three separate issues related to that message are displayed. Selecting the first, she can open JIRA (Figure 30) and see the entire issue, including priority, scheduled completion and resolution status.

JIRA is the first of the project management tools to be connected to SysML models by Syndeia. The division of responsibility between system engineer and project manager has always been somewhat ambiguous, but the application of MBE across the entire system model and tool chain gives both sides better visibility on system development progress and clearer communication channels for problem resolution.

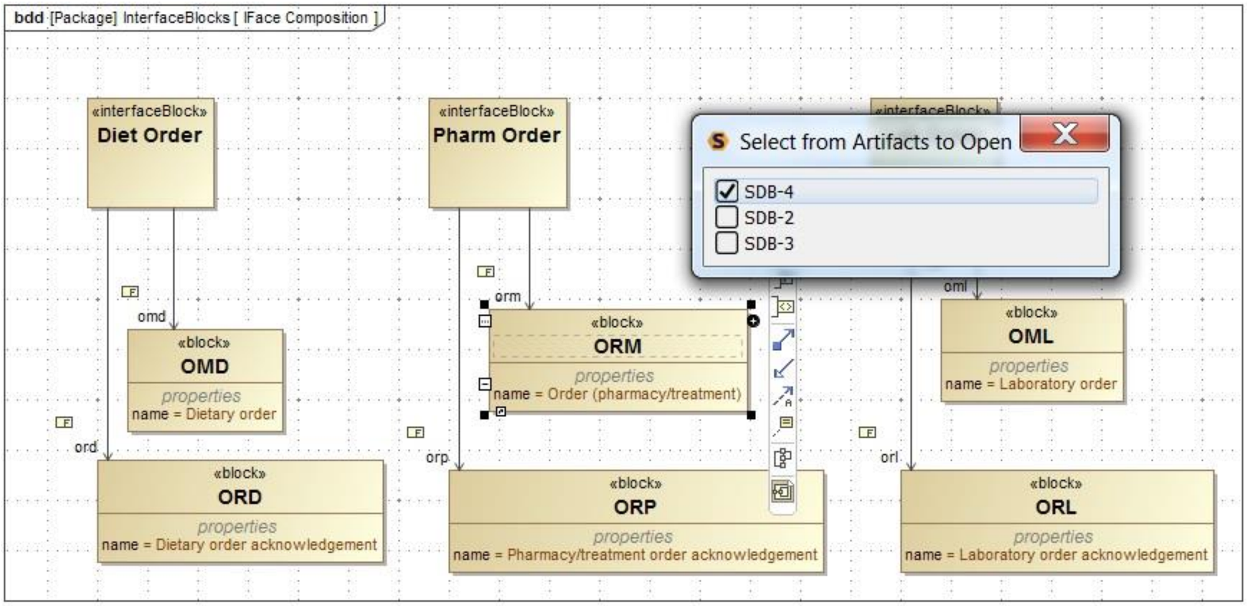


Figure 29 Opening linked JIRA issues from ORM block in SysML from diagram using Syndeia reference connection

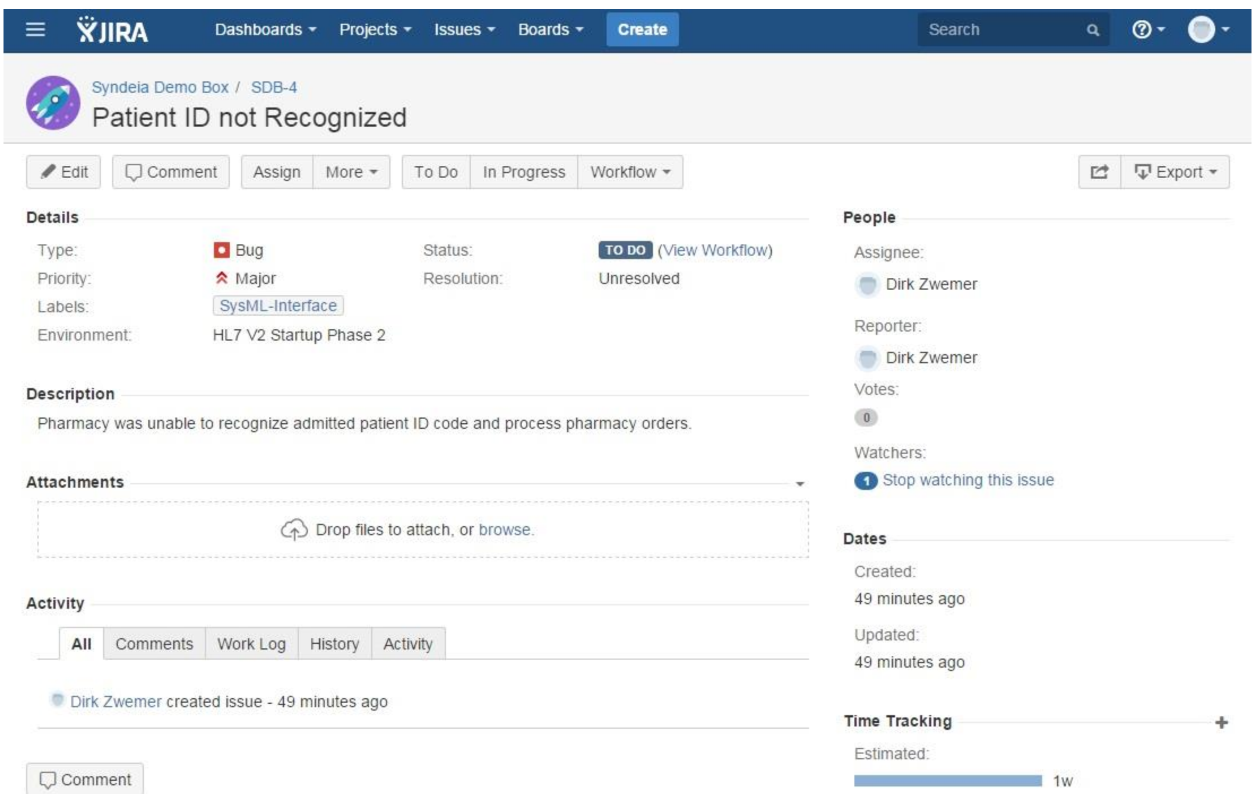


Figure 30 JIRA Issue record opened by Syndeia from SysML model

The Future of MBE for Healthcare

In this paper, we have demonstrated a wide range of applications for Model-Based Engineering in the healthcare domain. In particular, the ability to connect information across a wide range of engineering tools and data repositories, to create a unified system model, is critical to meeting our need to improve healthcare outcomes without unsupportable cost increases.

The use of MBE in this field can only grow. Whole new fields like epigenetics, which looks at the interaction between the genome and environmental factors, rely on the ability to connect models previously treated as independent. The data generated by ubiquitous networked sensors in the Internet-of-Things, ranging from our wristband pulse monitors to hospital diagnostic equipment, must be managed as a system-of-systems. All these factors are forcing us to abandon the narrow silos of specialization and apply disciplined system thinking, that is, systems engineering, to the problems.

Making this possible will require changes in the nature of MBE in response. All the examples we have looked at have put the system engineer at the center of the system model, as guardian and manager of the SysML modeling tool. But all members of the team have legitimate need to access the distributed system model. Both the requirements manager and the CAD designer need to know which designs are impacted by a change in requirements. Tools like Syndeia must offer potential to connect, query and visualize the system model from any vantage point in the tool chain or engineering process.

In the healthcare domain, the team expands to include medical practitioners, lifestyle advisors, and critically, the human subjects/patients themselves. This means the system model must be available through user-friendly interfaces not based on highly technical modeling languages. It means availability on web browsers, tablets and smart phones.

Fortunately, these needs are being addressed by many active workers in the field, in government, academia, and business. The transition from Model-Based Systems Engineering to Model-Based Engineering is in full swing and few areas will be as impacted as healthcare and biomedicine.

About the Author

Dr. Dirk Zwemer (dirk.zwemer@intercax.com) is President of Intercax LLC (Atlanta, GA), a supplier of MBE engineering software platforms like Syndeia and ParaMagic. He is an active teacher and consultant in the field and holds Level 4 Model Builder-Advanced certification as an OMG System Modeling Professional.
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