MBSE Initiative – SE2 Challenge Team

COOKBOOK FOR MBSE WITH SYSML

Issue 1

19/01/2011

Authors

Name	Affiliation
R.Karban	ESO
T.Weilkiens	oose
R.Hauber	HOOD Group
M.Zamparelli	ESO
R.Diekmann	
A. Hein	TUM

Change record

Issue	Date	Section / Paragraph affected	Reason / Initiation Documents / Remarks
1	19/01/2011	All	First release

Contents

1 Introduction

1.1 Scope

This document provides modeling patterns, recipes, guidelines, and best practices for the application of SysML. The presented examples are rather methodology independent and can be used (maybe with some adaption) in any MBSE environment.

Furthermore, it provides additional explanation on SysML syntax, semantics, and concepts. It partially annotates the SysML specification.

This Cookbook gives also some advice on general system modeling strategies and assumes basic knowledge of SysML. The Cookbook is not an introduction to SysML.

Our examples are about the Active Phasing Experiment (APE) project and modeled with the modeling tool MagicDraw from NoMagic. Unless mentioned otherwise everything is independent of these can be applied to other domains and tools.

1.2 Purpose

Each project has to establish a minimal set of rules for using SysML constructs and how to organize the model. SysML is just a language which can be used or abused.

The document provides to the modeler solutions for day to day modeling problems, the modeling “technicalities”. Applying those recipes the modeler can focus more on the content of the system of interest than on modeling problems.

Systems Engineering diagrams always look so simple!

The Systems Engineering exercise is to first make the problem real to the reader/participant, then second to show an 'obvious' solution. To a casual reader these systems decisions should look like no-brainers - that is the value of systems engineering.

This cookbook is organized in this way:

Chapter 3 contains recipes about the organization of models

Chapter 4 proposes style, layout and naming conventions

Chapter 5 gives guidelines about modeling the system views.

Chapter 6 gives guidelines about modeling requirement and use cases.

Chapter 7 contains recipes for modeling the system structure.

Chapter 8 describes the modeling of interfaces.

Chapter 9 deals with the behavior modeling.

Chapter 10 provides guidelines for modeling non-functional aspects.

Chapter 11 is about document generation out of the model.

Chapter 12 discusses the integration with other engineering disciplines.

1.3 About SE^2 and APE

In the framework of INCOSE’s strategic initiative, the *Systems Engineering Vision 2020*, one of the main areas of focus is model-based systems engineering. In keeping with this emphasis, the European Southern Observatory (ESO; http://www.eso.org/) is collaborating with the German Chapter of INCOSE (http://www.gfse.de/) in the form of the “MBSE Challenge” team SE^2. The founders of the team were Robert Karban (ESO), Tim Weilkiens (oose) and Andreas Peukert (TUM). Afterwards Dr. Rudolf Hauber (HOOD Group), Michelle Zamparelli (ESO), Rainer Diekmann, and Andreas Hein (TUM) joined the team.

The team's task is to demonstrate solutions to challenging problems using MBSE. The Active Phasing Experiment (APE; see Gonte et al. 2004), a European Union Framework Program 6 project, was chosen as the subject of the SE^2 Challenge Team (http://mbse.gfse.de/). Many technical products in the telescope domain show an increasing integration of mechanics with electronics, information processing, and also optics, and can therefore be rightly considered as optomechatronic systems.

The SysML models were created by reverse engineering from existing documentation and from interviews with systems engineers. We will make use of Ingmar Ogren's concept of a common project model (Ogren 2000) to establish a common understanding of the system.

1.4 Abbreviations and acronyms

SysML	OMG Systems Modeling Language
IBD	Internal Block Diagram
BDD	Block Definition Diagram
PAR	Parametric Diagram

Table 1. Acronyms

1.5 Glossary and definitions

Not applicable.

1.6 Document conventions

TBD

2 Related documents

2.1 Reference documents

The following documents provide background information as to the present document. Under no circumstance shall the content of reference documents be construed as applicable to the present document, in part or in full, unless explicitly mentioned in the present document.

RD1 SysML Spec v1.2

RD2 The Art of Systems Engineering, Maier, Rechtin, CRC Press 2002

RD3 E. Hull, K. Jackson, J. Disk, "Requirement Engineering", Springer, 2005.

3 Overview of the APE Case Study

Large telescopes pose a continuous challenge to systems engineering due to their complexity in terms of requirements, operational modes, long duty lifetime, interfaces and number of components. A multitude of decisions must be taken throughout the life cycle of a new system, and a prime means of coping with complexity and uncertainty is using models as one decision aid.

The potential of descriptive models based on the OMG Systems Modeling Language (OMG SysML™) is shown in different areas: building a comprehensive model serves as the basis for subsequent activities of soliciting and review for requirements, analysis and design alike.

Furthermore a model is an effective communication instrument against misinterpretation pitfalls which are typical of cross disciplinary activities when using natural language only or free-format diagrams. Modeling the essential characteristics of the system, like interfaces, system structure and its behavior, are important system level issues which are addressed.

Also shown is how to use a model as an analysis tool to describe the relationships among disturbances, opto-mechanical effects and control decisions and to refine the control use cases.

The Active Phasing Experiment has been supported by the FP6 research program of the European Union. It started beginning 2005 to finish in June 2009. The consortium which participated to this research project is composed of the Instituto de Astrofísica de Canarias in La Laguna in Tenerife in Spain, Fogale Nanotech in Nîmes in France, the Laboratoire d'Astrophysique de Marseille in France, the Osservatorio Astrofisico di Arcetri (INAF) in Italy and of the European Southern Observatory (ESO).
Some of the next generation of giant optical telescopes will be equipped with segmented primary mirrors composed of hundreds of hexagonal segments. It is necessary to operate at the diffraction limit of such telescopes if the telescope is to use adaptive optics and be a science driver, and this can only be achieved if the segments are well-aligned both in height, called from now on "piston", and in tip and tilt. The fast control of the rigid body positions of the segments will be based on measurements made with edge sensors.
These, however, can only measure differential movements between adjacent segments and therefore have to be supplied with reference values for the absolute measurements of the piston steps at the intra-segment borders. At the moment, such reference values can only be obtained with a precision of the order of a few nanometers by optical measurements, preferably using the light of a star in the field of the telescope.
The Active Phasing Experiment has then been proposed by the ESO to demonstrate its capability to align in tip-tilt and piston within few nanometers the segmented primary mirror of a giant telescope, performance which has not been made up to now in Europe. The goal was to simulate a VLT having a segmented primary mirror composed of 61 segments in order to demonstrate the functionality of 4 different optical phasing technologies and also new control principles using theses Optical Phasing Sensors (OPS).
The four OPSs have been first tested in laboratory using an atmospheric turbulences generator and VLT simulator. Then it has been shipped and installed on the Nasmyth platform of Melipal (UT3) on Paranal. A total of 30 nights were dedicated for the commissioning and the experiment on sky. APE has been dismounted and shipped back to Garching in June 2009.

The essential purpose of the Active Phasing Experiment was to explore, integrate and validate non-adaptive wavefront control schemes and technologies for an European Extremely Large Optical Telescope (ELT). This includes:

- Evaluating and comparing the performance of four phasing wavefront sensors, in the laboratory and on-sky;
- Integrating segmented aperture control into an active system (including field stabilization and active optics), and driving both the active system and the segments control system from the output of the system.

To this end, APE was conceived as a technical instrument fully compliant with the ESO VLT/instrument standard to be installed and tested on-sky at a Nasmyth focus of a VLT unit.: The telescope provided all active functions (field stabilization, focusing, centering and active deformable mirrors) and the APE instrument emulated the optical effect of segmentation only.

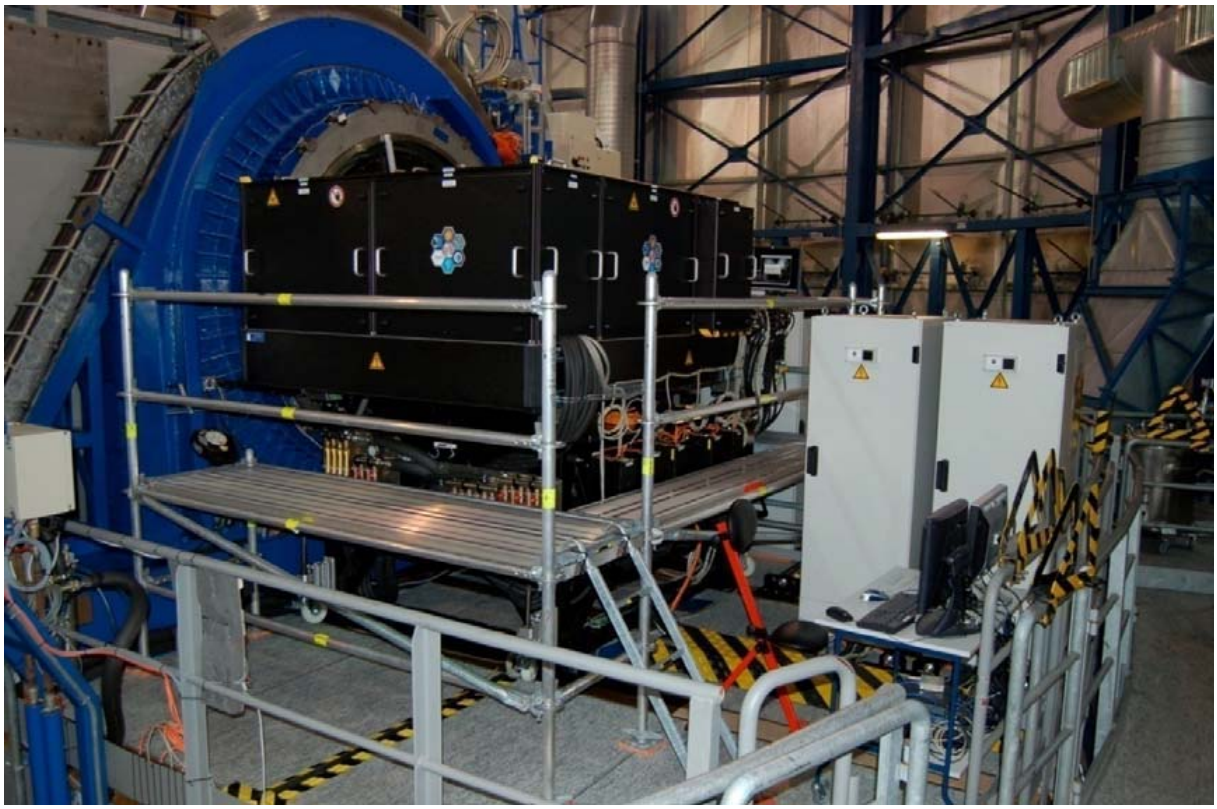


Figure 1 APE fully installed on Melipal Nasmyth A.

In practice, this was realized by re-imaging the telescope pupil onto a small Active Segmented Mirror (ASM), and by directing the output beam(s) of the instrument towards the Optical Phasing Sensors module.
The segments of the mirror were activated in piston and tip-tilt with 3 piezo actuators and controlled in closed loop using the Internal Metrology (IM) developed by Fogale Nanotech. The optical phasing sensor module included four OPSs, each based on a different technology and developed by a different partner. IAC had the responsibility to develop a curvature sensor, LAM a phase and spatial filtering sensor, INAF a pyramid sensor, and finally ESO had to develop a new type of Shack-Hartmann sensor and also the Opto-Mechanical Bench (OMB).

APE, as any complex system, has a large number of functional, performance, physical and interface requirements which have to be satisfied. This implies the need for a professional requirements engineering and management during the project. This is the first application of SysML during the development.

APE has been designed as a modular system on a 3 by 2 m2 optical table. The main subsystems are a turbulence generator (called MAPS), the Active Segmented Mirror, a dual wavelength phase shifting interferometer called Internal Metrology, four optical phasing sensors, the junction boxes and the OMB. The OMB is considered as a sub-system in itself and contains all opto-mechanical components which have not been listed as a subsystem like the derotator, the calibration unit, the off-axis parabola etc.
Three electronics cabinets contain the amplifiers, the analogue-to-digital converter cards, the controllers and the nine central processing units required for the control of the electronic components of APE (six CCDs, five translation stages, twelve rotating stages, two fast steering mirrors and the 183 actuators of the 61 segments incorporated in the ASM). The cabinets are linked to the OMB via the junction boxes. The control system alone consists of 12 computing nodes.
On sky the telescope replaces MAPS. In total there are 42 optical surfaces (lenses, filters, mirrors, beam splitters, etc.) between the focus of the telescope and the entrance foci of the phasing sensors.

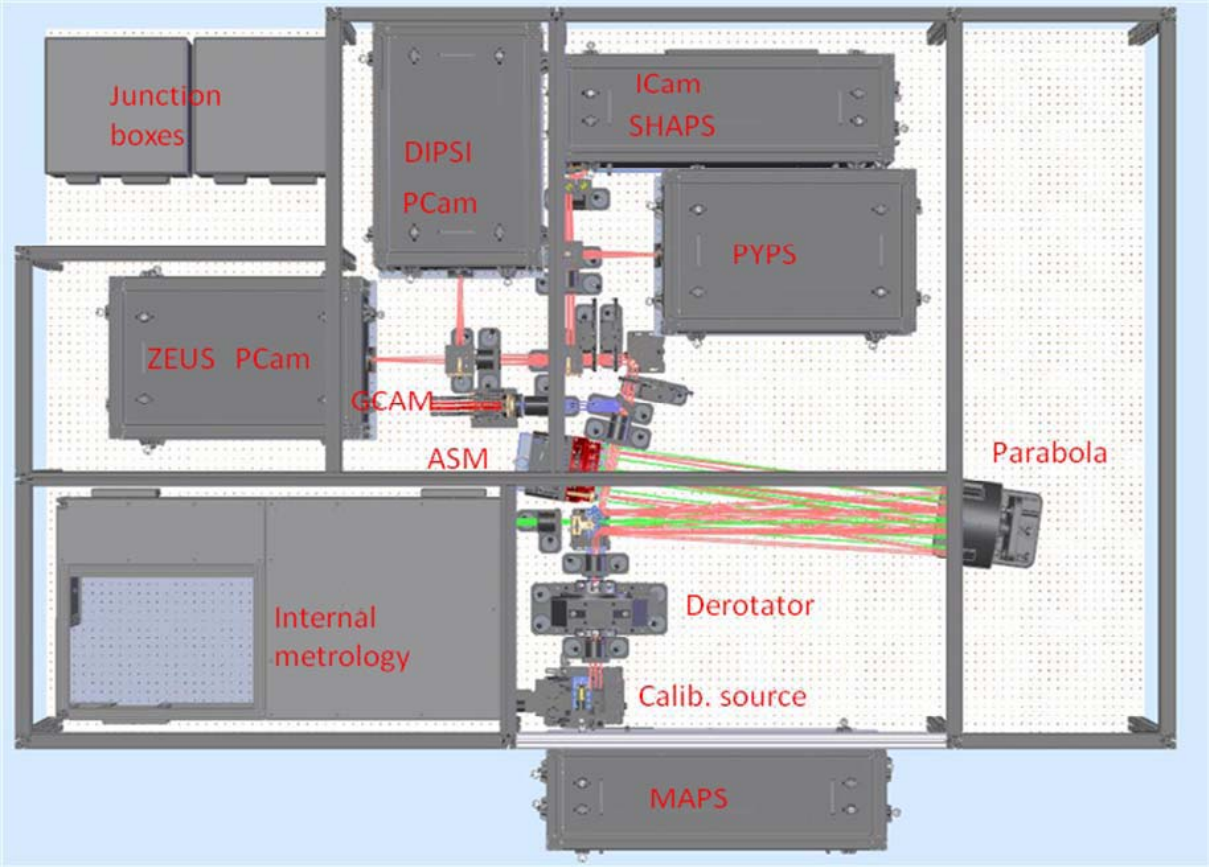


Figure 2 Top view of the APE bench

These elements offer all kinds of optical, mechanical, electronic and software interfaces, both system internal and external to other systems. It also challenges the control, since there are several open and closed loop systems required. A significant amount of data is produced by image processing data flows. Since APE will be deployed in the lab and in an already existing telescope, slightly different functional aspects are active depending on the deployment mode. Therefore different interfaces to existing systems are needed.

All these characteristics made APE well suited to evaluate SysML potential in tackling similar issues.

SysML is only a graphical language. It defines a set of diagrammatics, modeling elements, a formal syntax and semantics. As any language (formal or informal) it can be used in many different ways and many wrong ways too. Most notably the creation of nonsense models is possible.

The SE^2 MBSE challenge team defines as its main goals to

- Provide examples of SysML, common modelling problems and approaches.
- Build a comprehensive model, which serves as the basis for providing different views to different engineering aspects and subsequent activities.
- Demonstrate that SysML is an effective means to define common concepts.
- Demonstrate that a SysML model enhances traceability

The Cookbook covers topics like naming conventions, model annotations, external references; necessary system models, aspects and views; heuristics for modeling system requirements; guidelines for modeling the system structure (product tree, context variants, design variants, re-usable parts, system hierarchies); Interface modeling (logical and concrete, mechanical and flow, ports); allocation strategies; test case tracing; parametrics for performance models; style and layout issues.

4 Model organization

If you start modeling a complex system considering many different engineering aspects you can end up very fast in a very confusing model because of a unclear organization of all its model elements. Therefore organizing the model in a proper way is crucial for the understanding and usability of the model.

4.1 Overall Model organization

SysML packages are the element to organize the model. How packages are used for organization is of fundamental importance in order to have a scalable, consistent, and navigable model structure which works also for large models. The model structure supports different levels of abstraction and deeply nested system hierarchies.

The SE2Profile defines an Ontology for the model's organization where every package has a defined meaning, and certain diagrams must exist within those packages for navigation and definition of system elements.

The model is organized and decomposed along the product tree (i.e. the product breakdown structure) of the system being modeled. At each decomposition level a recurring package structure appears which corresponds to the different aspects of the system (e.g. structure, behavior, requirements, etc.).

4.2 Structuring the model using packages

To increase readability of and support navigation within the model, these guidelines for setting up model packages should be followed:

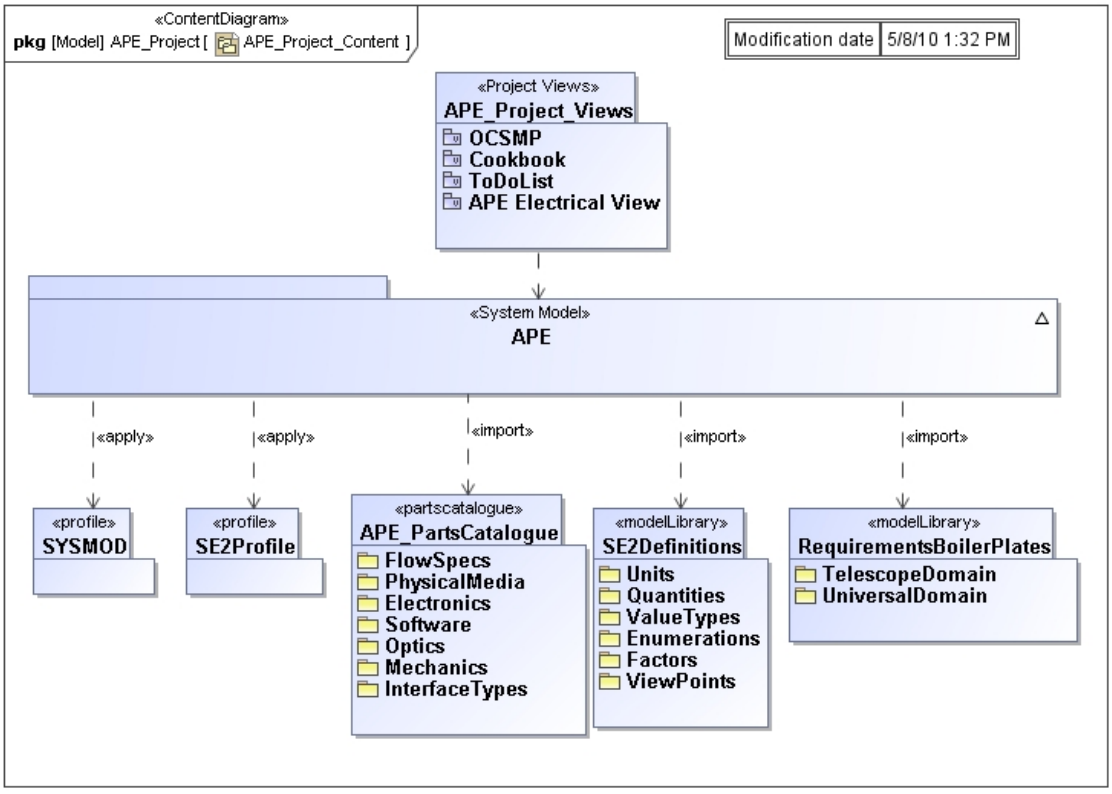


Figure 3 Top Level package content diagram

- Packages are the basic tool for separating concurrent modeling tasks and assigning responsibility.
- Use recursive package structure patterns in the model to establish a good and easily understandable model structure: packages created at the highest level of the model shall be repeated for every lower level
- Structures (the design) are organized according to the system's product tree.

- Use packages to separate different aspects (each serving a distinct purpose) of the system. Having, conceptually, independent aspects allows:
    - Independent reorganization, if needed
    - Easier integration (import) of an external requirements model (like Doors)
    - Each aspect becomes simpler.
    - You can link in a more obvious way the model elements with <<trace>> and <<satisfy>>.
- Create separate (auxiliary) packages containing model information, references to external information (like drawings, existing requirements or design documents) and information about the model. They are prefixed with _ (underscore) to distinguish them from packages which represent a view of the system.
- The top level package is <projectname>_Project. It contains the System Model package, the used parts catalogs, applied profiles, and other model libraries.
- The BDD of each substructure defines its elements and therefore its product tree
- Group Comments, Errors and Issues in separate packages to find them easily.
- Recurring packages in every model level are:
    - Behavior
    - Context. The package Context exists typically only at the top level because the lower level context is implicitly defined by the IBDs of the higher level.
    - Data
    - Items
    - Performance
    - Requirements
    - Structure
    - Traceability
    - Variations
    - Verification
    - Views
    - _Comments
    - _Drawings
    - _Errors
    - _External
    - _Issues
    - _Problems
    - _Rationales
- At the top level the Requirements package contains Objectives, Stakeholder requirements and System requirements. Whereas on lower levels it contains only derived requirements of the sub structures. They are kept together with the design to have a consistent package, e.g. to give to a contractor. The same applies to behavior. Every decomposition level defines its behavior, which is part of the higher level behavior.
- Naming convention for model elements are another important point to improve understanding. For example, all APE packages related to a certain (sub) system have as a prefix the name of the (sub) system, i.e. its owning package to have a unique identification of the package for navigation. e.g. APE_Requirements, ASM_Requirements.
- All packages have stereotypes applied with a defined semantic according to the Model Structure Ontology.

Figure 4 The Containment tree of the Model Structure

The _Content diagram is a package diagram and is used to navigate with in a sub-system. It shows all its aspects as structure, performance, requirements, behavior, etc.

The _ProductTree is a block definition diagrams and is located in the structure package. It shows the product tree; i.e. how the sub-system is composed.

The purpose of the product tree diagram is merely to give a managerial perspective of which parts need to be built or procured, also, but not exclusively to get cost information for the project. The criteria to include elements by means of composition in this diagram is, that they have been built/procured explicitly for the system. The product tree **does not** in general show a snapshot of a system configuration. Multiplicity information is relevant for a product tree. Use the composition relationship in a whole-part relation when the whole and the part share the same life-cycle, use reference otherwise.

The need to provide uncluttered readable diagrams normally conflicts with the one to produce a high level overview of which parts are crucial / relevant to the system. It is recommended that a product tree diagram only contain at most two levels of decomposition. The need to have an all exploded

comprehensive product tree may in theory be satisfied by automatically merging all existing product tree diagrams into a big one (remember, each sub-system contains recursively its product tree).

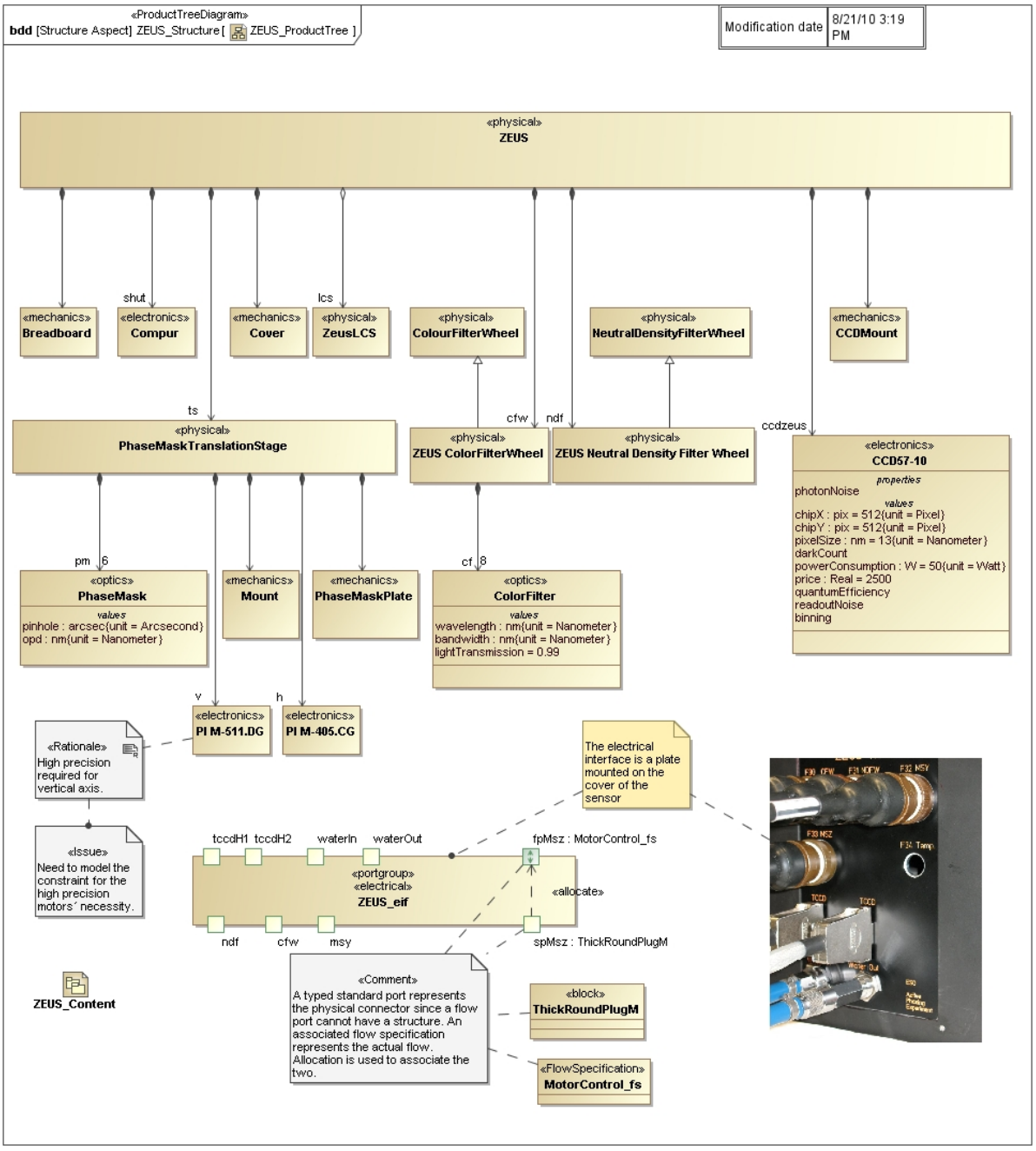


Figure 5 Product Tree of the ZEUS substructure

ZEUS is one of the evaluated phasing sensors (Figure 5) and is based on the modified Mach–Zehnder interferometer phasing sensor. It is mounted on a breadboard and consists of a shutter, a cover, a color filter wheel, a neutral density filter wheel, and a translation stage which carries a phase mask. Different phase masks can be moved to the focal position by means of a translation stage, able to move in the X and Y directions.

The two filter wheels located after the phase mask translation stage:

- A neutral Density Filter wheel: a set of 8 different neutral density filters are available
- An optical filter wheel: a set of 8 different optical filters centered on different wavelengths and with different bandwidths are available

4.3 Levels of Detail

The level of detail of a model is a very contentious issue. Systems can easily be “modeled to death” just for the sake of modeling.

Therefore the purposes of the model should be defined upfront, like:

- Which stakeholder shall use the model for what purpose?
- What does the modeler or systems engineer want to achieve with the model?
- What information shall be extracted from the model?
- Should the model give an overview or define in detail all flows?

We recommend to ask and answer these questions for each greater model element as well.

What is modeled and which model elements are used depends from the answers to the questions; e.g. a system engineer needs more sophisticated modeling elements to express different aspects, while a tester may need only test scenarios modeled simple in sequence diagrams.

4.4 Levels of abstraction

The levels of abstraction depend very much on the used methodology. The methodology defines if a logical (functional) model is built, if the logical model is only about behavior or also about structure, how the functional model relates to the physical model (the bill of materials), etc.

Since the intention of this cookbook is to keep it largely methodology independent, a simple split in functional and physical model is done.

- one modeling level is functional, describing system behavior (e.g. activities)
- one modeling level is physical, describing system structure (e.g. blocks)
- allocation is done by allocating behavior to structure

The physical model corresponds to a bill of material, i.e. a system which can be purchased off a catalogue.

Functional/Logical structure elements and their technological representations could be:

Functional/Logical element	**Technological Element**
Display	LCD, CRT, HMD, LED, etc
Receiver	Analogue radio receiver, DVB-T, etc
Electric Generator	Solar cells, Diesel-engine, Water-turbine, etc.
Cooling Unit	Fridge, Fan, Peltier, etc.
Container	Shipping container, air container, etc
Data Storage Device	Disk, USB stick, DVD, etc.
Computing Node	Desktop, Embedded, Blade-Server, etc.
Motor	DC, Stepper, etc.

For each technological element there is in the end a concrete technology which is part of the bill of material and can be bought. For example, a particular Mercedes Diesel-engine, or a particular Siemens Water-turbine is used for the final system which complies with the performance constraints.

Typically, the concrete items are collected in a catalogue of pieces which can be re-used for every system.

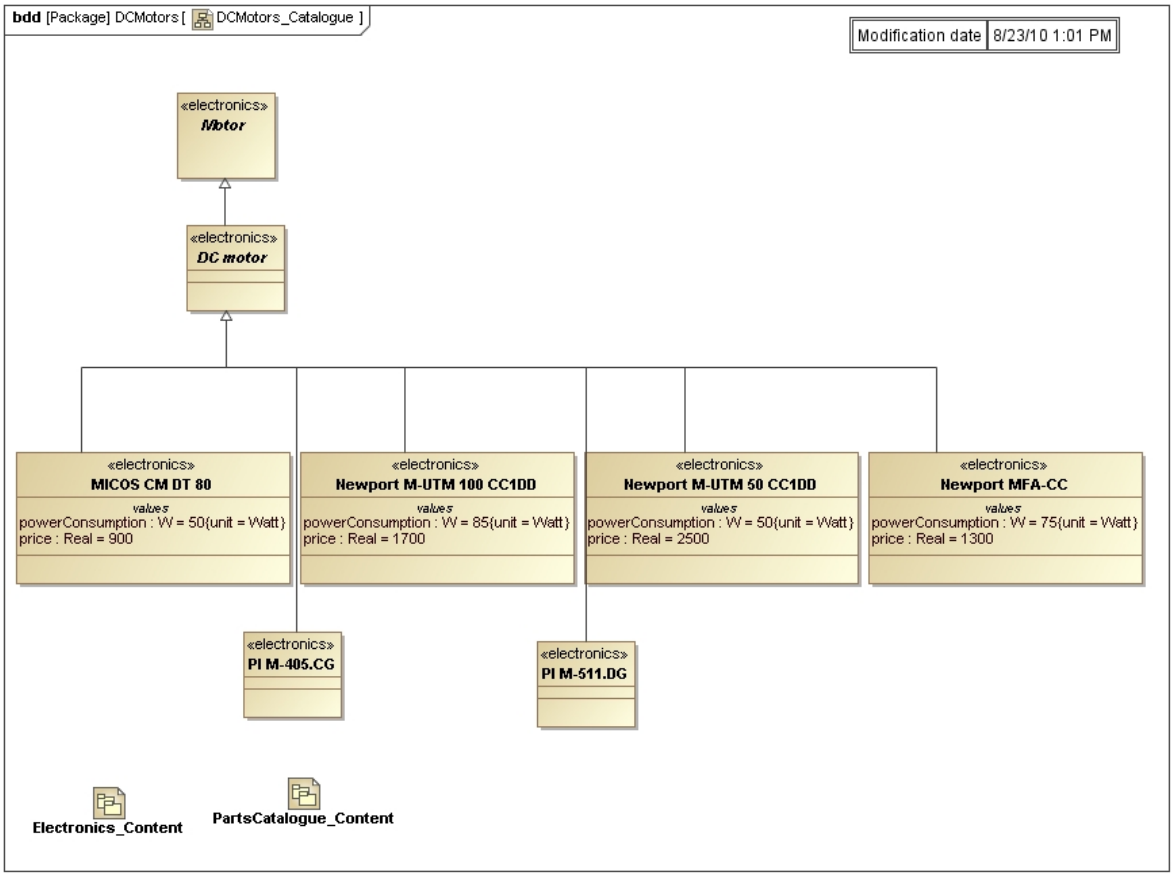


Figure 6 Different DC motor types in a parts catalog

In the beginning of modeling it is often unclear which particular catalog item will be used in the end. It will depend on different factors, like cost, performance, supplier warranty, etc. There might be even different variations of the system evaluated.

14 Style, Layout, Naming Conventions

5.1 Formalizing the model with domain specific stereotypes

A major challenge is to keep the model organization, naming, and style consistent. One way is to define naming conventions and enforce them. However, since they are only strings it is more difficult to check them automatically. Having only naming conventions is also quite restrictive and a simple typo can change its meaning.

Therefore it is better to define one or more Ontologies (formal definition of terms and concepts and their relations), see chapter 12.

The Ontologies are implemented in the model by stereotypes, domain specific extensions of the SysML language.

This Cookbook defines a set of stereotypes which gives every model element, diagram, etc. a meaning. This meaning corresponds to the definition within the modeling Ontologies.

For example, a BDD which is used as product tree (product breakdown) diagram has the stereotype <<ProductTreeDiagram>>, an IBD which represents the electrical view of a block has the stereotype <<electrical>>, or a package which contains the behavioral aspect of the system has the stereotype <<Behavior Aspect>>.

Those stereotypes are introduced along the way.All stereotypes are defined in the <<profile>> SE2Profile.

5.2 Naming Conventions

5.2.2 Naming of diagrams

Although each diagram has a fully qualified name within the model and is therefore unique, naming conventions make it easier for the modeler to navigate and understand the context of a diagram.

The header of a SysML diagram consists of four parts: **<diagramKind> [modelElementType] <modelElementName> [diagramName]**. The first 3 elements are set automatically by the modeling tool. Only the diagram name is set individually by the model builder.

- <diagramKind> is the type of the diagram
- [modelElementType] is the type of the model element that the diagram represents
- <modelElementName> refers to the element which is represented by the diagram
- [diagramName] describes what can be seen in the diagram; should be unique and say something about its context.
- If necessary, modelElementName is followed (after underscore) by more information, what the diagram contains:
    - postfix modelElementName of BDDs and IBDs with containing package name, e.g. bdd [Structure Aspect] APE_Structure [APE_ProductTree]
    - postfix modelElementName with specific view that are modeled e.g. ibd [Structure] **ibd** [System] APE [APE_Electrical], **ibd** [System] APE [APE_Mechanical]
- Use diagram info with timestamps and who modified last the diagram

The following postfix notations are used for the following diagram types:

Diagram Type	Meaning and stereotype	Postfix naming convention
BDD	Product tree, <<ProductTreeDiagram>> Shows the product breakdown for a system element.	_ProductTree
PKG	Content, <<ContentDiagram>> Shows the package structure within another package for easier navigation	_Content
IBD	Engineering Specific View <<electrical>>, <<optical>>, <<mechanical>>, <<information>>, <<thermal>>	_Eelectrical, _Optical, _Mechanical, _Information, _Thermal
PAR	<<element constraint>> Constraining a system element.	_Constraint
BDD, CLASS	Define system independent element, like quantities, units, stereotypes.	_Definition

- _ProductTree … BDD
- _Content … PKG
- _Electrical, _Optical, _Mechanical, _Information … IBD

- _Constraint … PAR
- _Definition … BDD, CLASS

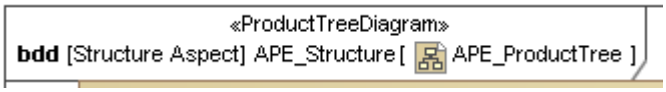


Figure 7 Diagram header with Naming Convention

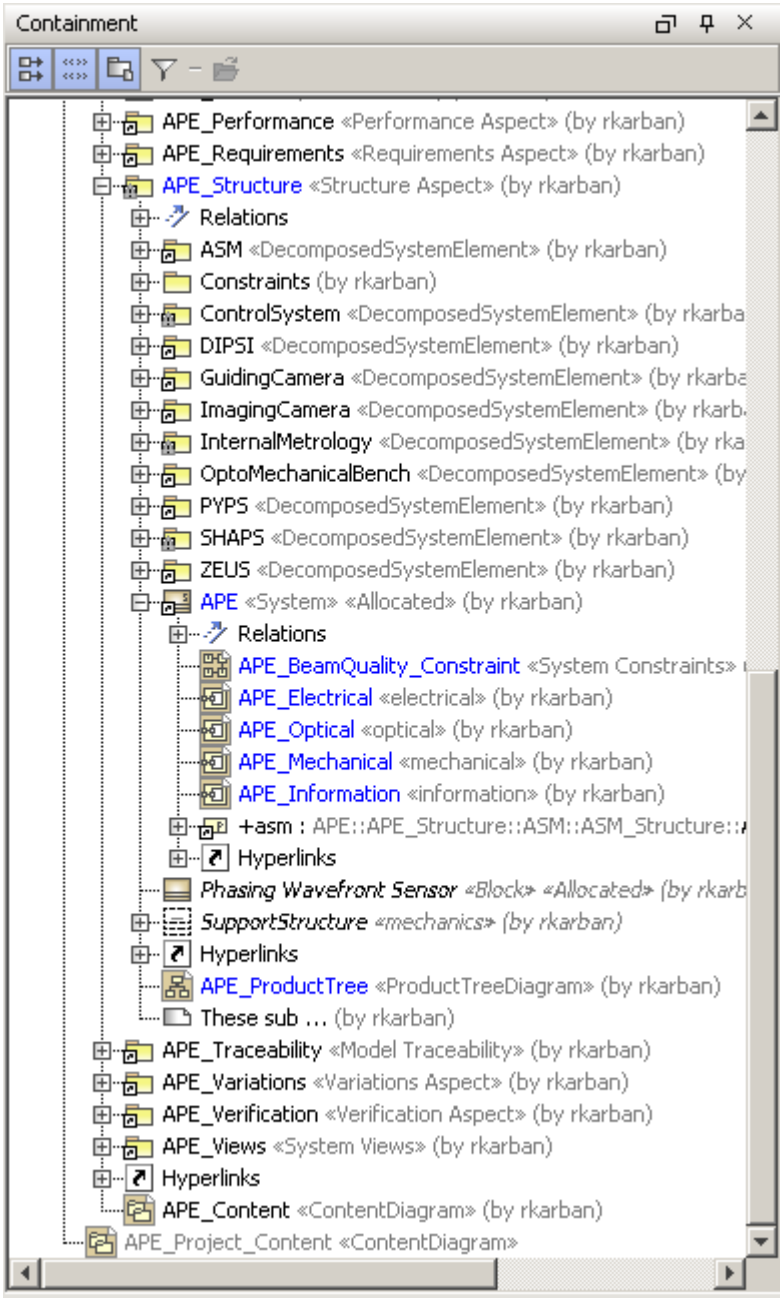


Figure 8 Naming Conventions as seen in the Containment Tree

5.2.3 Naming of modeling elements

In general, do not use SysML keywords (like connector or interface) as names in the model to avoid confusion between SysML concepts and the system model.

5.2.3.1 Role Names

Use Role Names for Part Properties only when there is more than one part of the same type; e.g. if you have a primary and a backup server.

5.2.3.2 Names of classifiers (e.g. <<Block>>, <<ValueType>>), Requirements, Activities, and Packages (Definition of something):

- use expressive short names
-
- do not write complete sentences, only string of words
- every word starts with a capital letter to distinguish Definition from Usage
- do not use underscores but use spaces to improve readability and allow word wrapping in the tools

5.2.3.3 Names of actions, pins, ports, parameters, attributes, operations and all properties (Usage of something):

- same as for classifiers but first word starts with lower case letter

5.2.3.4 Indicate type of model element in the name:

type	*suffix*
flow specifications	<name>_fs
standard interfaces	<name>_if
flow ports	<name>_fp
standard ports	<name>_sp
electrical interface portgroup	<name>_eif
information interface portgroup	<name>_iif
mechanical interface portgroup	<name>_mif
optical interface portgroup	<name>_oif

A <<portgroup>> is specification for an interface of a system element. It is explained in chapter 9.

5.3 Style and Layout

5.3.1 DO NOT use grids in any diagrams.

They really distract[1],.

5.3.2 Instead of emphasizing the diagram, emphasize the elements that are hyperlinked to diagrams.

In systems engineering culture one expects to drill down from the 0-th level. In general, it is recommended to emphasize the relationship between system elements rather than the physical packaging, or the diagram types and icons. To make that work you MUST hyperlink every single element to something else (except for trivial leafs).

In general, navigation should happen through the diagrams, and not through the containment tree. Having that in mind, the diagram has a lot more importance, in particular hyper linking diagram elements to other diagrams.

[1] In MagicDraw You can switch off the default under Options->Project->Symbols->Default->Diagram

5.3.3 Every time you place a SysML comment consider what editorial stereotype might bring it to life.

<<Rationale>>, <<Problem>>, <<Issue>>, <<ERROR>>, <<parsed>>. The above stereotypes use tagged values for metadata (there is an author:String tag). All mentioned stereotypes can be applied to SysML comments.

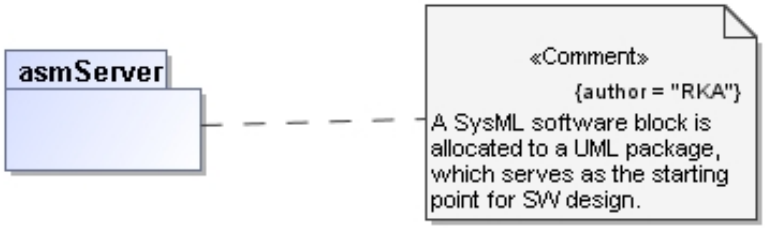


Figure 9 Comment with author tag

5.3.4 "Definition" BDD diagrams for a context are overrated. Focus on IBDs.

- Just use a product tree for each Block showing its attributes, operations, and nearest related elements[2].
- Reflect the systems engineering process with your system sub packages. And please always hyperlink every single package to a package diagram.

5.3.5 Span the Whole across its parts

To show better the Whole-Part relationship in a BDD span (graphically) the Whole Block graphically across the parts it is composed of. Figure 10 shows the product tree of the Active Segmented Mirror which is the most important element in APE. It consists of 61 hexagonal, piezo-actuated mirrors. Each segment is actuated by three piezo-actuators, which makes 183 position actuators.

[2] You can drag an IBD or BDD focus diagram for a Block onto parts typed by that Block in IBDs to "open the part up" into the Block that types it.
Place a matching BDD "product tree diagram" icon on the IBD of a Block

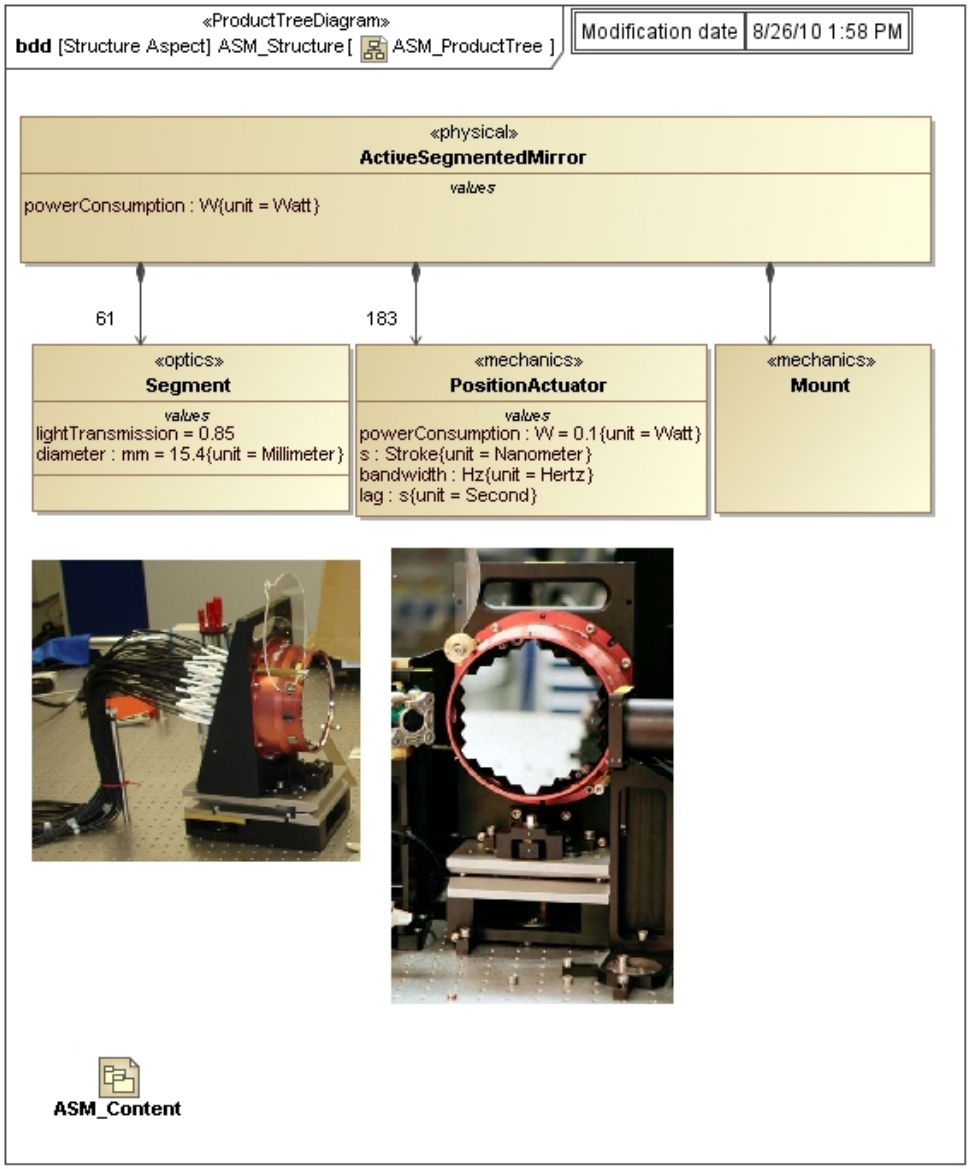


Figure 10 ASM Product Tree

5.4 Model Documentation

5.4.1 General

- Each relevant model element has to be documented, e.g. package, block, port, interface, connector, data, and property.
- For each diagram describe what it shows. Think about why you draw the diagram and for whom. Describe what is important but not directly visible: design decisions, and so on

Two types of documentation exist, documentation about the model and documentation relevant for the system being modeled.

5.4.2 Documentation about the model

This documentation contains information why something has been modeled in a particular way, or if it unclear how to model something.

Annotations regarding the modeling approach or the meta-model:

- <<Comment>>:
  - for documenting system specific modeling approaches and decisions.
  - for documenting model elements which for example are extracted from a document, to document where they come from
- <<Issue>>: for marking questions on modeling methodology, e.g. what stereotypes should be used; if an <<issue>> is solved by decision of the team, its solution becomes part of this Modeling guidelines or its stereotype is changed to <<Comment>>
- <<ERROR>>: for marking SysML tool problems; use red borders with black text on white (not red background) for error comments \
- <parsed>> : a model element has been automatically parsed from a text document

5.4.3 Documenting the System being modeled

Annotation can contain information about the system elements of the system that is being modeled:

- regular notes: for documenting the content of the system you model, to enhance understanding of the system;
- <<Problem>>: for marking a potential problem in the system development e.g. requirements cannot be met or interface conflicts
- <<Rationale>>: for justifying any decision during the development, e.g. <<derive>> of a requirement or decision on design alternatives

[3]

This allows better use of the documentation for generation of printed documents.

6 System Views

6.1 Guidelines for necessary system aspects and perspectives

The necessary views depend on the purpose of the modeling. Typical views were adopted from [RD2], which defines Behavior, Data, Purpose/Objectives, Performance, Form, and Managerial models as parts of an integrated system models.

The integrated system model consists of different sub-models which address the different aspects.

- Behavioral (Functional) aspect
- Context aspect
- Data aspect
- Performance aspect
- Requirements aspect (including the Use Case model)
- Structural aspect
- Variations aspect

[3] IMPORTANT: In MagicDraw the specification of every model element has a Documentation category where plain text or HTML text can be entered. Use this category to maintain information about a system element instead of maintaining the text directly in a SysML Note. When a Note is attached to a symbol, the related documentation can be displayed in the Note automatically (select from the Note's context specific menu 'Text Display Mode' -> 'Show Documentation'). Other modeling tools provide similar concepts

- Verification aspect

We do not use SysML <<view>>s, because a SysML <<view>> may not contain model elements, but we considered it important to group the aspect relevant elements together with the diagrams..

There are several additional packages for organizational reasons.

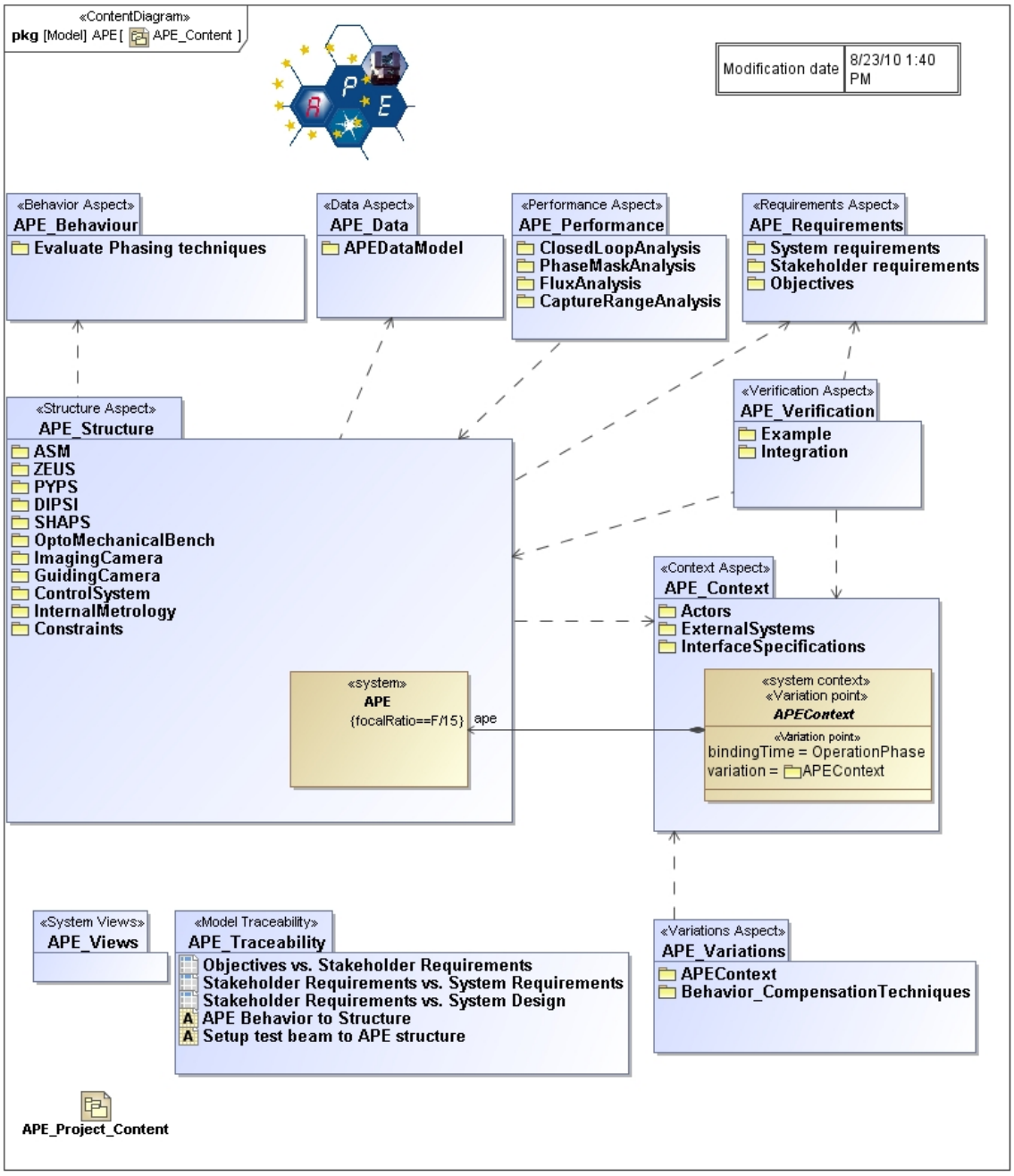


Figure 11 Top level diagram showing the system aspects

Each aspect contains different engineering perspectives, in particular the structural model, serving a specific engineering perspective, like optical, mechanical, or electrical. Each domain has its specific set of perspectives; e.g. for the telescope domain these are optical, mechanical, and electrical perspective. The APE concentrates on the physical perspectives.

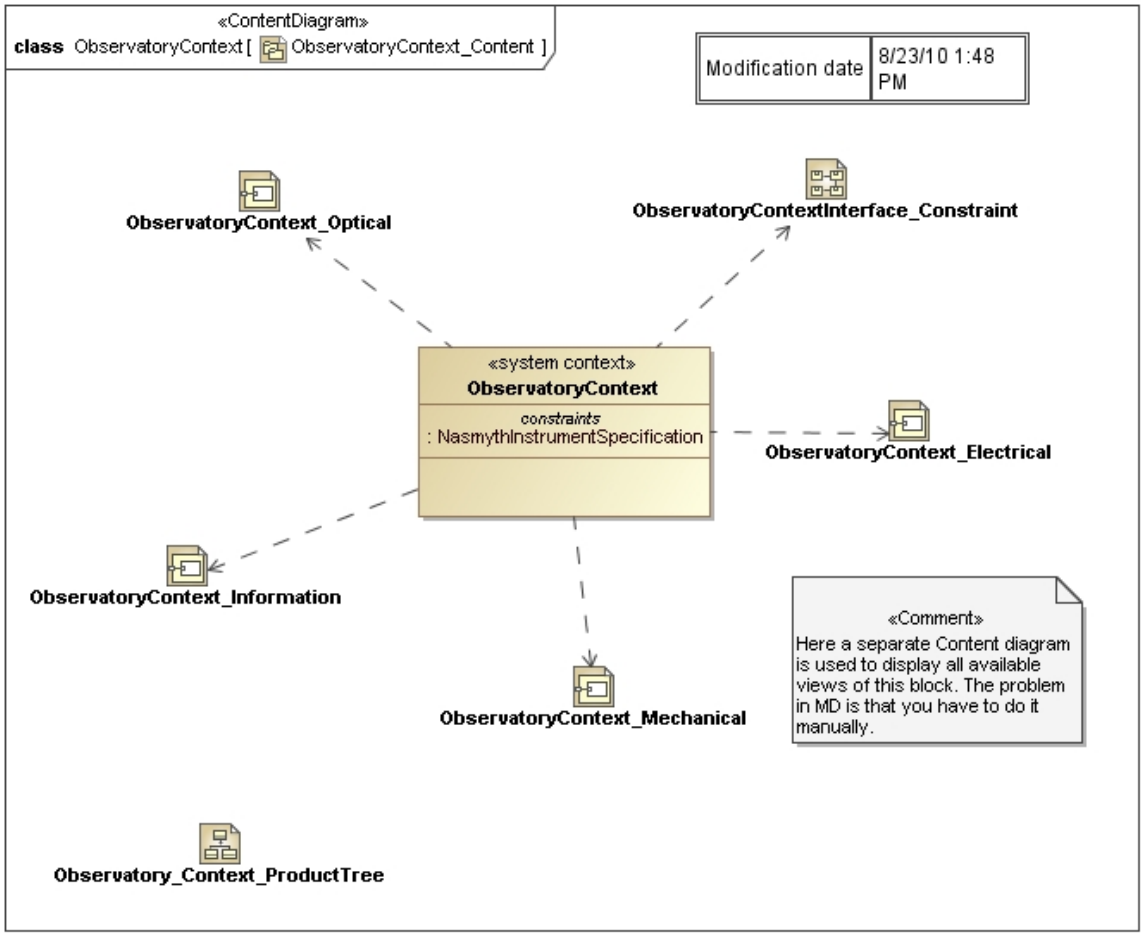


Figure 12 Content Diagram of Engineering Views of the ObservatoryContext Block

Remark: The dependency relationships between the system context and the diagrams of the views are not strict conform to SysML, but we think they improve understanding.

A <<block>> owns one or more IBDs for the relevant engineering perspective. For navigational reasons, it can contain also a content diagram which is hyperlinked to the block and serves as an entry point (Figure 12).

A split of the engineering views into different IBDs makes sense for blocks with multiple connectors for each engineering view. If there are only few connectors, a single IBD, which combines all views, can be sufficient.

Which engineering views should the model contain?

- The system context and any structure require different views and definitions. They are represented by different IBDs and BDDs. The recommended suffixes are:
  - _Mechanical, _Optical, _Electrical, _Information, _Thermal for IBDs
  - _Example, _Content, _ProductTree for BDDs
- Use the respective stereotypes for the connectors in IBDs:
  - <<optical>>, <<mechanical>>, <<electrical>>, <<information>>

The IBDs of each discipline are stereotyped the same way as their connectors, i.e. <<optical>>, <<mechanical>>, <<electrical>>, <<information>>. The IBDs are nested within the Block of which the engineering views show the internal connections of that Block.

6.1.1 Mechanical Perspective

The mechanical perspecive shows how system elements are connected mechanically or how they interact mechanically. This happens at a fairly abstract level to give an overview of the system. Each part of the system will have a corresponding part in a mechanical CAD drawing.

The properties, like mass, size, color should be synchronized between the system model tool (e.g. MagicDraw) and the CAD tool (e.g. SolidWorks). This allows an integration and analysis of the mechanical properties with other system properties; e.g. how much electrical power is required to move a mechanical piece.

The mechanical perspecive of the ZEUS substructure in Figure 13 shows some mechanical elements in the model and the real system. You can identify for example two filter wheels and a translation stage.

Flows between the parts can be mechanical forces.

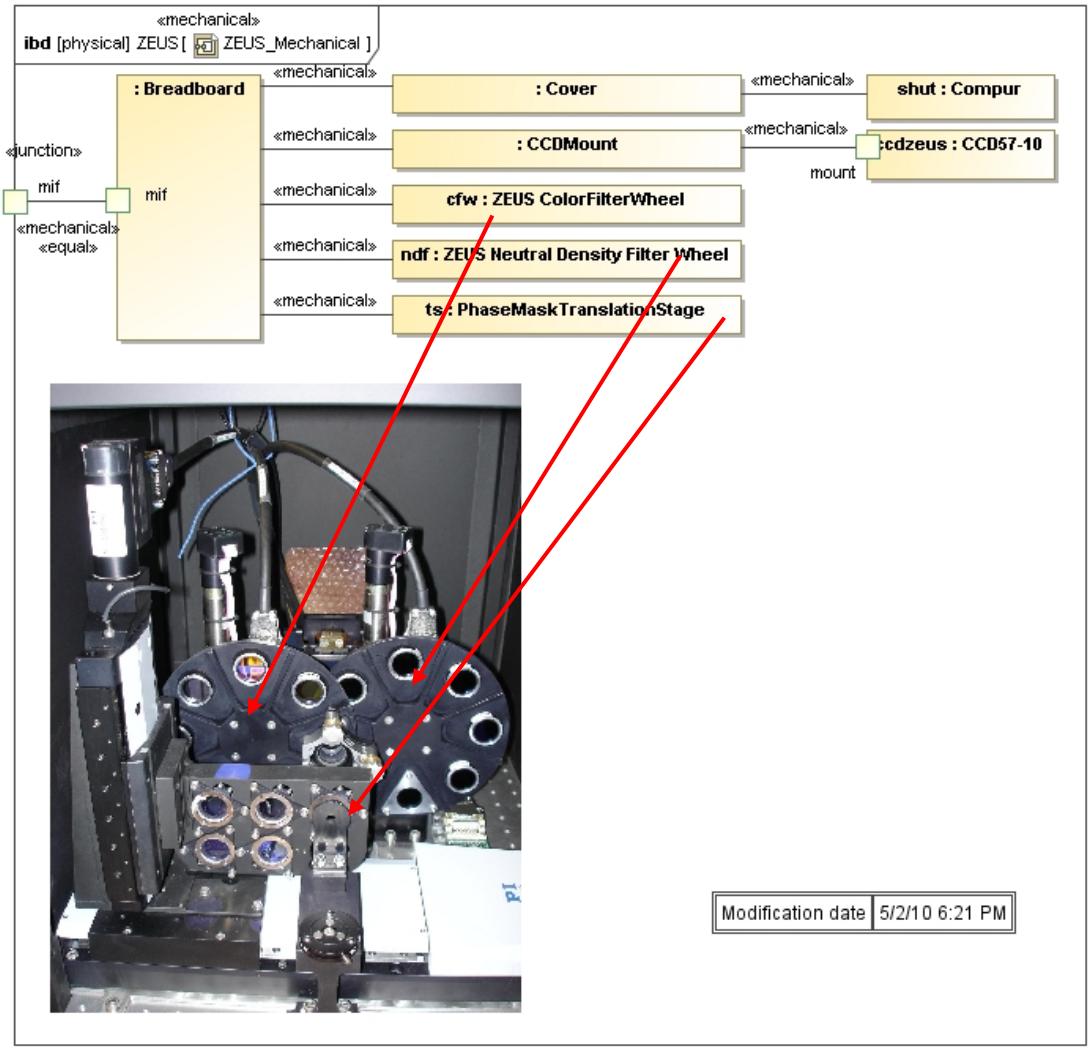


Figure 13 Mechanical View of the ZEUS substructure

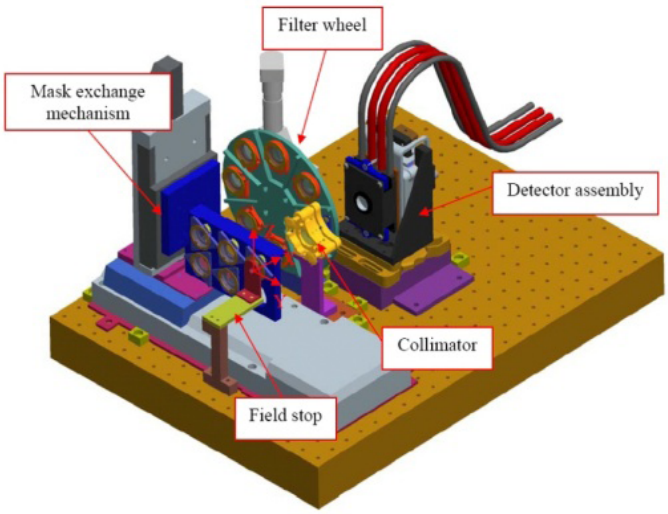


Figure 14 ZEUS 3D view of the opto-mechanical concept

6.1.2 Optical Perspective

The optical perspective shows how a light beam propagates through the system. Each of the optical components has optical properties, like a transmission factor of a filter. Like in the mechanical perspective the optical components and their properties should have their corresponding parts in an optical design tool, like ZEMAX. And, like in the mechanical world the optical properties can be analyzed for trade-off together in the system model. For example, at system level a trade-off analysis could be made between the sensitivity of a CCD and the transmission of the optical system in order to get a certain flux at detector level (Figure 16). More on how a system model can support interdisciplinary analyses can be found in chapter 13.

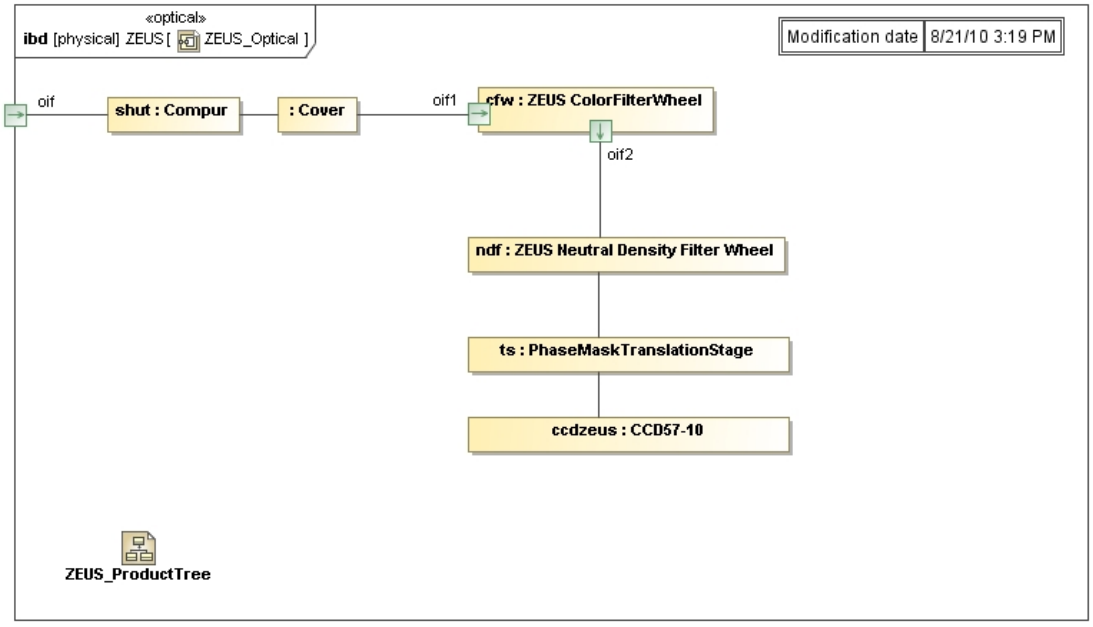


Figure 15 Optical Perspective of the ZEUS substructure

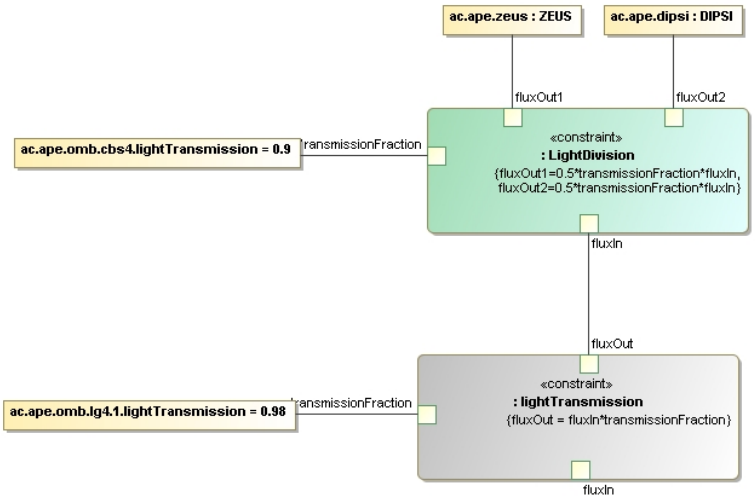


Figure 16 Part of a Parametric diagram analyzing the flux in the system

6.1.3 Electrical Perspective

The electrical perspective provides insight on all electrical connections in the system, like plugs, sockets, cables, and wiring. The system level model can be quite high level or very detailed like a wiring scheme. The Systems Engineer could layout the high level electrical system which is then detailed by the electrical engineer. This refinement can be done in the same SysML model, in a specialized tool, or in a combination of the two.

The high level electrical layout of the ZEUS substructure is shown in Figure 17.

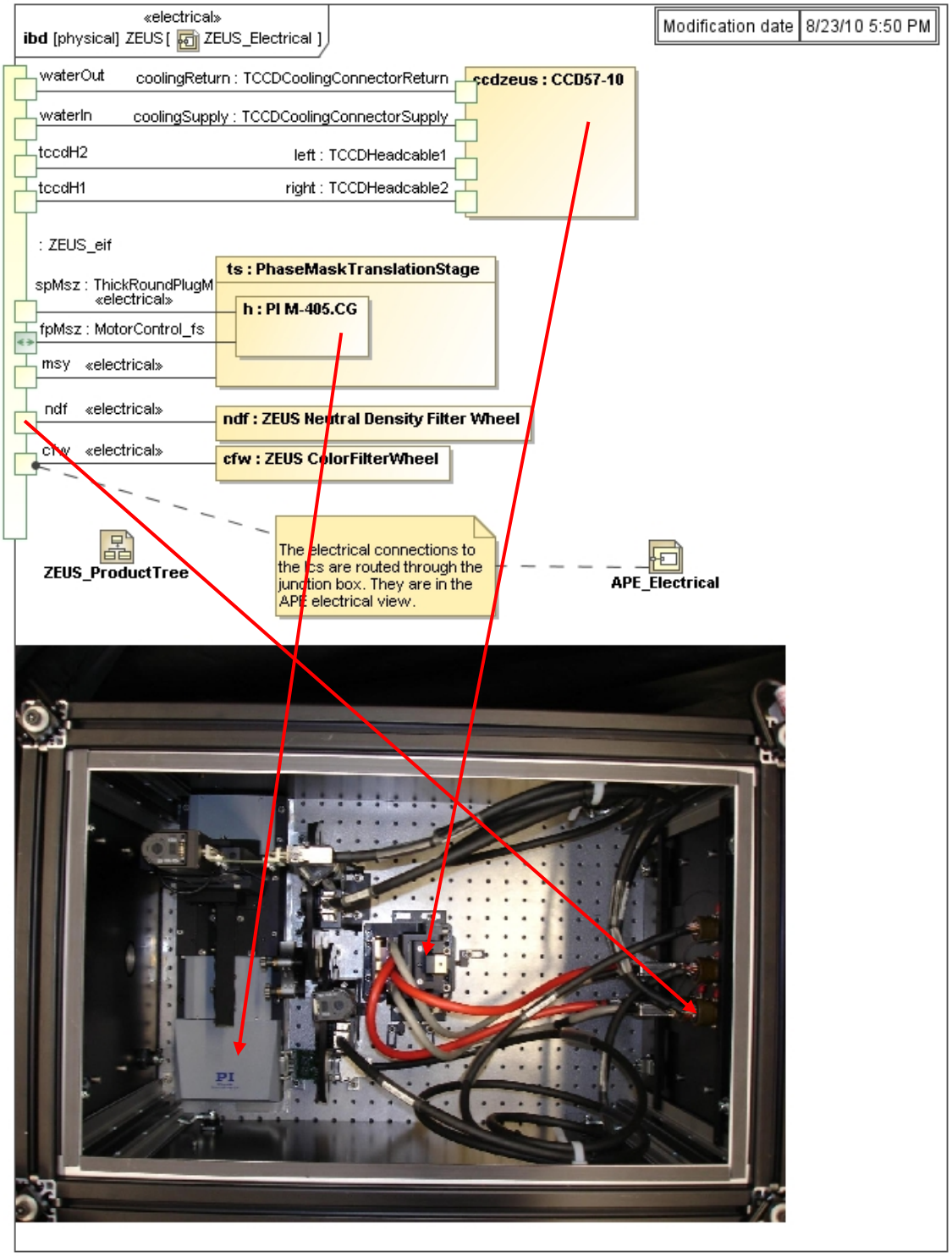


Figure 17 ZEUS electrical perspective

6.1.4 Information Perspective

The information view is used at system level to avoid software design to creep into system design. Information IBDs can become software context diagrams in the software design, e.g. UML diagrams showing the interfaces.

The information view shows which information flows among system parts, independent if they are propagated as electrical signals or as Ethernet packets. The information in an information IBD

correspond almost one to one to the object flows in the activity diagrams but in the IBDs they are related to system elements and not to behavior as in activity diagrams.

The information view could be considered as a kind of logical view. In fact, it is supposed to model the information which flows through the system at its highest abstraction level. When data is involved, typically a protocol stack is involved in the flow (like the ISO/OSI layer model). Because of the many involved layers the line between logical and physical model can be drawn almost anywhere for flowing data. Figure 18 shows two Local Control Systems (ZeusLCS and AsmLCS) which control a wave front sensor and the mirror, IMCS which controls the internal metrology, and the supervisor which coordinates the LCSs.

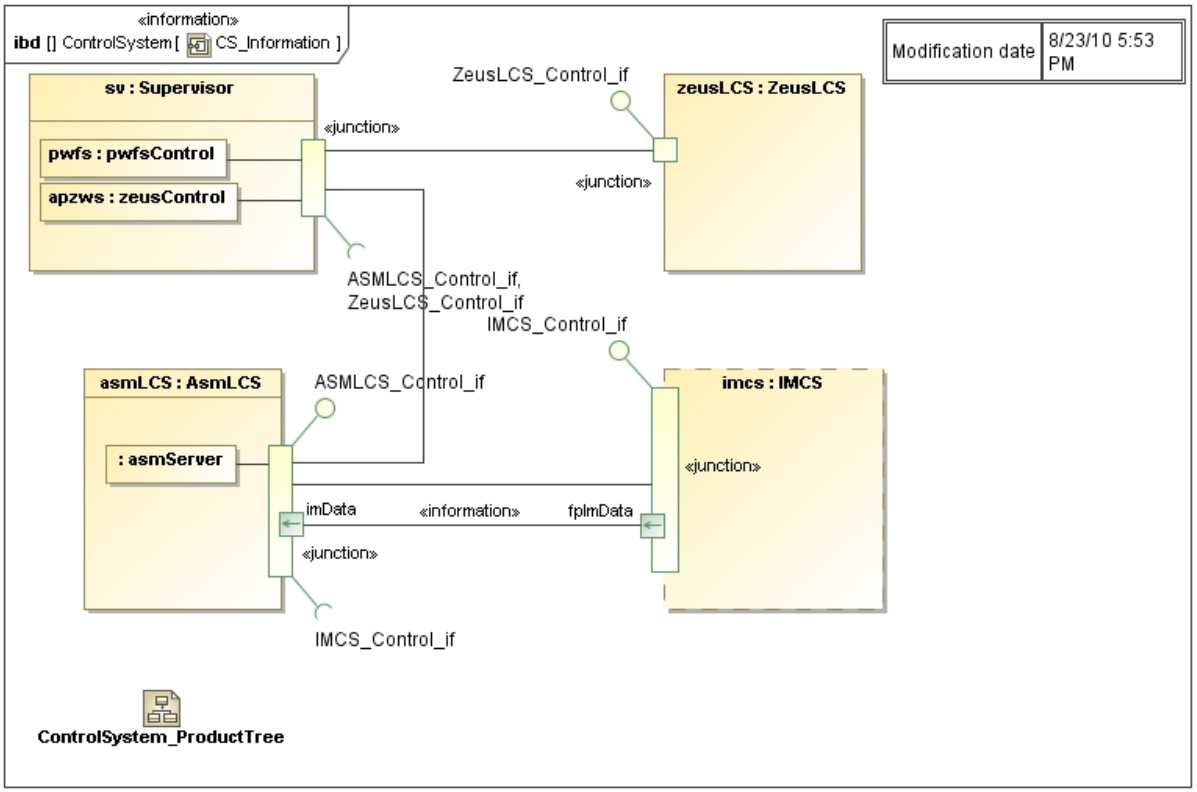


Figure 18 Information View of the Control System

6.1.5

6.2 Relationship between Model Aspects

The relationships between model aspects are mostly modeled via allocation. Different allocation strategies are described in chapter 15.

Most of the MBSE methods prescribe a logical/functional and a physical model. Their elements are typically related via <<allocate>> relationships.

The APE model is simplified to show SysML modeling concepts and methods.

The BehaviorAspect <<view>> describes the functional decomposition of the system, and is mostly technology independent. It describes the system from a pure functional point of view, using activity diagrams, interaction diagrams, and state machine diagrams.

The BehaviorAspect <<view>> satisfies requirements. The behavior is then allocated to the physical structure (the <<StructureAspect>>), which has to implement the functions; be it mechanical, electrical, or software.

7 Requirement and Use Case modeling

7.1 Context Modeling

7.1.1 Purpose of context diagrams of a system

The purpose of the context diagram is to determine the system scope. It identifies the parts which belong to the system and which do not – the system boundaries.

The system context shows the system as a black box and all interacting external elements. All external elements are shown as actors; they can be systems, persons, etc.

In order to model the context of the system, a special <<system context>> block is created which acts as a container of the system and all external actors. In Figure 19 it is called APEContext. The system being modeled is called APE with the stereotype <<system>>. External non-human entities are blocks stereotyped as <<external>>. Human entities are represented by stick-men <<actor>>.

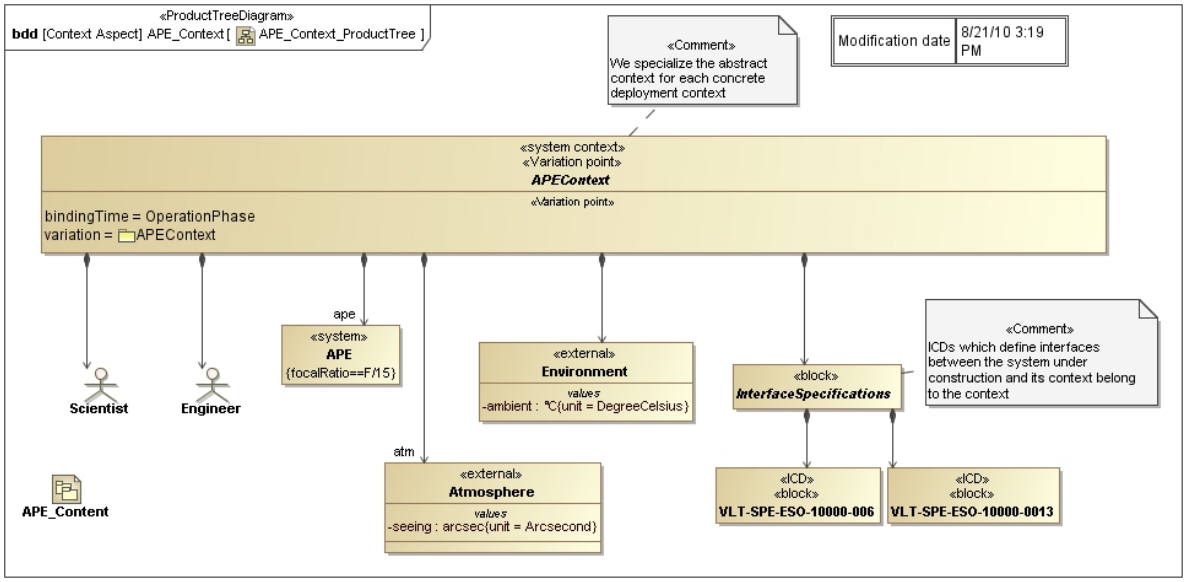


Figure 19 "Product Tree" of the System Context

The actors are involved in use cases requesting a service from the system.

When breaking down the system each decomposed system element has a context at decomposition level. Taking the example of a control system, the actors are the ones which are controlled but still inside the system's boundaries. The context diagram should show the concerned system and its relationship to external entities. That does not mean that one needs a context diagram for each and every subsystem!

At top level of the model, the real system is shown in its context. The connections of the system with the outside world are shown in the IBD of the special context block (Figure 20 shows the optical context). For each engineering discipline a different context IBD can exist. Note that APE can exist in different contexts. Here it is shown in the observatory context, where LensGroup1 of APE (mounted on the OptoMechnicalBench) is optically connected to the NasmythAdapter of the telescope. The

NasmythAdapter provides the opto-mechanicl element which “hands” over the light collected by the telescope to the instrument, APE in this case.

How different contexts are modeled is shown later.

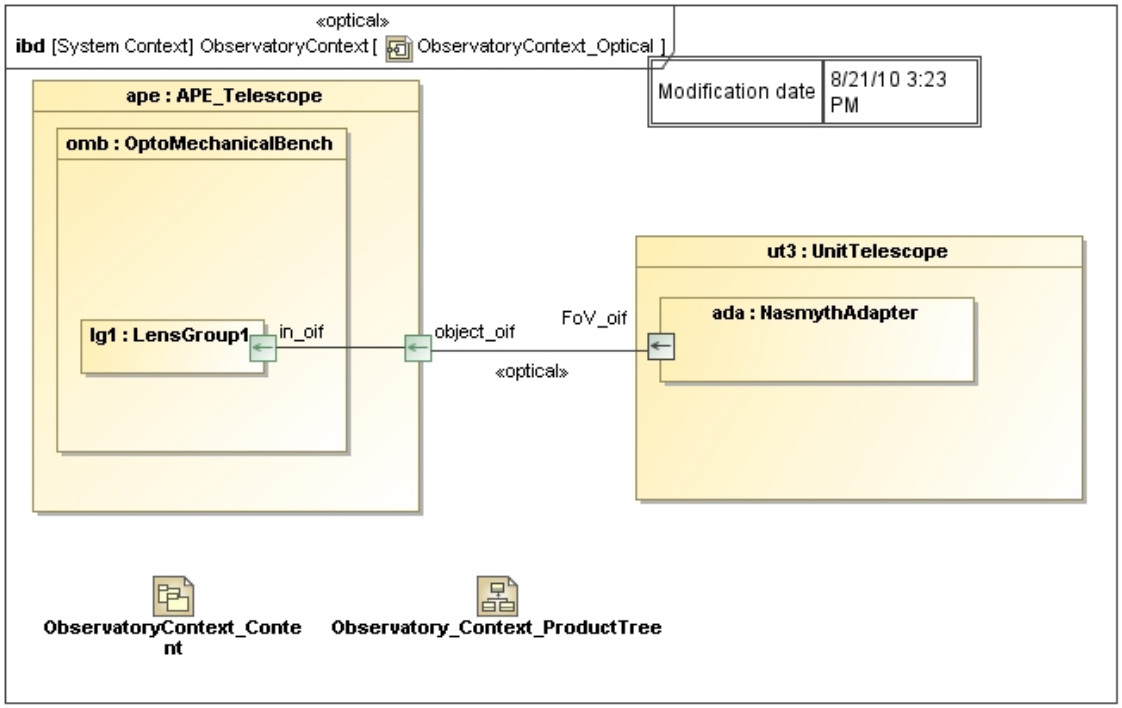


Figure 20 IBD of the Optical Context of the APE system at the telescope

To describe for example all internal connections of APE create an IBD of APE, which has the properties Control System, ZEUS, Bench, etc. Mostly each subsystem is simply used by another system or subsystem at a higher level. Therefore you do not need repeat the same thing. i.e. create a context and describe its structure.

Rather, create another IBD in a block for each subsystem as a context because the structure of this System defines also the context of each of its subsystems.

However, mostly it suffices to simply reuse each block or subsystem in a higher context. Typically <<external>> means something that is NOT modeled in the entire system. You need to address the so-called 0th level, which is the (entire) <<system context>>. It provides the top-level context for your SINGLE <<system>>. The project thus handles ONE <<system>>. That ONE <<system>>may be subject to <<external>> influences THAT ARE NOT MODELLED precisely. The detailed modeling starts at the 1st level, the <<system>>.

The mechanical IBD of the APE system (Figure 21) shows the internal, mechanical, connections of APE but at the same time is the context diagram of its parts, like ZEUS. The context diagram of ZEUS is then simply the IBD of its containing higher level, APE.

All the opto-mechanical elements are mounted on an optical bench, therefore there are <<mechanical>> connectors between the elements and the bench. The connections are modeled at varying levels of detail. Sometimes a simple connector indicates a mechanical connection, sometimes a port represents a mechanical interface of an element.

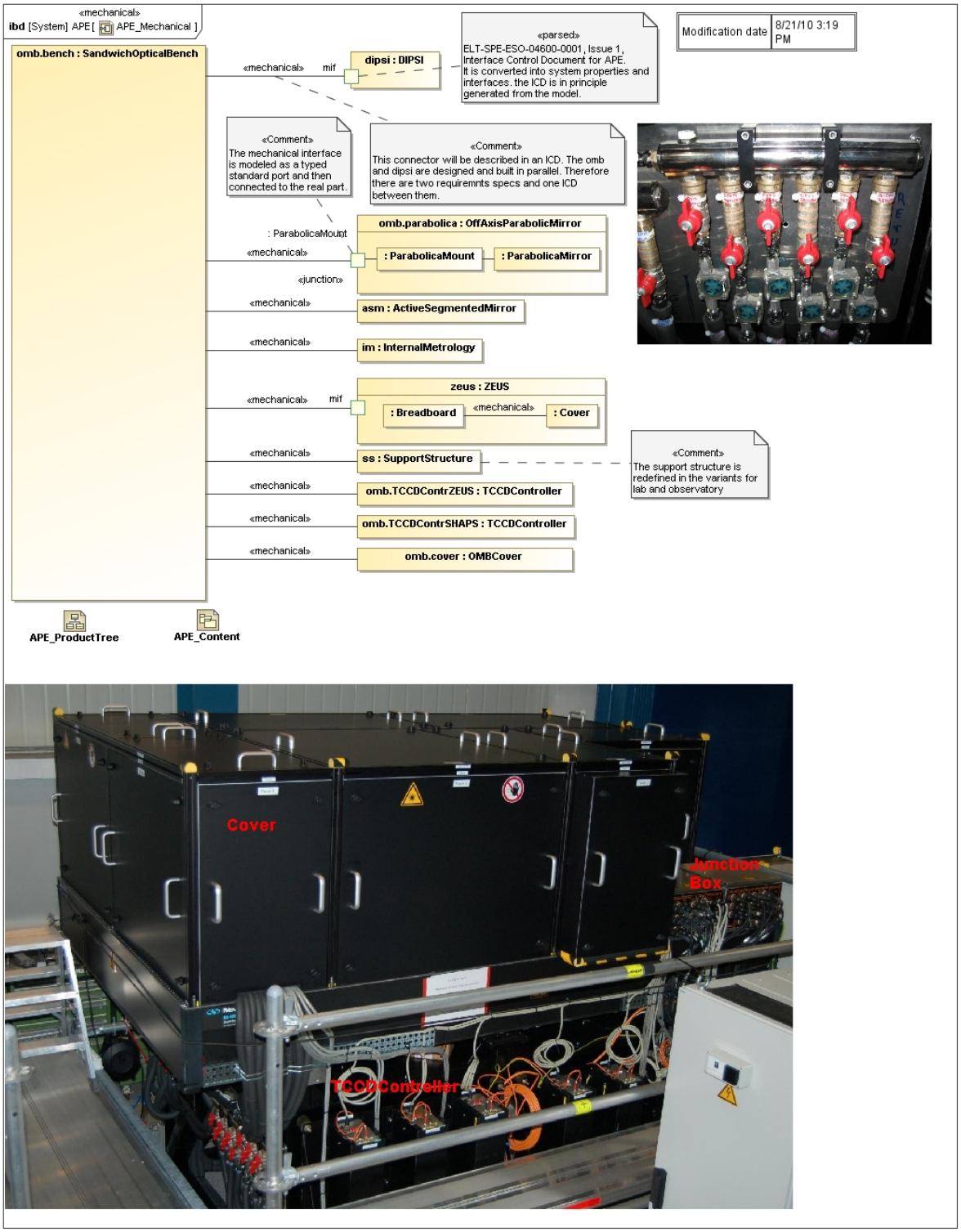


Figure 21 Mechanical IBD of the APE system

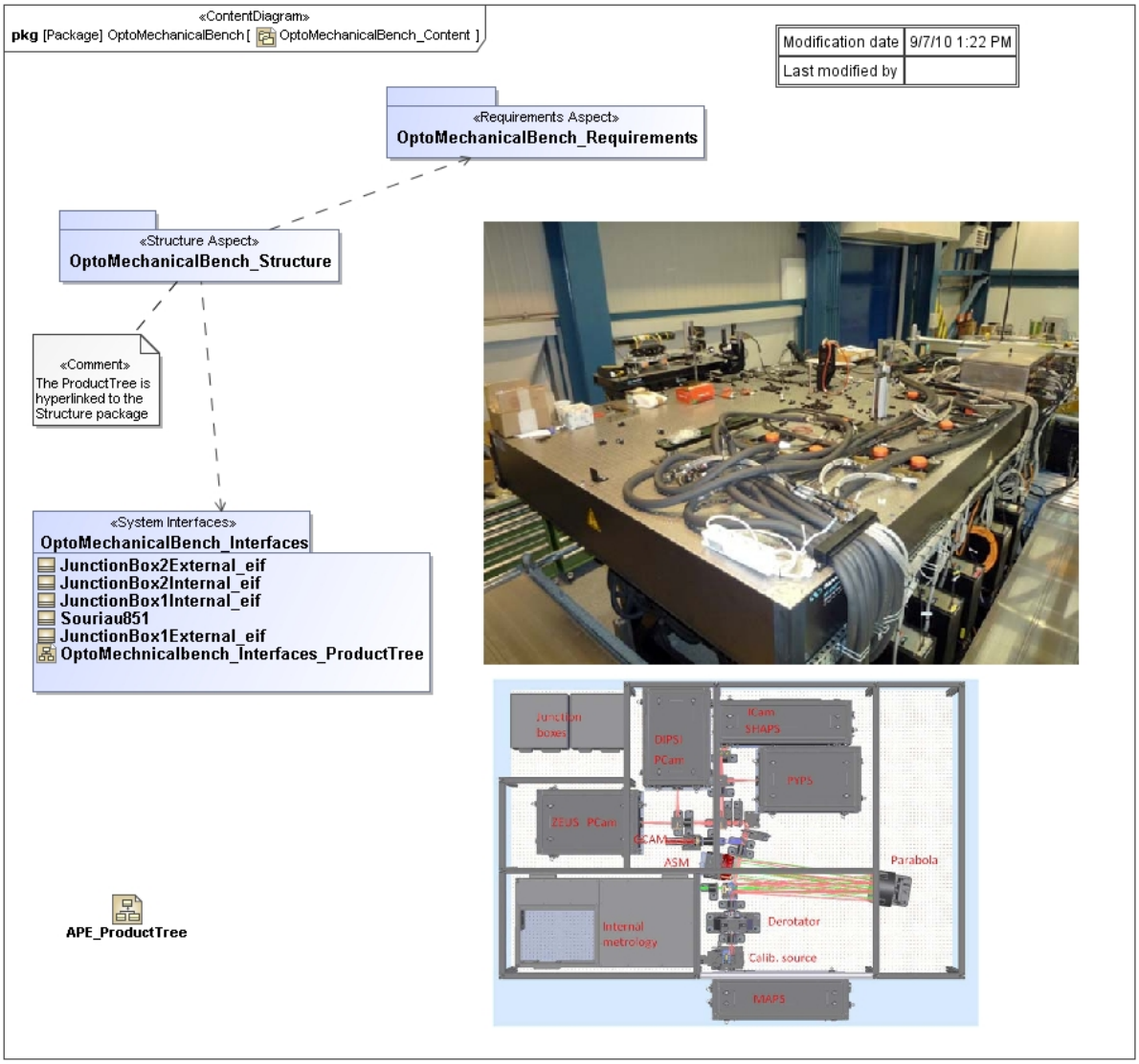


Figure 22 Model of the OMB

Typically, one enters a project and finds a 0th level <<system context>> that provides a context for the <<external>> and <<system>>.

7.1.2 Modeling the information flow in the context diagram

If information flow to external is modeled to improve understand of the context relations of the system, model the information flow as flow items on the connections. Pay attention to avoid diagram cluttering, and achieve completeness.

If necessary create a separate diagram for the information flow to each external system.

7.1.3 Modeling different contexts

The System context is modeled using IBDs. Our main focus is on system interfaces.

Three different possibilities are shown to model an interface

- Combination of mechanical and flow interface at block level (Model physical and logical properties at border of block without opening it.)

- Mechanical and flow interface at part level
- Mechanical and flow interface at block and part level.
- Abstract interface representing and ICD (using standard ports).

A problem is ensuring consistency between ICD document and the model which is used to create the CD.

APE is deployed in the lab and at the observatory. Each environment has slightly different interfaces or external actors, i.e. the context is different. The different contexts are modeled as variants, which are explained in detail in chapter 14.

For each relevant aspect (mechanical, optical, electrical) the context is modeled. To avoid cluttering by IBDs, for each context a separate block is created which inherits from a common, <<abstract>>, context block. The common block contains the elements which are shared among the other contexts. In the APE example the abstract context block is called APEContext, and can be identified by the slanted characters in the name. For each context, this block is specialized. The blocks are called ObservatoryContext and LaboratoryContext.

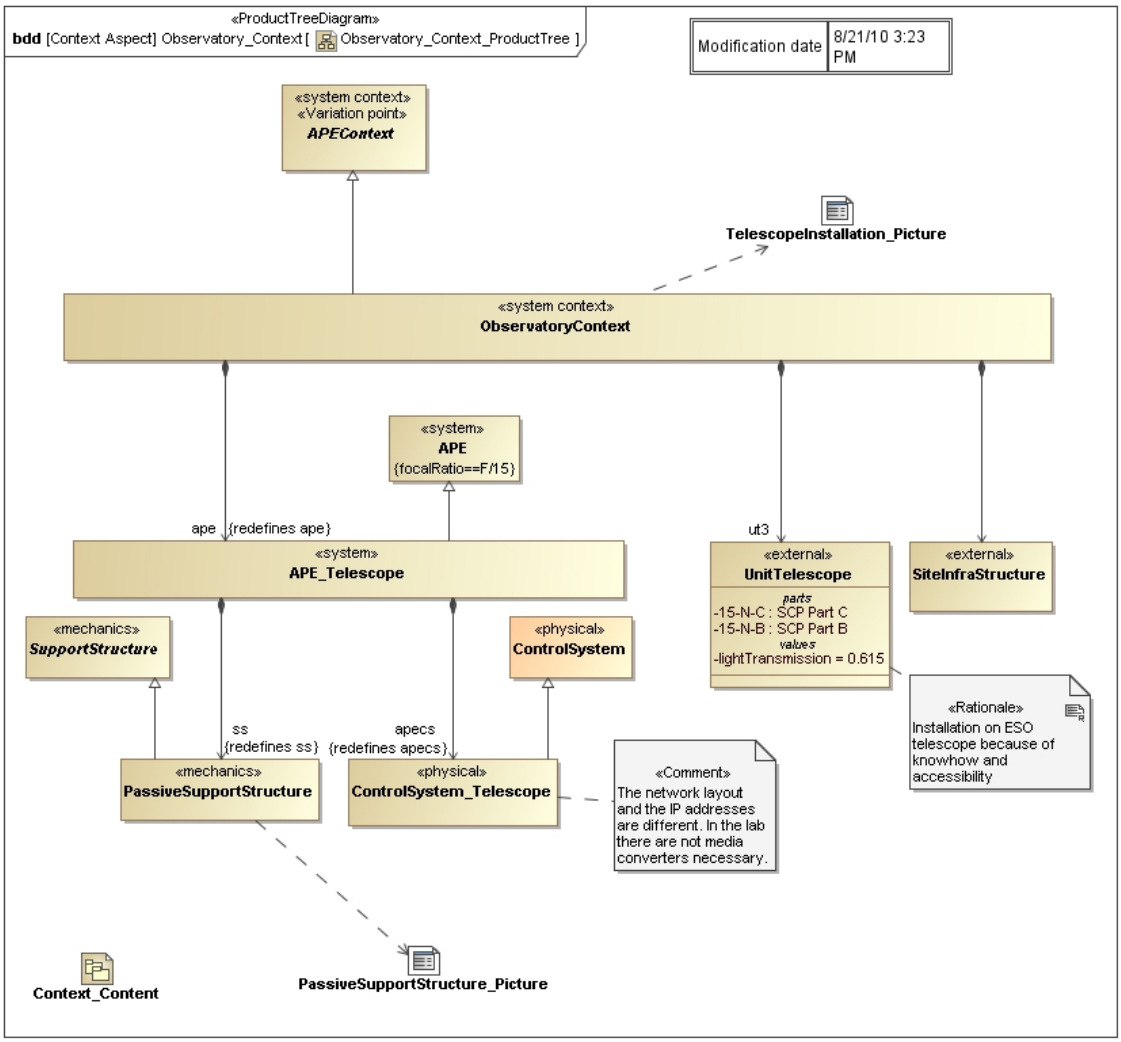


Figure 23 Product Tree of the Observatory Context

In the case of APE, the SupportStructure, the ControlSystem, and other items differ slightly for the ObservatoryContext, which can be seen as specializations in Figure 23. Again, there exist IBDs for this particular context, as shown in Figure 24.

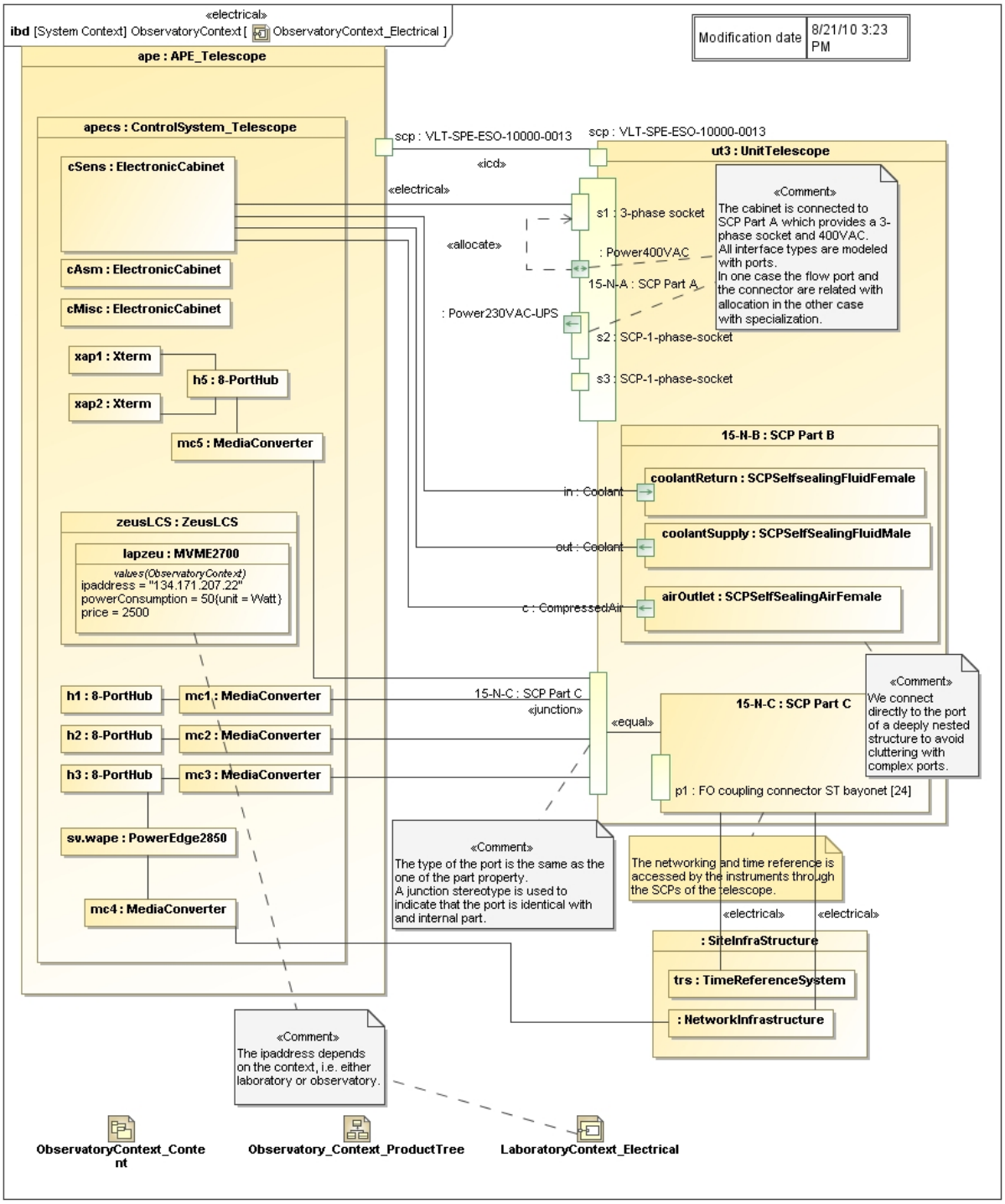


Figure 24 Electrical IBD of the Observatory Context

7.2 Use Case Modeling

7.2.1 Purpose of a Use Case

A use case is a sequences of interactions between the system and the actors to achieve a specific purpose for the triggering actor. We used use cases for refining high level requirement. Refinement means elaboration in this context, i.e. add more information about the interaction and provide a better

understanding of the requirement. However, Use cases can also used as basis for elaboration of lower level requirements.

A use case describes how a functionality/service is offered by the system as description of the interaction of the system and its actors.
The system is like a "service provider".

A use case has at least one actor, is started by a domain specific trigger and ends with a domain specific outcome. The sequence between trigger and outcome is coherent in time, i.e. there is no domain specific interruption.

The use case shall be described with an essential sequence, which is the standard success scenario. It should not contain any decisions about technology or design. Non-standard sequences (exceptions, etc.) are described with additional activity diagrams.

Describe use cases only with **essential** steps (i.e. raise them to a higher level of abstraction and describe them technology independent). A use case should usually have between 2 and 8 steps.

A use case can be encompassed by preconditions and post conditions for a more precise description, but there may not be a 1:1 mapping of pre- and post condition to later state machine implementations.

A trigger is generated OUTSIDE the system and starts the execution of a use case. The result of the use case is an EXTERNALLY observable consequence. Pre- and post conditions are the state of the system. They are INTERNAL.

A use case can be restricted by a business rule. They should go to a separate section and the use case should only refer to them because they might be applicable to several use cases.

A use case can be associated with non-functional requirements (performance, safety, etc.). Since the performance requirements might apply across use cases or across the system, it is better to reference them only to avoid duplication and allow better traceability.

There are two types of use cases:

- Primary - Primary use cases are directly connected to actors, they have a trigger, an outcome and post-conditions. They represent the core value for the actors.
- Secondary - Secondary use cases have no actors, no trigger, no post-conditions and are a mean to factorize common paths in primary use cases. Use them only when you have more than three instances of the same path.

A use case should have a name, description, incoming/outgoing data, trigger, result/benefit, pre-/post-condition. The description elaborates the most important activities (aka scenarios). The steps of the activities should be described in its essential form, i.e. rather technology independent. For example, instead of “Enter PIN” the step should be “Authenticate User”. The number of essential steps serves as a measure for the effort to implement it.

Some of the APE system use cases and the corresponding GUI is shown in Figure 25.

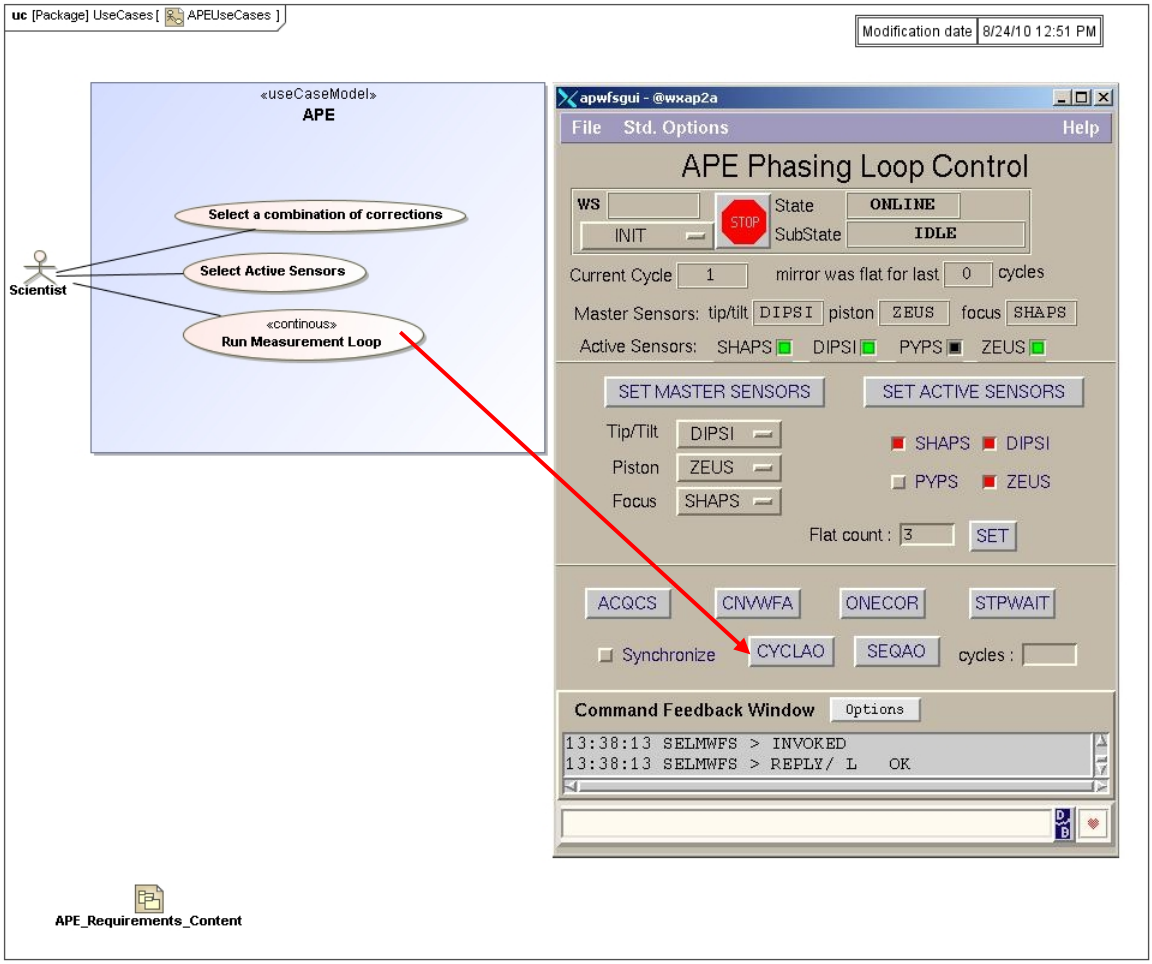


Figure 25 Subset of the APE System Use Cases

7.2.2 Modeling monitoring and control activities

A monitoring or control activity can be started, then it runs, and in the end it is stopped. Here is only ONE use case required. It would be triggered by the start and run until a message arrives to stop it. It can be modeled as a <<continous>> use case.

7.2.3 Modeling operations related to subsystems with use cases

For example, a lamp is switched on, then it is on and in the end it is switched off.

The use case would be rather simple and therefore does not add any additional information. You don't need a Use Case. Model it with a normal requirement that you want to switch on, off the lamp. However, to model the change of intensity you might refine this requirement with a use case.

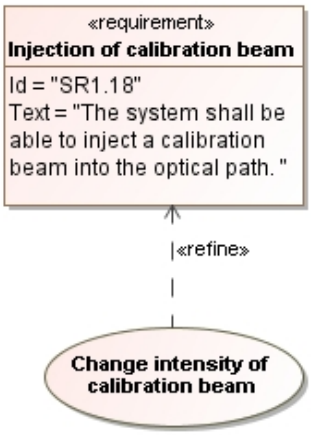


Figure 26 Refinement of System Requirements

7.2.4 External element types

The following type of actors can be distinguished:

- interacting actors - involved in use cases
- mechanical systems - interfaces defined but not involved in use cases
- environmental influences - like vibration forces

There should be different diagrams for those categories. Every external element MUST have a defined interface (interface in sense of System Engineering).

7.2.5 Modeling a system of systems with use cases

Use cases should have only ONE level for a certain system, the <<primary>> use case. Use cases shall not be deeply nested because it bears the risk of doing structured analysis with use cases. That's not the intention of use cases, because each use case shall have a measurable benefit for the actor.

Note: use cases can be used at different level. However, we do not recommend using different use case levels for Telescope domain.

<<secondary>> use cases are a pure organizational aid to avoid duplication of information. Between <<primary>> and <<secondary>> use cases exists the <<include>> relationship. However, use <<include>> only if more use cases share the same functionality. Avoid building structured analysis like <<include>> tree structure!

7.2.6 Use Cases vs. Standard UML Interfaces

- Use interfaces to elaborate Use Cases at lower levels
- The panel (with knobs and gauges) of a subsystem is represented by a set of Use Cases
- From the perspective of another subsystem the same functions are modeled by interfaces, try to avoid Use Cases among systems
- Always let ports realize an interface. More flexibility
- The connector from a port at system/assembly border acts as delegation

7.2.7 Tracing test cases to use cases and requirements

A specification for a subsystem often contains requirements on the necessary tests to be executed, the test requirements. A client, for example, would specify test requirements if the subsystem is contracted to a supplier. The supplier has to meet those test requirements. Those requirements are not the detailed procedures but only requirements for them.

The details of the <<Test Case>> are described by activities, sequence diagrams or state machines. Furthermore, the model should describe who executes the test. Test cases ccan be directly derived from use cases, because each scenario of a use case is a test case.

An example verification model is shown in Figure 27 which shows the relations among all the participating entities. The TestRequirement is derived from a SystemRequirement, and refined a Test Use Case. The set of <<Use Case>>s corresponds to a traditional test plan.

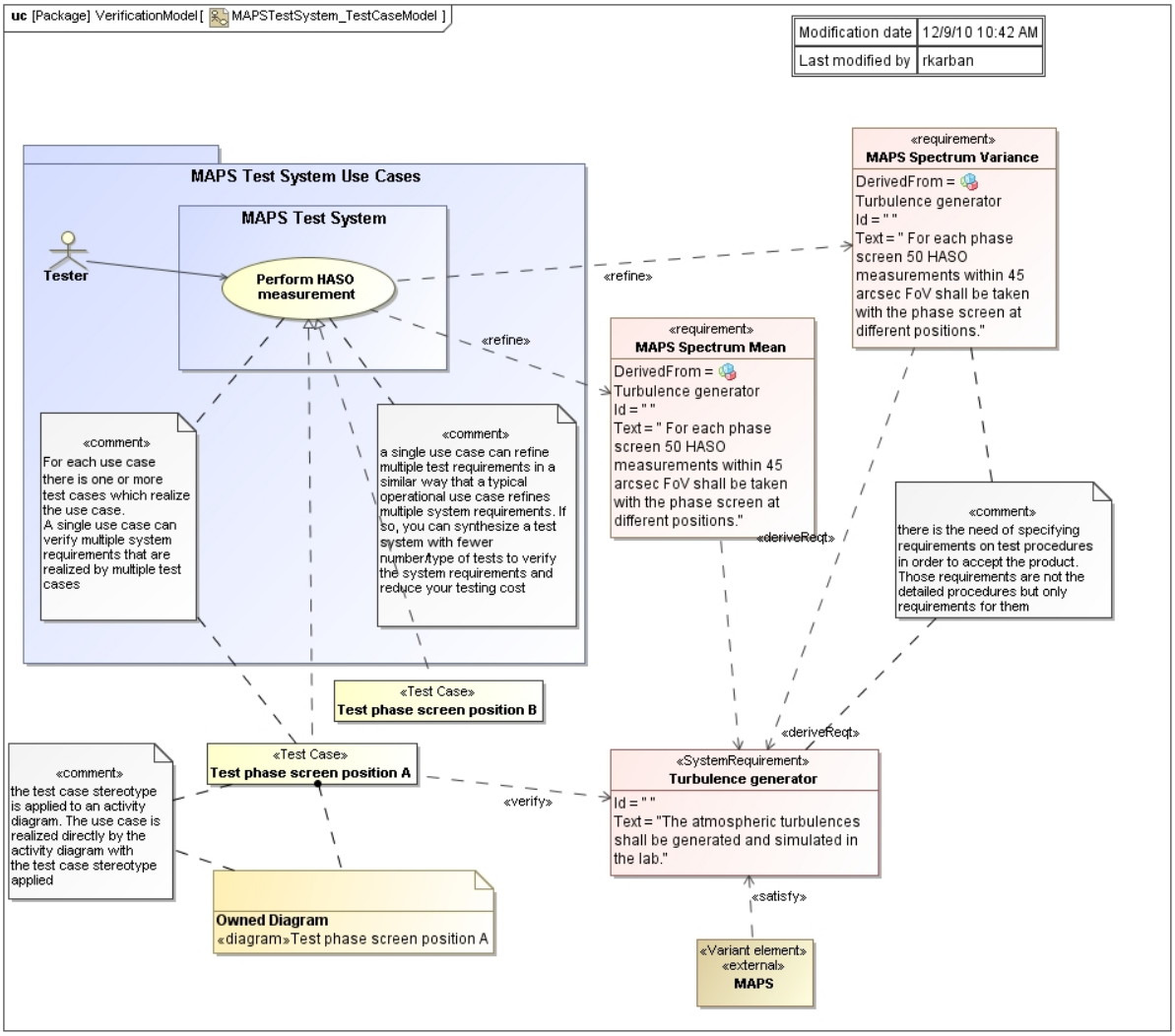


Figure 27 Example model of Test Cases and System Requirements

Each Use Case is realized by one or more <<testCase>>s, which in turn <<verify>> the SystemRequirement. The <<testCase>> can be described by activity diagrams. In fact, a single use case can verify multiple system requirements that are realized by multiple test cases. The actors represent the roles involved in the test.

Refer to [RD1] for realization relationship. Actually, the test case stereotype is applied to an activity diagram. The use case is realized directly by the activity diagram with the test case stereotype applied. One way in which this approach would add value is if a single use case can refine multiple test requirements in a similar way that a typical operational use case refines multiple system requirements. If so, you can synthesize a test system with fewer number/type of tests to verify the system requirements and reduce your testing cost. This needs to be assessed.

7.2.8 Naming of Use Cases

- Create a first set of use case with only their name in the form: "verb + [qualified] object". You can do that by creating actors and use case bubbles.
- Use active (not passive) verbs. Avoid vague verbs like "Do" or "Process". Avoid low-level verbs such as create, read, update, delete.
- Each object name in the use case name should be defined in the glossary.
- Here are some verbs for informative Use Cases: Analyze, Discover, Find, Identify, Inform., Monitor, Notify, Query, Request, Search, Select, State, View
- And for performative: Achieve, Allow, Change, Arrange, Classify, Define, Deliver, Design, Ensure, Establish, Evaluate, Issue, Make, Perform, Provide, Replenish, Request, Setup, Specify
- DO NOT put any non-functional requirements into use case.

DO NOT put any business rules in Use Case - only reference them.

7.2.9 Do I need to refine every requirement with a Use Case?

No. You only focus on the main services in the use cases and not on trivial things.

7.3 Guidelines for modeling requirements

The SysML specification defines the <<requirement>> model element, its properties (ID, name, text), relations among requirements (e.g. <<deriveReqt>>), and relations to other model elements (e.g. <<satisfy>>. However, the semantic of those relations are not defined in a formal sense and are subject to interpretation. Therefore it is necessary to define some kind of heuristics, guidelines, and practices how those relationships should be used in order to have a consistent model.

7.3.1 Requirements Engineering Best Practices

According to Requirements Engineering best practices there are multiple levels of requirements:

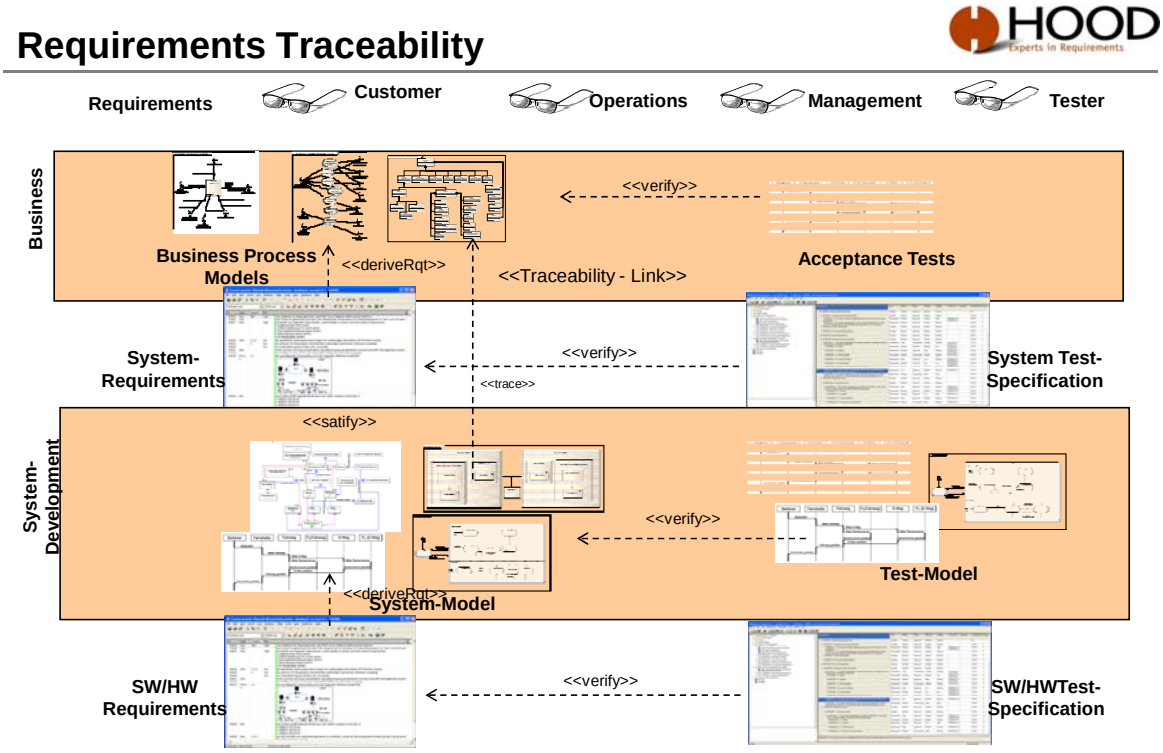
1. Stakeholder Requirements are the top level of requirements. They capture the needs of users, the customer and other sources of requirements like legal regulations and internal company high level requirements. Stakeholder Requirements making the stakeholder needs "smart"; i.e. using requirements quality criteria to generate a precise and understandable set of feasible and verifiable requirements, which is complete and consistent. If we visualize such a stakeholder requirements in SysML, we use the SysML Requirement Element stereotyped by <<StakeholderRequirement>>.
2. The next level is system requirements. The aim of system requirements is to set precise technical requirements for the system development. System requirements are derived from stakeholder requirements by considering existing technology, components and so on. If we visualize such a system requirements in SysML, we use the SysML Requirement Element stereotyped by <<SystemRequirement>>.
3. The next level(s) are subsystem and component requirements. The aim of subsystem and component requirements is to set precise technical requirements for the development of a subsystem/component. Subsystem/component requirements are derived from system requirements by considering existing technology, components, and interfaces and so on. If we visualize such a subsystem or component requirements in SysML, we use the SysML Requirement Element stereotyped by <<ComponentRequirement>>.

.

If it seems that you can get a complete and consistent set of stakeholder requirements or that the customer is very solution-driven it makes sense to capture also the actual objectives of the customer, why he wants the system; e.g. business goals or desired capabilities. In this case, the objective can help the engineering to find an optimal solution for achieving the objective not hidden by solution-constraint requirements. If we visualize such objectives in SysML, we use the SysML Requirement Element stereotyped by <<Objective>>.

7.3.2 SysML for Requirements Development

Since a long time there are a lot of specialized Requirements Management tools like DOORS, Caliber, IRQA and so on. These tools are built to efficiently manage requirements information; i.e. handling attributes filtering information and establishing and analyzing requirements traceability. So, why using SysML for requirements? Well, SysML has its strength in visualizing system engineering information and emphasizing specific aspects and relations of system engineering elements. Therefore why not using the best of both world and synergizing SysML and traditional Requirements Management?



Modeling and especially SysML are perfect tools for requirements development, because by abstraction and focusing on specific aspects model are a very good communication tool to achieve a common understand between the customer, user and supplier. E.g. use case diagrams and activities can be used to gain a common understand of the underlying business process.

Block (and class) diagrams can be used to capture business objects and their relation. IBDs can be used to find/set the scope of the system and identify interfaces.

All these models can be used as basis for requirements specification and the resulting requirements should be traced to these underlying models.

7.3.3 Modeling for Requirements Specification

Depending on the constraint of the project, modeling can be also used for requirements specification:

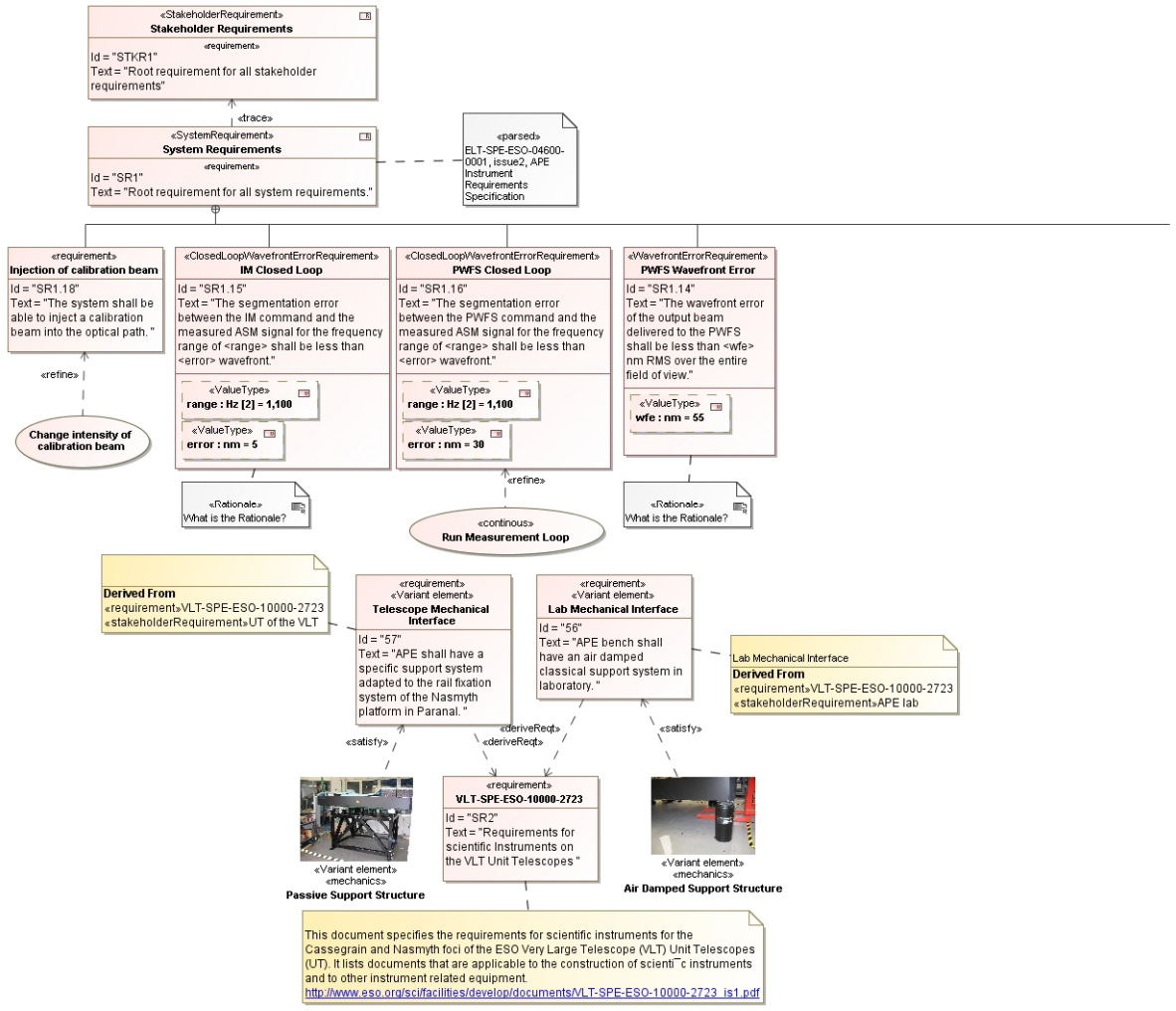
- Use Cases can specify the intended usage of a system or application
- Activity diagrams can specify the intended workflow of a business process
- SysML Block diagrams can specify the handled business objects/information and their relations
- SysML Internal block diagrams can specify the context and interfaces of a system
- SysML ports can specify technical details of a system or SW interface
- Sequence diagrams can specify the message flow and timing of a specific scenario
- Activity diagram can specify the workflow of a use case or an service
- State diagram can specify the system states and modes of the state of a particular business object
- Block constraints can specify non-functional properties of a system/subsystem; e.g. system.weight <= 1400kg; system.color = anodized black
- Feature properties can specify quality of service of feature/service; processOrder().availability = 99.95%

7.3.4 From Requirements to SysML Architecture Models

Based on existing input requirements, the system architects identify their solution “space” and develop multiple possible solutions. Next these “solution candidates” have to be evaluated and the global maximum has to be selected. SysML provides brilliant means for developing and documenting

- structural aspects of the solution candidates in terms of IBDs
- and behavioral aspects in terms of activities and sequence diagrams.

However, it should be documented how these solution candidates implements the requirements. That’s were SysML requirements drop in: SysML requirements are perfectly suited to visualize the impact of requirements on the architecture.



Since graphical SysML requirements are not suited to perform typical Requirements Management activities like filtering requirements by complex attribute filters and analyzing requirements links graphs, our suggestion is to use SysML <<Requirement>> to visualize requirements managed in a traditional Requirements Management tool, which provides a tabular form. However, in the future the capabilities of the modeling might change and make a separate RM system superfluous.

7.3.5 Guidelines for modeling the system requirements

- SysML requirements are not a replacement of Requirements management (RM) tools but a visualization aid for architectural important requirements.
- Distinguish Objectives, Stakeholder Requirements, System Requirements and Analysis elements (e.g. Use Cases)
- The objectives describe the major goals of the project. They are modeled with requirements elements, stereotyped objective.
- The stakeholder requirements describe the system from the perspective of the stakeholder, mostly technology independent. They are modeled with requirement elements, stereotyped as stakeholderRequirements. Stakeholder Requirements are <<traced>> to objectives.
- Requirements shall be decomposed with <<contain>> (i.e. nesting) only on the same abstraction level as a purely organizational mean until they are verifiable
- Use <<deriveReqt>> among Stakeholder and System requirements because they are tightly coupled and cannot change without impact on each other. System requirements restate User Requirements from a System (Technical) perspective. Usually they assume a design decision which shall be justified by a <<Rationale>>

- Use <<refine>> to elaborate a requirement with another model element, like a use case refines a requirement, a state machine, an activity, an interaction or a table, text document and so on represented by a block (in UML you represent such elements by the artifact which is not part of SysML).
  Strive to use <<refine>> within the same level of abstraction.

- Do NOT use a user requirement package if the system is part of another system (system of systems).
- Use <<deriveReqt>> for (system) requirements that are discovered by some design or analysis effort, which do not restate a user requirement but rather apply to the next lower system level or next level of abstraction. They shall be justified by a Rationale (e.g. Technical report) or <<trace>> to an existing design
- Use <<copy>> to integrate existing requirements, like interface requirements, international standards, policies etc. Model them with a requirement element where its name is the document number. The elements belong to the context of the system.
- Use <<trace>> to show explicitly the dependency of a requirement to a design (a block), justified by a Rationale
- Use <<trace>> to model the relationship between functional and non-functional requirements.
- Use <<trace>> between top-level containers of each level to indicate that there is some kind of relationship among their nested elements.
- If it is difficult to decide if to use refine or derive - choose either. the important thing is that there is a relationship between them. The semantic difference between refine and deriveReqt is secondary.
- Use a RM tool like DOORS (if available) to manage the requirements and trace them to model elements. If some requirements are very important (e.g. security, reliability, performance, ..) they could be shown using the SysML <<requirement>> elements and the <<satisfy>> dependency.

7.3.6 Background derived requirements

- The derived requirement depends on the value of the source requirement that is generally based on a form of analysis.

- The derived requirement is not a member of a 'set' of the supplier requirement in the same context as the contained relationship. The supplier requirement can be complete and contain no additional requirements with or without the derived requirement. Derived requirements are derived from different other requirements and have their own lifeline.

- When all derived requirements are met it does not mean that the others, where they are derived from, are met. In general, a derived requirement is more specific and directed toward some sub-element of the project.

- Derived requirements often occur through the process of analysis. They are the technical choices for each function. Each stage of derivation will involve some assumptions about the design of the system. A derivation often involves a specific analysis.

- A derived requirement often applies to the next level of the system. For the above example "the vehicle shall achieve a speed of 30 km/h under the specified conditions in table 1", a derived requirement may specify the weight, power, coefficient of drag, etc for the components of the vehicle in order to achieve this value.

- Derived requirements can change as a result of changes in the design, usually without reference to the customer, so it is very important to keep track of what's derived and what's not. You don't want some old internal decision constraining your future ability to meet your real customer requirements.

7.3.7 Stakeholder vs. System requirements

Stakeholder requirements are often part of the contract and define what the stakeholder is expecting from their (non-technical) point of view. System requirements are requirements that the real system

shall meet in order to fulfill the stakeholder requirements. The system requirements refine the Stakeholder requirement from a technical point of view. You can attach a rationale to the relationship to show how you arrived at the refinement.

7.3.8 How do I model relationships between requirement and design element?

- If a design element fully satisfies a requirement, use the <<satisfy>> dependency
- If a design element exists due to the requirement (but not fully satisfy the requirement, use the <<trace>> dependency

7.3.9 How should I structure a requirement hierarchy?

The top-level requirements are ON THE ENTIRE SYSTEM and not packaged near a specific design solution. Requirements are put in a separate, top-level package, and recursively for each decomposition level in a separate package, which is stereotyped <<RequirementsAspect>>. Putting them in a separate packages is also for practical reasons to define the scope of dependency matrices.

In a fully MBSE based approach there is no explicit requirements modeling necessary for each level. The requirements exist implicitly in the model as operations, constraints, functions, attributes, etc. because the design information of one level become the requirements of the next deeper level. However, it might be necessary to create explicit requirements anyhow. They are collected in the <<RequirementsAspect>> package.

At least, the Stakeholder Requirements, System Requirements, and possibly Objectives shall be modeled, also in a full MBSE approach. Those three types and their relations are shown for a part of the hierarchy in Figure 28.

Typically, there should be a specification for each major component that is being developed either internally or subcontracted.

Each specification will have its own requirements diagram and be contained in its own package. Use a trace to indicate an abstract relationship between the specifications. The requirements derivation is directly supported by some type of analysis as indicated in analysis xyx. Use the callout notation to reduce the clutter.

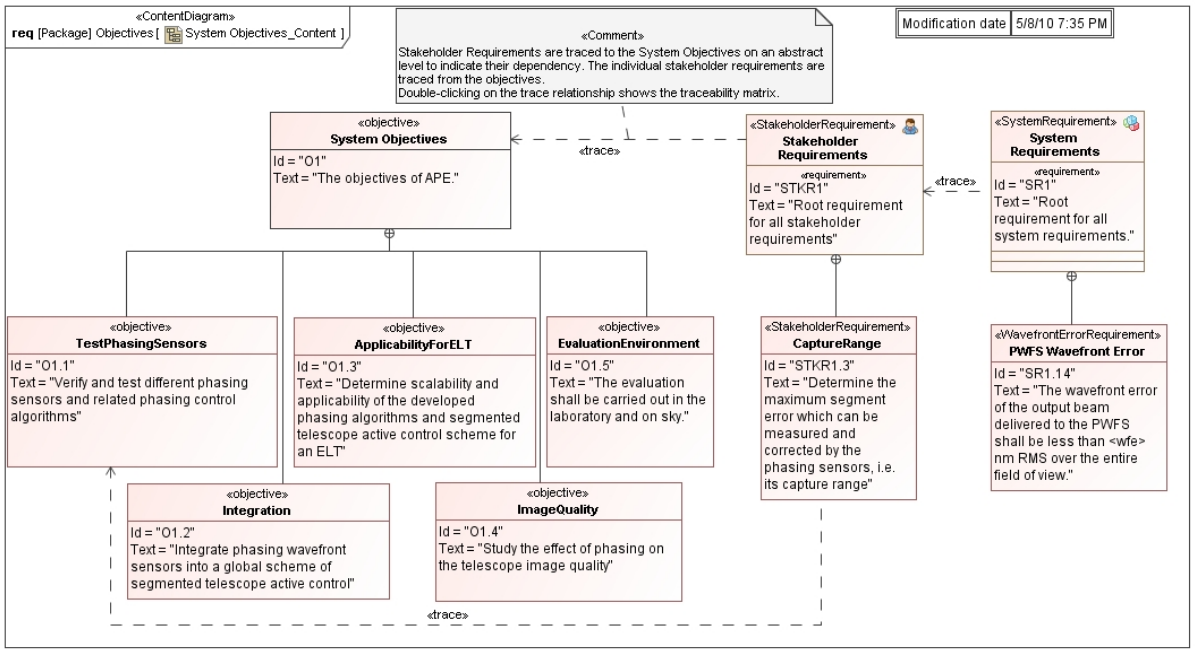


Figure 28 Relationships among different requirements types

Most relations between Objectives and Stakeholder Requirements are hidden in Figure 28 to avoid clutter. It is much more convenient to show them in an (automatically) created matrix as in Figure 29.

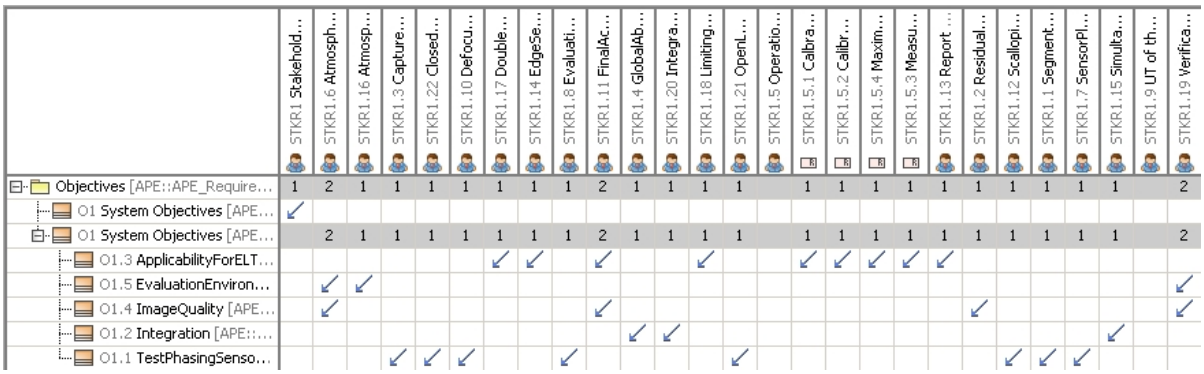


Figure 29 Dependency matrix between Objectives and Stakeholder Requirements

Above a certain number of requirements, they become difficult to visualize graphically. It is better to use the tabular format as in Figure 30.

#	ID	Name	Text
1	SR1	System Requirements	Root requirement for all system requirements.
2	SR1.1	ReferenceCoordinateSystem	APE shall have a reference coordinate system centred on the UT optical focus on the Nasmyth position. The origin of the coordinate system is the Nasmyth focus. The coordinate system uses the metric system. The surface of the APE breadboard is defined by the X and Y axis. The X-axis is parallel and has the same direction as the optical axis of the Nasmyth focus. ---
3	SR1.13	VLT standard. (RD14).	APE will be implemented on the VLT. All the electronics, software, platforms and control system must be
4	SR1.14	PWFS Wavefront Error	The wavefront error of the output beam delivered to the PWFS shall be less than <wfe> nm RMS over the entire
5	SR1.15	IM Closed Loop	The segmentation error between the IM command and the measured ASM signal for the frequency range of
6	SR1.16	PWFS Closed Loop	The segmentation error between the PWFS command and the measured ASM signal for the frequency range of
7	SR1.17	PWFS Reference Source	The reference source shall have magnitude v, seeing s, at wavelength lambda

Figure 30 System Requirements in Tabular format

APE has to satisfy certain interface requirements in order to be allowed to be installed on the telescope. SysML constraints can also be used to define quantifiable system interfaces. Figure 31 shows a parametric description of the physical interface between a VLT Unit Telescope and an Instrument placed on one of the telescope's Nasmyth platforms. The system properties of the telescope (e.g. volume, mass) constrain the properties of the attached instrument; in the example the

instrument is APE. The constraints of the «constraint» NasmythInstrumentSpecification (1) evaluate the properties of APE against the properties of the telescope. On either side, those properties become in turn requirements of the lower level system hierarchy and determine the properties of its parts. In the end, a mass roll-up of the complete APE system can be done to verify that it complies with the constraints given by the specification. On the telescope side, the allowed quantities are propagated down the system hierarchy to properly reflect the design decisions taken at the highest level.

For example, the telescope has an allowedMass property with a value of 8000kg. The Constraint specifies that the realMass shall be less or equal than the allowed mass. The real mass of APE is set to 5000kg. This mass can be used to establish requirements at the lower levels of APE itself, using constraints again.

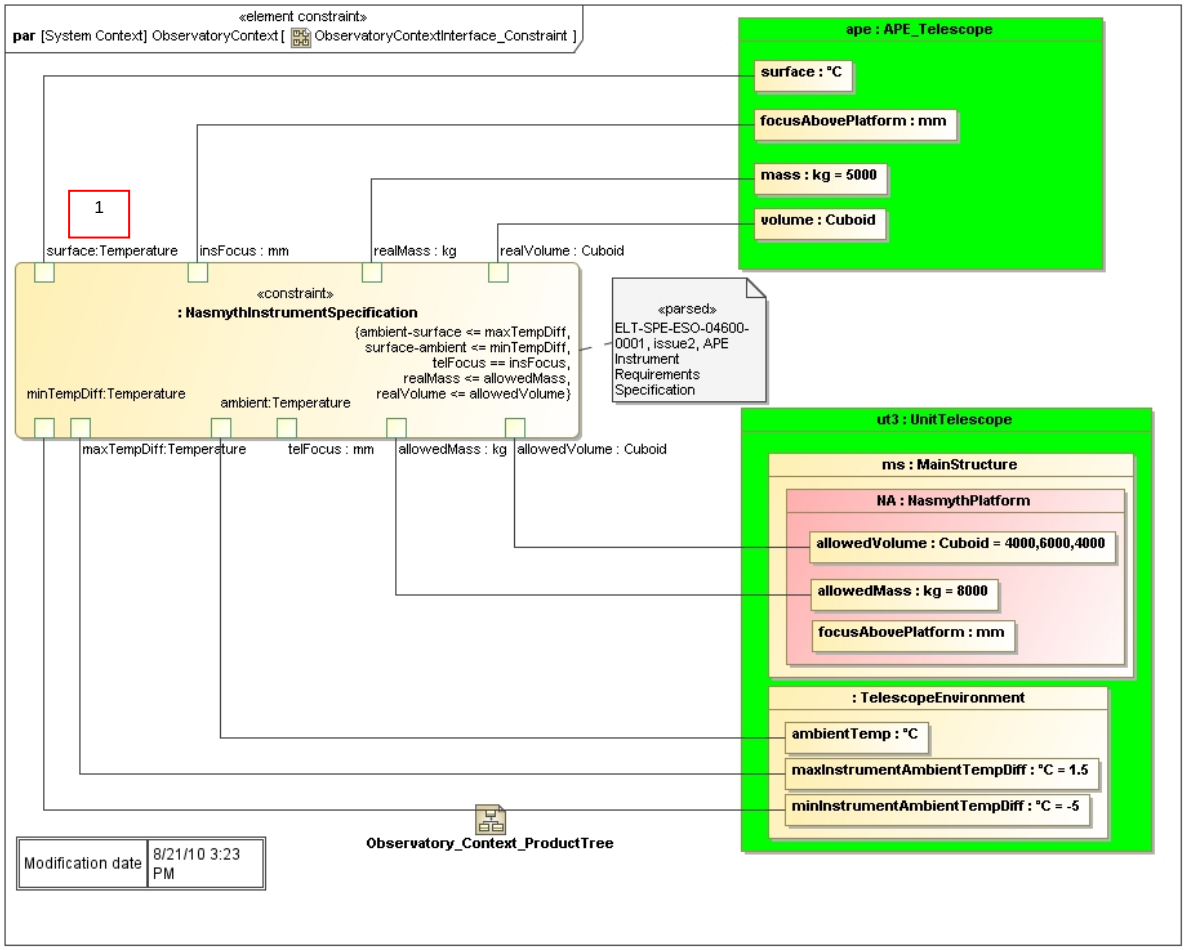


Figure 31 Interface Requirements model as Constraint

Another example of modeling requirements formally with constraints is the following. The original APE requirements document contains a requirement: “The quality of the input beam shall be the same as the beam fed into the wavefront sensor”. The APE optical view defines the item properties, called beamIn and beamToSHAPS which represent the incoming beam and the one delivered to one sensor as seen in Figure 32

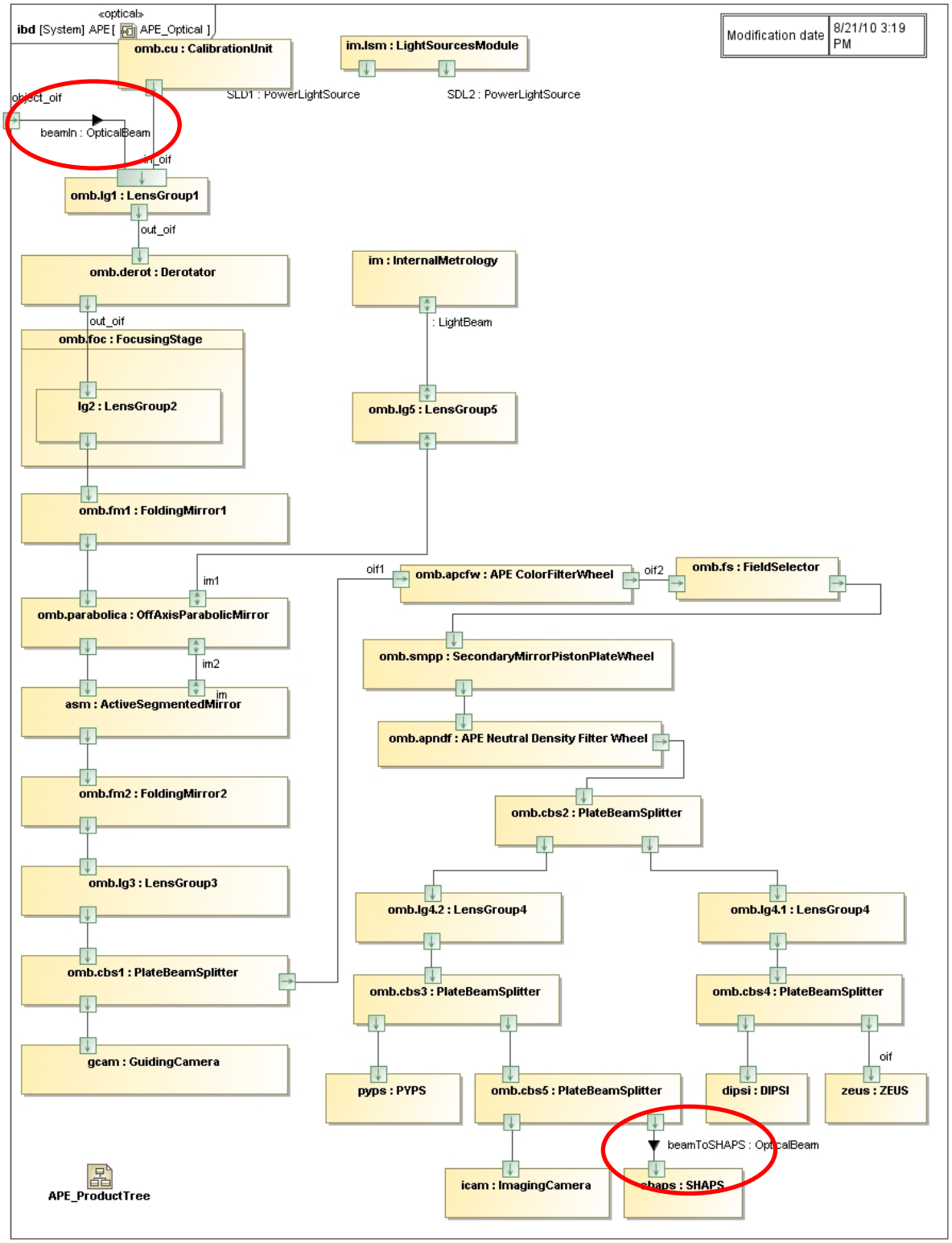


Figure 32 APE optical view

The properties of those two beams can be constrained with an appropriate constraint which defines their relationship as shown in Figure 33.

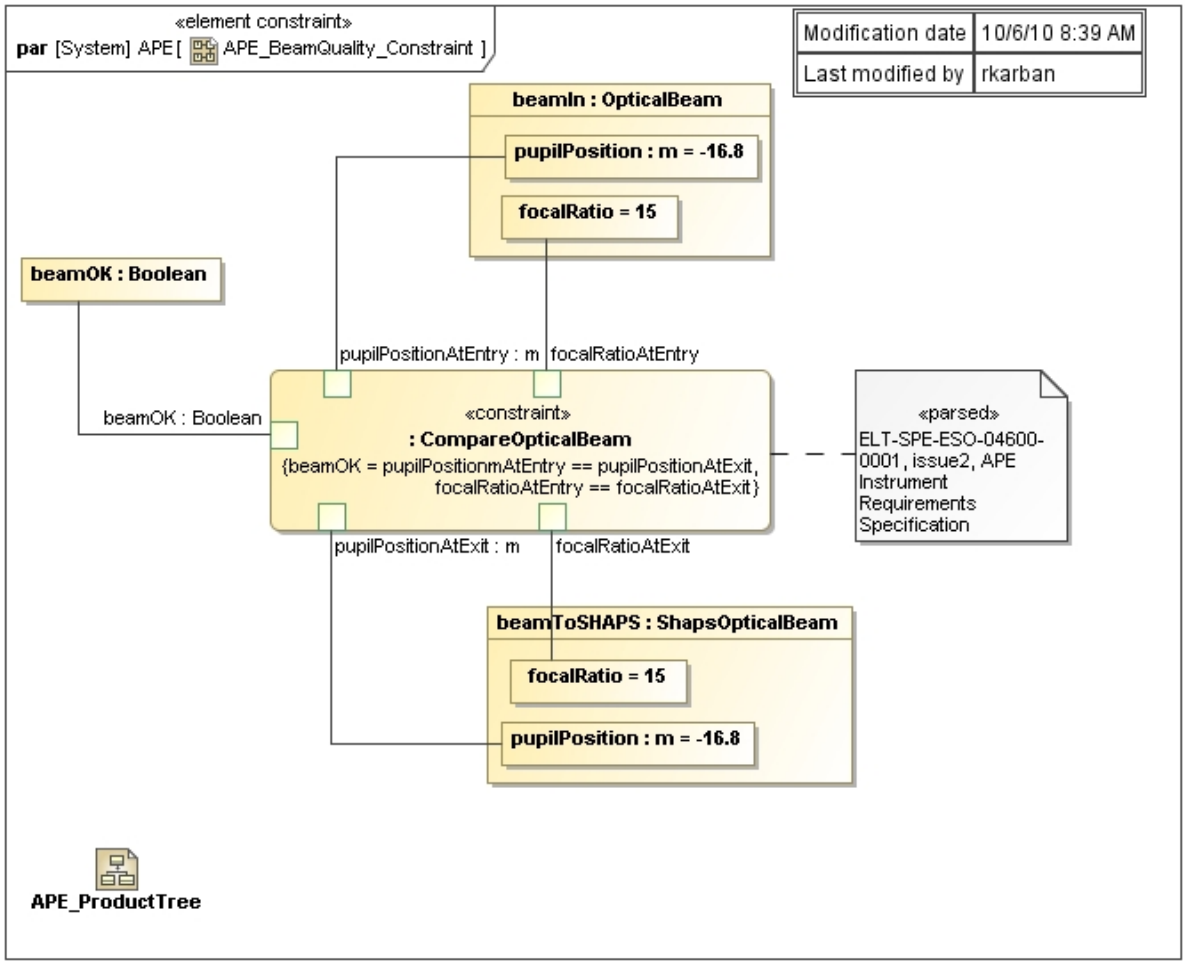


Figure 33 Constraint on optical beams

7.3.10 Requirements quality criteria

There are quality criteria for requirements:

- A requirement must be understandable
- A requirement must be verifiable.
- A requirement should be independent of the technical realization; i.e. do NOT contain any technical details.
- A requirement must be feasible; i.e. it should be possible to model how the requirement is satisfied by other model elements.

7.4 Requirements Boilerplates and binding to design

There are many levels of model re-use. The following sections concentrate on requirements, and system constraints. By applying a model based approach, requirements, and system interfaces become much more than simple text as they can be automatically validated and re-used. Design decisions and constraints at abstraction level N determine implicitly system properties at level N+1. Writing explicit requirements for the lower abstraction levels becomes superfluous as they are expressed implicitly in the model.

Generic boilerplates for requirements [RD3] are adapted to fit the telescope domain and form a domain specific language (DSL) for requirements. They are customized from the standard SysML requirements by defining and applying stereotypes. The quantifiable parameters of the requirements are leveraged by a strongly typed customization as shown in Figure 34. The attributes are of type nm and Hz, as defined in `ClosedLoopWavefrontAttributes(1)`.

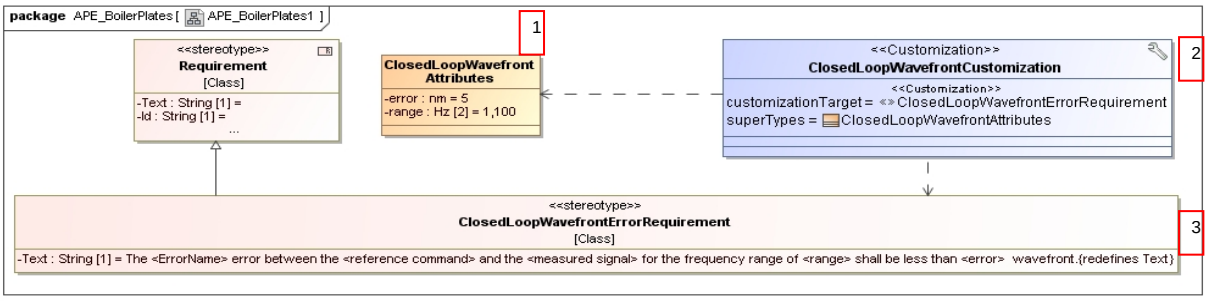


Figure 34 Definition of requirement boilerplates as a domain specific language.

Each boilerplate becomes an element of the DSL and can be reused in new systems (the `ClosedLoopWavefrontCustomization (2)` is merely a tool artifact to tie the derived stereotype to a default attribute values set).

7.4.1 Instantiation of Boilerplates

When a boilerplate is instantiated, the default text is copied automatically and the attributes defined in the DSL become the attributes of the concrete requirement with its own default values. The system requirements IM Closed Loop (4) and PWFS Closed Loop (5) in Figure 35 are instances of the boilerplate ClosedLoopWavefrontErrorRequirement(3) in Figure 34.

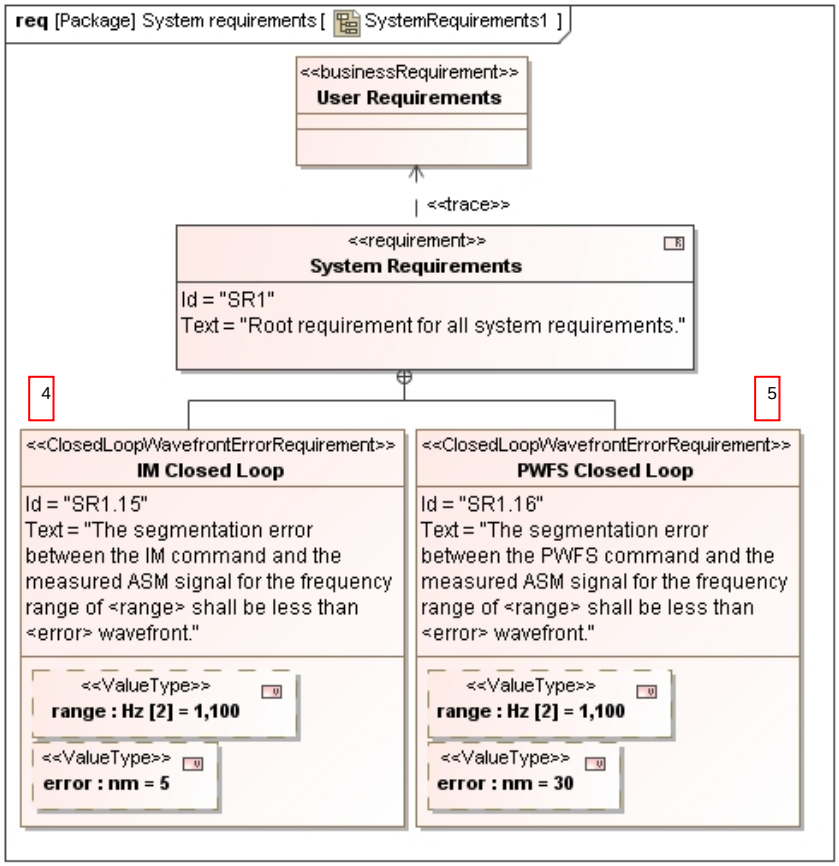


Figure 35 Instances of boilerplates

7.4.2 Constrain the Design

The strongly typed parameters[4] of the requirement enable the modeler to bind them to properties of the system under design using the SysML «ConstraintBlock» in parametric diagrams. Together with the properties of the actuator (lag and bandwidth), the parameters of the PWFS Closed Loop requirement determine the sampling frequency. The model of their relationship is expressed as the «constraint» ClosedLoopModel (6), as shown in Figure 36. This «constraint» represents in itself a reusable element and constrains the design at the system level. The sampling frequency is propagated down the system hierarchy, namely the control system, via another «constraint», the MaxCorrectionTime (7) which determines system properties further down the hierarchy. For example, the meanTCCDAcquisitionTime (8) is constrained by a SensorSensitivityModel (9) and associated requirements of the reference source.
Furthermore, trade-offs among requirements, system properties, and sub-system properties can easily be evaluated by executing the parametric model of the system. Therefore, requirements can be automatically verified against the design and vice versa.

[4] While modeling tools already partially support parameters for requirements, this will be recommended for future revisions of the SysML specification

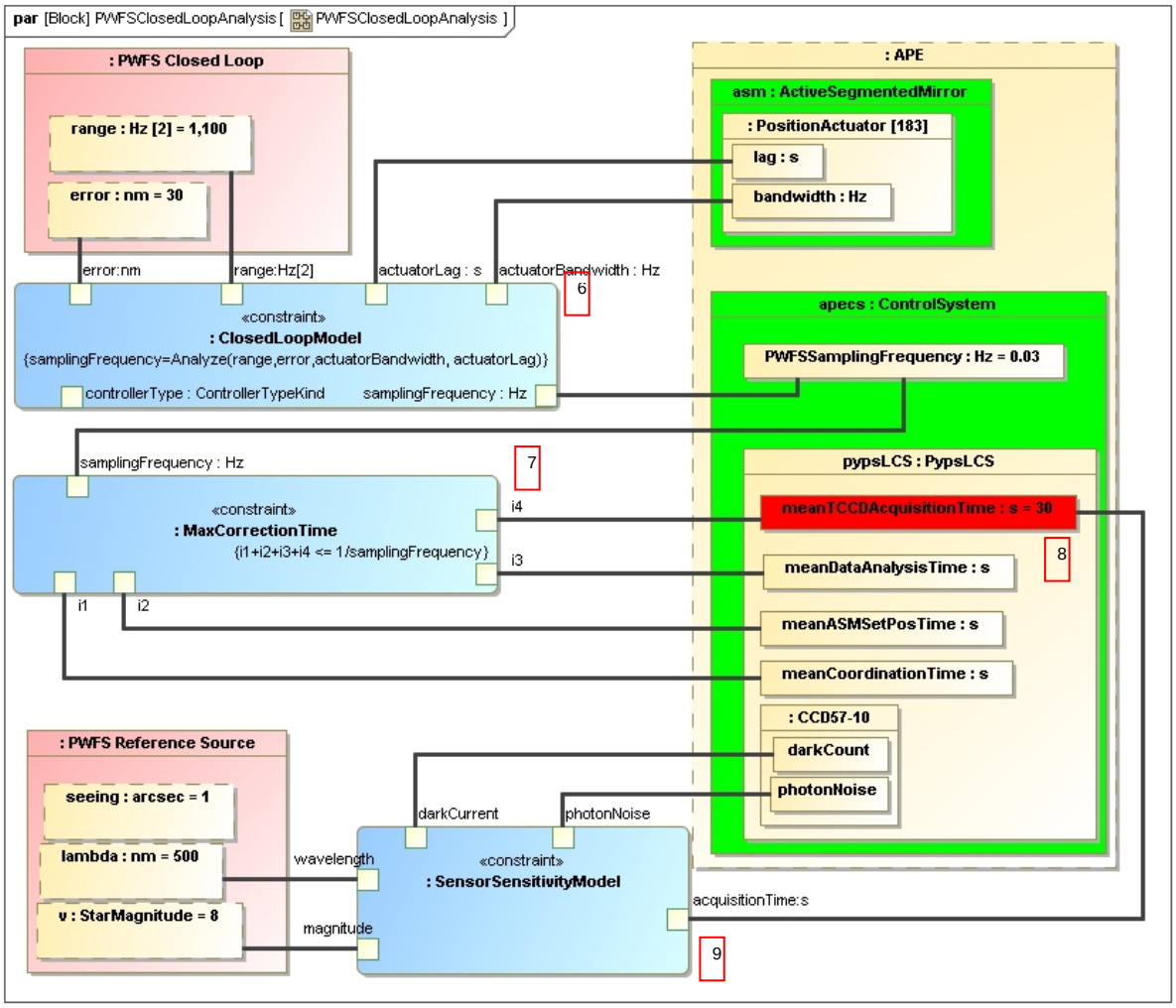


Figure 36 Constraining the design with requirements

The SysML provides the means to bind those properties to constraint parameters to constrain the system design. Requirements can be re-used in a formal way and create a consistent requirements specification across projects.

8 Structure modeling

To model the structure of a system, SysML offers two kinds of diagrams that works together:

Block Definition Diagrams (BDD) show the architecture building blocks of a (sub-)system in form of a product tree. Furthermore, they define the properties and features of the building blocks.

The Internal Block Diagram (IBD) shows how the building blocks are connected to realize the (sub-)system.

8.1 Starting to build a design model

For easy navigation you should create always pairs of IBDs and a BDD. From the IBD you should be able to navigate to the BDD which defines the Block which is the context of the IBD. From the BDD you should be able to navigate to the corresponding IBDs of a Block.

You are indeed encouraged to build the (sub-)system by “dragging” blocks from the BDD to become parts in the IBD like an engineer building assemblies.[5]

Define all the blocks in a BDD (Figure 37) and then use the blocks. This BDD defines the product tree of APE. APE consists of an ActiveSegmentedMirror, a GuidingCamera, etc.

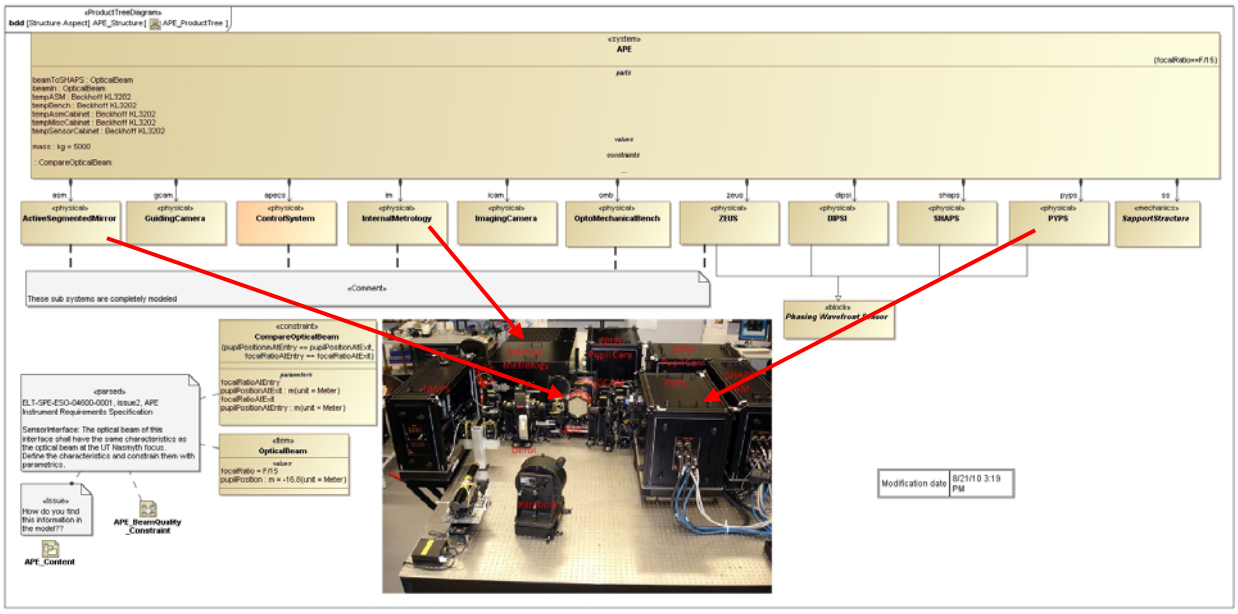


Figure 37 Product Tree of APE in a BDD

You can then GO BACK to the BDD to constitute a composition from the (sub-)system to the building block.[6]

8.2 Structure Breakdown

8.2.1 Definition of system hierarchies

Hierarchic breakdown of a system into smaller units is a well-known and always-used principle in systems engineering. Unfortunately the analysis of a system is not an unambiguous process. Several models can represent the same system in reality. It is therefore necessary to define some guidelines for the modeling of hierarchies in the SysML model.

In the Product Tree of the ZEUS Local Control System (ZeusLCS, Figure 38) The ZEUS opto-mechanical system is referenced. The ZeusLCS is assembled from some electronic boards, like a motor controller (MAC4INC) and an amplifier (VMESA01).

[5] In MagicDraw you can actually drag and drop blocks from BDDs to IBDs
[6] In MagicDraw use "create roles" or simply drag a property out of a block and the composition associations will be created.

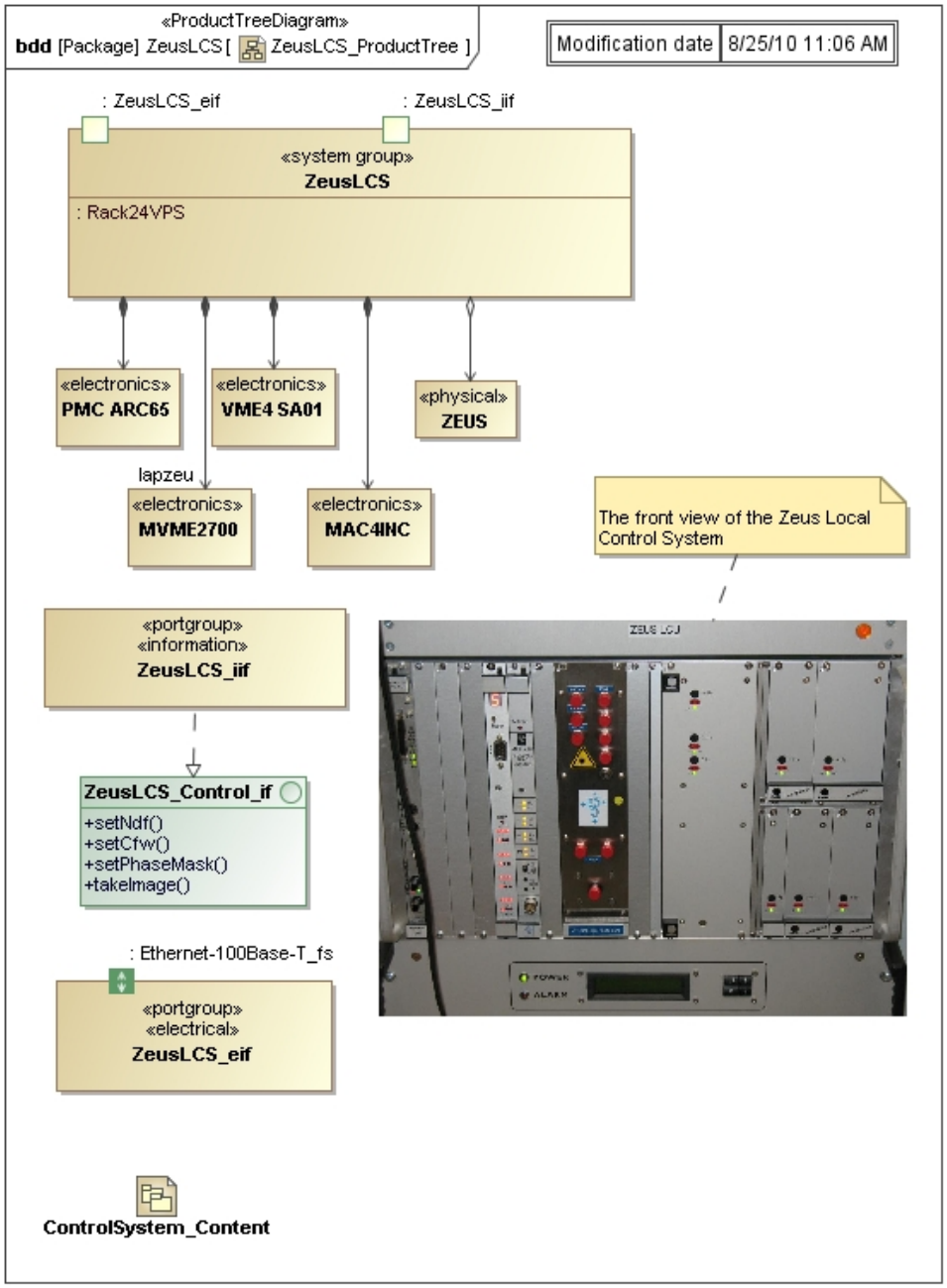


Figure 38 Product Tree of ZEUS Local Control System

The Information View (IBD) shows how information flows between the parts of the control system and the sensors and actuators of ZEUS (Figure 39).

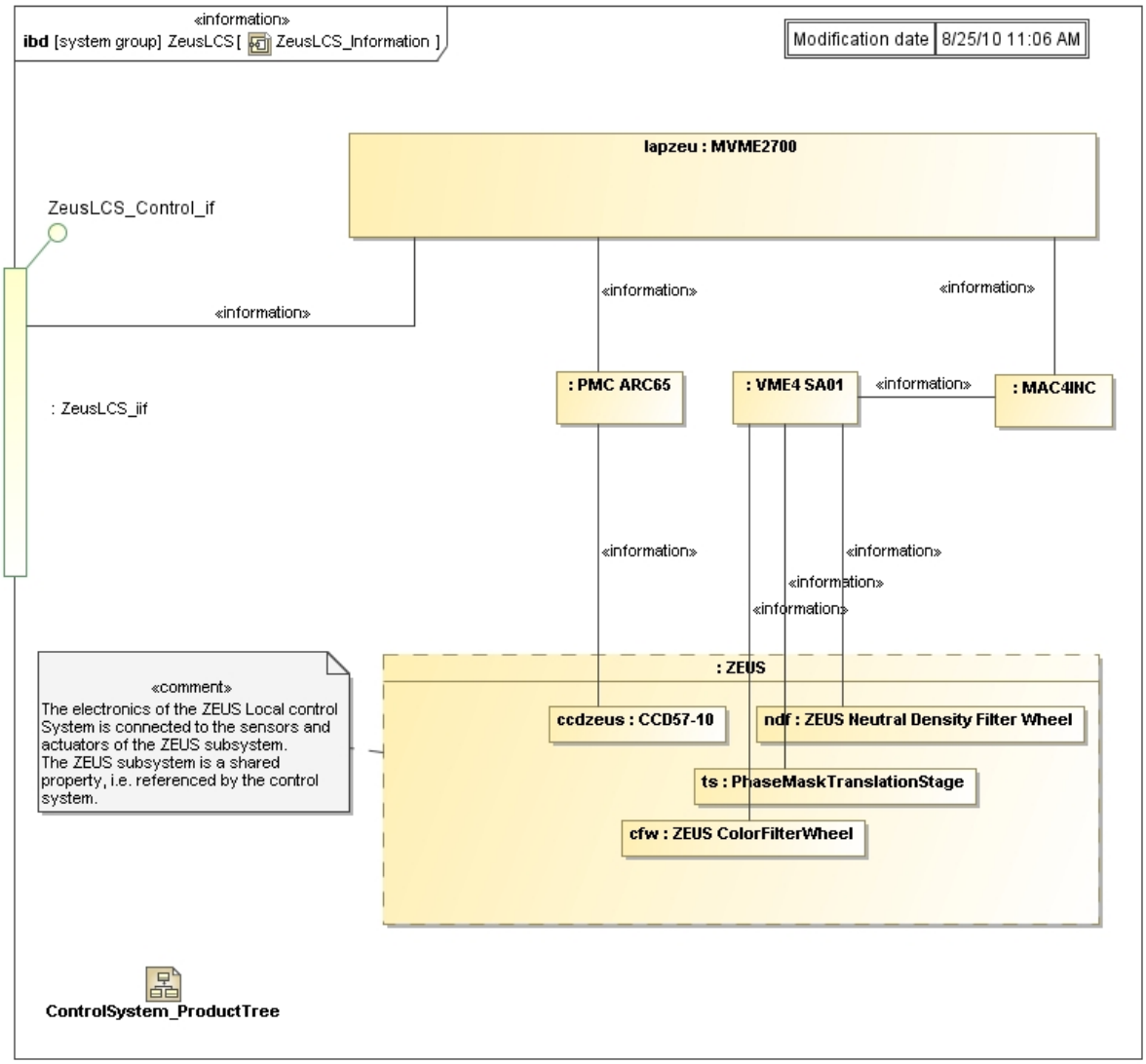


Figure 39 ZEUS Information View

The electrical connections can only be shown in the IBD of the APE system, at the next higher level of the structure because several substructures of APE are involved, like ZEUS, ZeusLCS, and the JunctionBox (Figure 40). Alternatively, the connections could also be shown in the IBDs of the substructure, using references, using shared part properties like the dashed ZEUS part in Figure 39 but this maybe end up in a maze of references and potentially creates confusion.

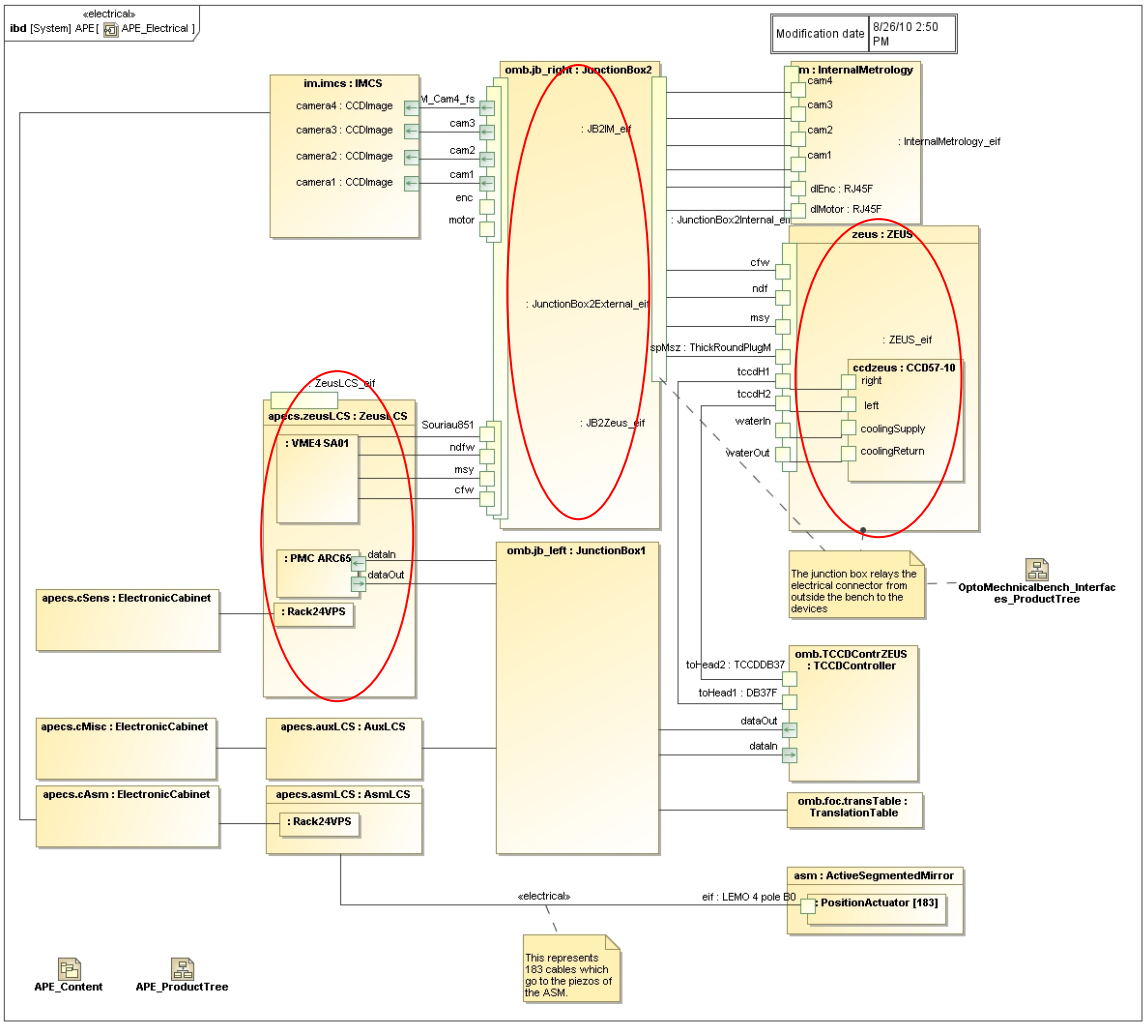


Figure 40 APE Electrical View

The modeling of hierarchies in the SysML model is very closely related with the question, at what system level interfaces (represented by SysML ports) shall be attached to a block. Examples for these issues are:

- Differentiation between functionally grouped (sub) systems with abstract interfaces vs concrete components with real interfaces:
  EXAMPLE: The entertainment system in a car consists of many components: speaker, radio, TV, cables, etc. These components are modeled as parts of the entertainment system, which is modeled as a subsystem of the complete car. The components are distributed all over the car (geographically), e.g. the loudspeaker is built into the door. It is very difficult, or even impossible, to model the entertainment system as black box without modeling the components of it, because the entertainment system is just an artificial grouping of "real" blocks. If one wants to model the interfaces of the entertainment system, this is not possible at the subsystem level directly, because only (concrete) components have real interfaces. Therefore the components must be modeled and the ports then attached to these blocks. Use the stereotype <<system group>> for those types of systems. The other parts of the car can reference (shared property) the components of the entertainment system to indicate their physical location.
- Modeling of connectors crossing several levels of a system hierarchy:
  EXAMPLE: If one wants to model the connection between one component of the entertainment system (e.g. radio) with one component of the power supply system (e.g. battery), this can only be done with a connector directly from the radio port to the battery port. This looks simple at the moment. However, the connector between both components crosses

two levels of hierarchy on its way: If one would just take a look at the subsystems, entertainment system and power supply system, you would also see the connection, because radio and battery are parts of these subsystems. Junction ports can be used in this situation.

The Local Control System (which is responsible for a substructure, like the ZEUS wave front sensor) of the APE Control System can be considered as a <<system group>> because it interfaces with sensors and actuators of the opto-mechanical system.

The Local Control System “creeps” into the opto-mechanical system and has interfaces with deeply nested parts of the system under control. Nevertheless, the Local Control System can be tested standalone (using simulation) and can therefore be considered as a subsystem of its own right. From the point of view of the supervisory part of the Control System it appears like a black box with a well defined interface that hides the internals and delegates the requests coming from the supervisory part.

8.2.1.1 SysML elements to model connected nested structures

The basic elements to model connected nested structures are ports and connectors.

Usually, an interface is seen as a part of a subsystem. e.g. the Nasmyth platform is part of the main structure, the SCPs are part of the telescope, electrical sockets in a building are interface at the outmost layer but are hierarchically very deep.

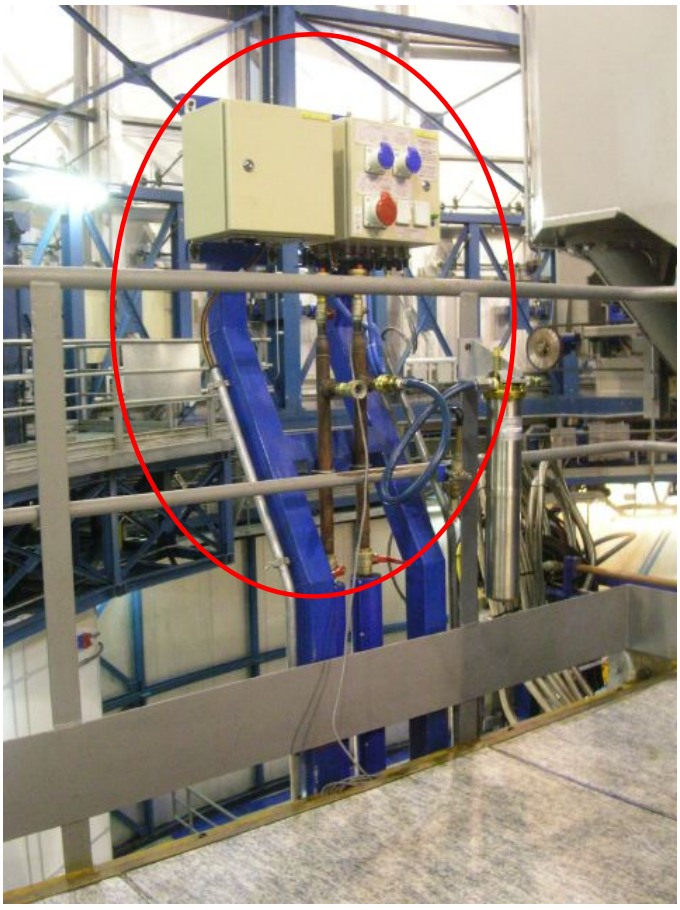


Figure 41 SCP at a Nasmyth Platform

Depending on what needs to be shown there are three different approaches:

1. A block is used to type a standard port and represents at the same time the part property without explicitly modeling as separate property. In the case it is not important to show it as part property and to have a physical property (like a plug) visible at the border of a block. Complex (nested) ports are used (15-N-A:SCP Part A in Figure 42). It's a simple approach, but the element is not listed as a part in the product tree.
2. Connect directly to the part property or the part property's port (15-N-B:SCP Part B in Figure 42). Also a simple approach, but the connection is hidden when the inner parts of the enclosing part are hidden.
3. Relay through the port at the border to a part property in case the part property is important and needs additional modeling. In this case stereotype the port as <<junction>>. The stereotype classifies the outer border port simply as representation of an inner port but not as a part of its own right. Junction ports do not delegate connectors, they are rather a window into the part and simply relay the connection (15-N-C:SCP Part C in Figure 42). The modeling of this approach is more complex, but the elements are listed in the product tree and there is a connection between the enclosing elements even when the inner parts are hidden.

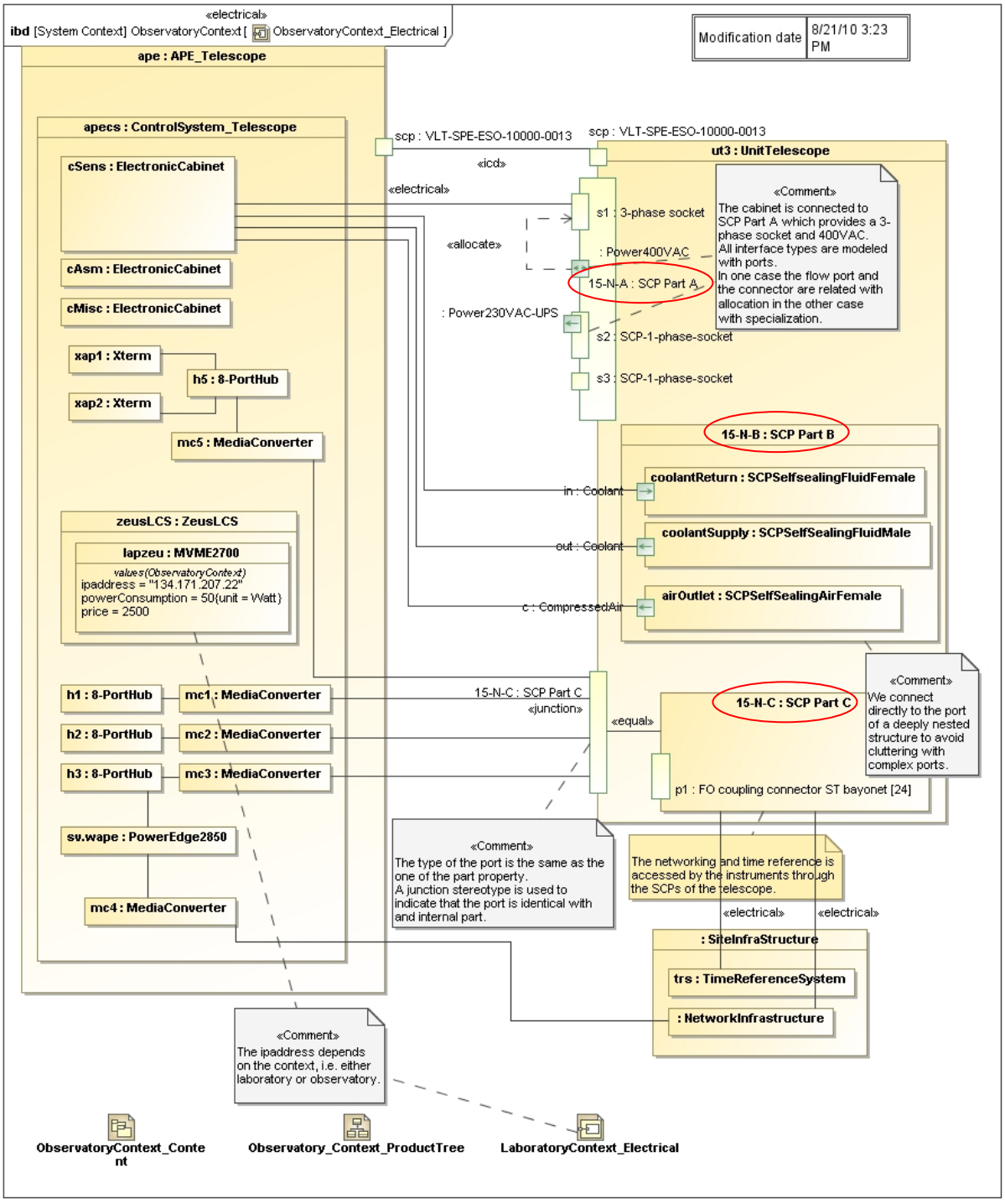


Figure 42 electrical view of APE and the telescope

8.2.2 How do I distinguish a sub system and an assembly?

It is sometimes difficult to define what a subsystem or merely an assembly is.

Follow this definition:

A subsystem is a set of interdependent elements constituted to achieve a given objective by performing a specified function, but which does not, on its own, satisfy the customer's need.

Following this definition they are either a package (like the ASM in Figure 43) on their own or simply a part of a package (like LensGroup1 in Figure 44).

Do NOT use the stereotypes <<system>> or <<subsystem>> unless it is well defined. The definitions differ from one environment to another. In APE we use only plain block and the stereotype <<external>> to indicate blocks that do not belong to the system under design.

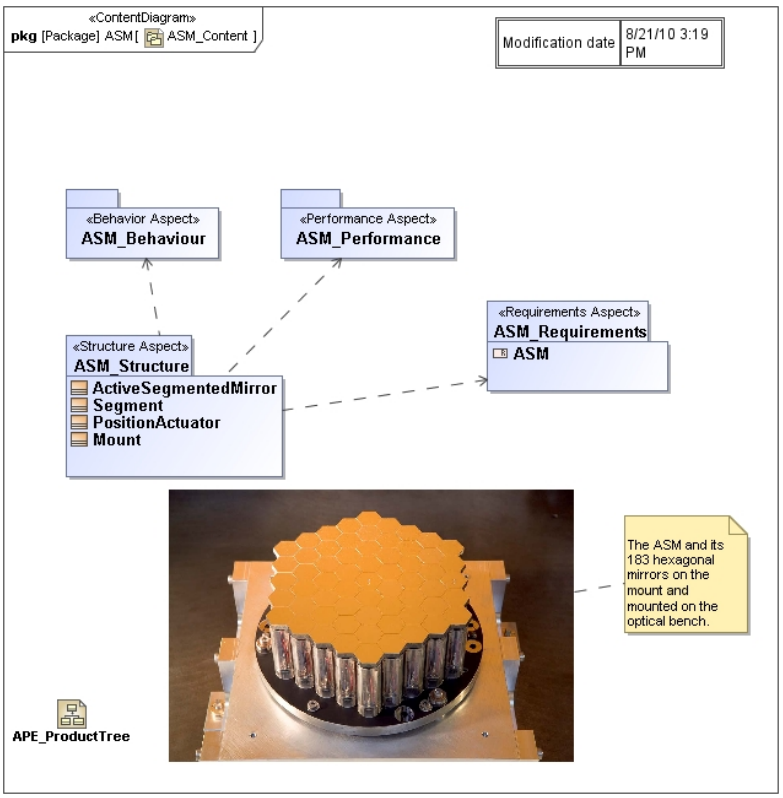


Figure 43 The ASM subsystem

In the Organization Ontology we stereotype to those elements either as <<DecomposedSystemElement>> (a separate recursive package structure is created) or as <<physical>>, <<electronics>>, <<mechanics>>, <<optics>>, <<software>>. <<electronics>>, <<mechanics>>, <<optics>>, and <<software>> form the leaves of the product tree which are not further decomposed at system model level.

A Block stereotyped as <<physical>> has a special meaning. It serves as a (modeling) container for leaf elements. Typically, leaf elements are reusable things, out of a catalog. When the system is assembled those parts are connected. The <<physical>> container serves as the context where those parts are connected. For example, the ZeusLCS (Figure 38), consists of a VME crate, a backplane, a CPU, IO boards etc. The Block ZeusLCS does not exist as a tangible item in the real world but its parts do. It serves as a container to show how the crate is connected to the CPU, how the CPU is connected to the IO boards, etc.

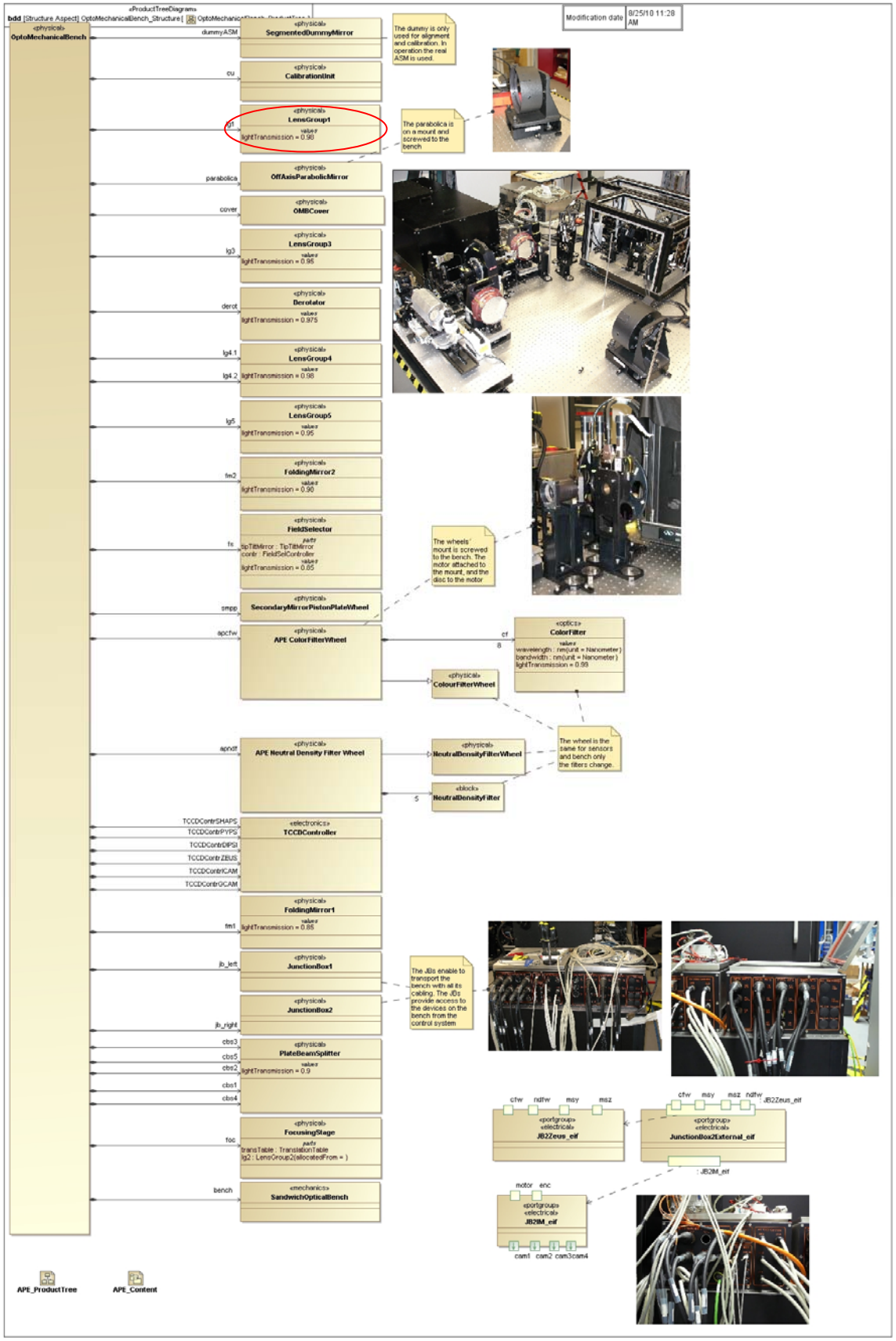


Figure 44 Product Tree of the Opto-mechanical Bench

8.2.3 Where do I put systems which are part of the project and needed in different contexts but not part of the system itself?

It depends what they are used for.

- Are they used for operation? Then they ARE part of the system.
- Are they truly external? Then they appear only in the context diagram.
- Are they specifically built to verify or test the system? Then they go in the Verification Aspect.

In the APE case, a specific Star Simulator was built to simulate stars in the lab. It is called MAPS. MAPS is not part of the operational system but built for the APE experiment. MAPS appears as external in the context variant of the lab.

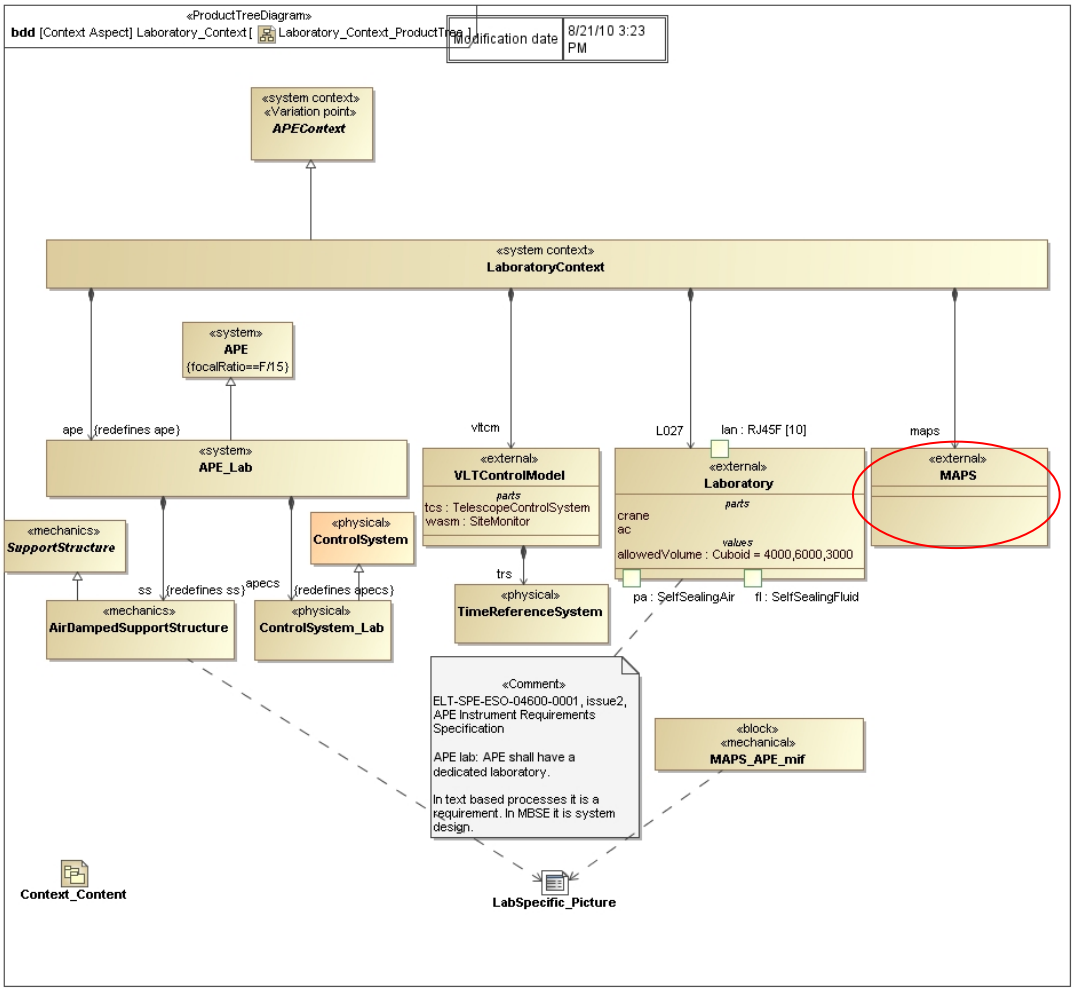


Figure 45 The Product Tree of the Laboratory Context Variant

8.2.4 Usage of <<external>>, <<system>>, <<subsystem>>

Let only your domains (top-level contexts) own the <<external>>s.

A BDD should definitely not mix up <<external>>s like dataflow into an internal system. If anything, the system to be built should be THE <<system>> or a <<subsystem>>, and anything that is a part of it should not be <<external>>. That is a job for a <<system context>> or a domain.

8.3 Structure Relations

8.3.1 What is the relationship between part, property and block?

If A is a block and you drop it on an IBD of block B[7], A does NOT become a property of block B. A is a block; it remains a block. The association implies the creation of a block property of B that is **typed** by block A.[8]

Blocks dropped into an IBD with its frame on become parts properties (of the context block for the IBD) typed by the dropped Block. This is a very useful feature and a natural way of building progressively hierarchical systems.

The fact that a given block is used in another structure is anathema. You can have any number of different contexts for the block of interest. A block is NEVER a part of a structure; a part typed by a block is.

8.4 Structure Properties

8.4.1 Representation of entities flowing in the system

Blocks or value types can be used to represent entities which flow in the system. They are the type of a Pin, an Activity parameter, a Flow Property, or an Atomic Port.

- Use blocks to model structures, like systems or discrete entities (e.g. parcels on a conveyor belt).
- Use value types to define types for quantitative characteristics (e.g. weight, speed, vector). These are typically things on which one has to operate. Value properties are always typed by a value type.
- Model things flowing through the system, like (non-quantifiable) physical entities as <<Item>>; e.g compressed air with pressure, water, light beam, magnetic field, or electric current (Figure 46). <<item>> is a stereotype of block .

[8] Drag and drop of an block on an IBD is conceptually meant, even if it is possible in MagicDraw.

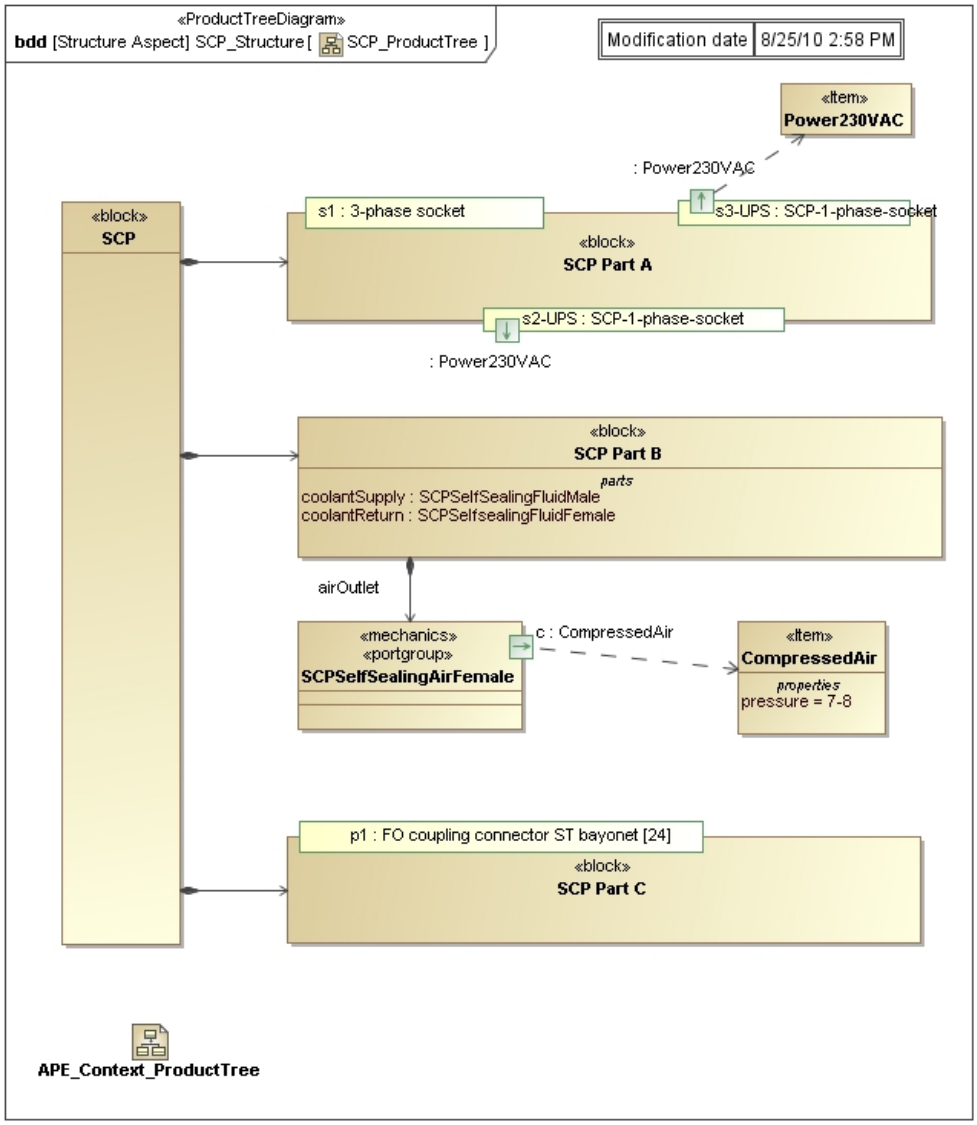


Figure 46 Product Tree of Service Connection Point (SCP)

8.4.2 If I have blocks of the same type (like 10 FPGAs) in the BDD how do I properly use them on the IBD as different properties?

If you define a property with a multiplicity, like an array of FPGA you will not be able to distinguish them in the IBD. They are considered as a single property. This is fine if the system can treat them all the same way.

If you want to treat them differently, e.g. there are different algorithm allocated to each of the FPGA or they have different electrical connections then you need to create for each of them a separate property or association with a role. The same block can serve to type different parts in an IBD. Each can have a different role name on the association end in the BDD.

8.4.3 Usage of public and private

Although SysML does not explicitly define visibility, most implementation do have a visibility tag for properties because they are built on top of UML.

Private means that those elements are only relevant internally to a block. They are not of any concern externally. Public means that everybody has access to them.

In SysML connectors can only cross the parts border and connect to nested parts if the isEncapsulated property of a Block is set to false. For an ICD only features accessible through a port are relevant.

8.5 Reuse of model structural elements

First it is important to realize, that parts are not reused, **just types of parts are reused**, i.e. a <<block>>. A part is the role of a block in a certain context.

If a catalog of re-usable elements (like CPUs, Motors, Cables, IO boards, etc.) is created, those elements are typically read-only and cannot be changed.

Abstract types are used as placeholder for specific building blocks. They are classified in different packages.

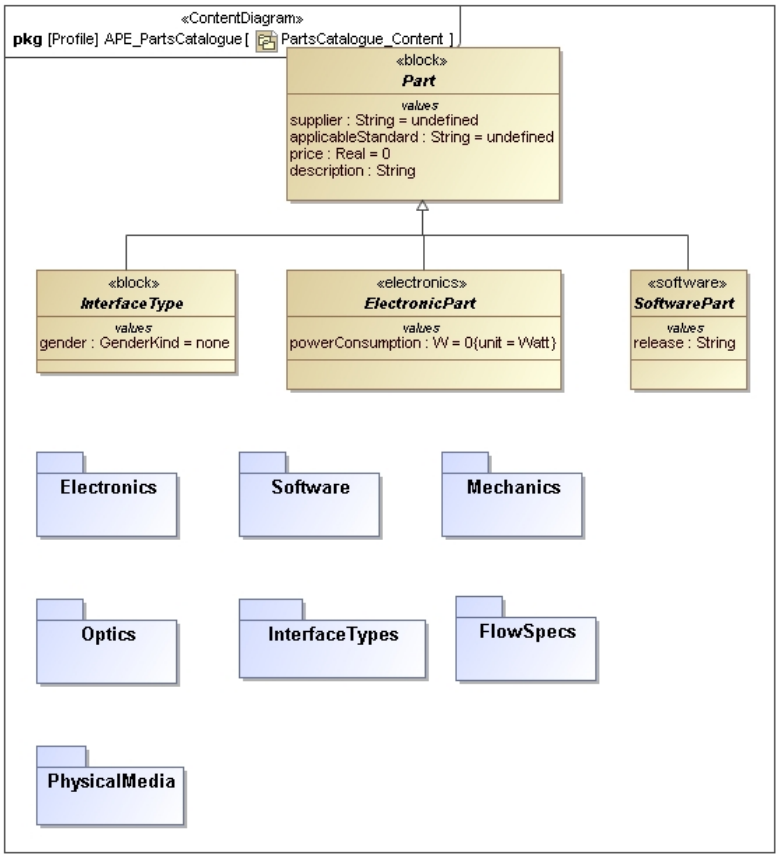


Figure 47 Top Level Organization of Parts Catalog

In order to assemble a system out of those re-usable elements a context or container is required. The product tree of this system is composed of all its (re-usable) elements, its parts. The engineering view (IBD) of this system shows how those parts are connected.

This container is not a real, existing, physical part. It is used to model how the real parts are connected.

For example, if you want to create a new VME computing node you need a VME crate, a CPU, and an IO board. All of them are re-usable elements, better the definition of those elements.

In the real world you would plug the CPU and IO board into the crate in order to assemble it. This does not work in the model. If you create a new part of type CPU within the crate it would change the definition of the crate. All crates would suddenly have a CPU board as a part property.

Therefore, a modeling container is used which is typed <<physical>>.

They are a container for grouping of physical elements and their connectors, for reuse purpose. “Plugging” the CPU into the crate means in modeling term to create a connector between the CPU and the crate in the IBD of the containing block.

Each of these containers contains one or more IBDs for different view (electrical, information, mechanical, optical).

The real physical elements are stereotyped <<mechanics>>, <<optics>>, <<electronics>>, <<software>>.

The following example shows a technical CCD (TCCD) system which consists of a PMC board which is mounted on a VME CPU board, a TCCD Controller box, a TCCD head, cables, and a higher level control system.

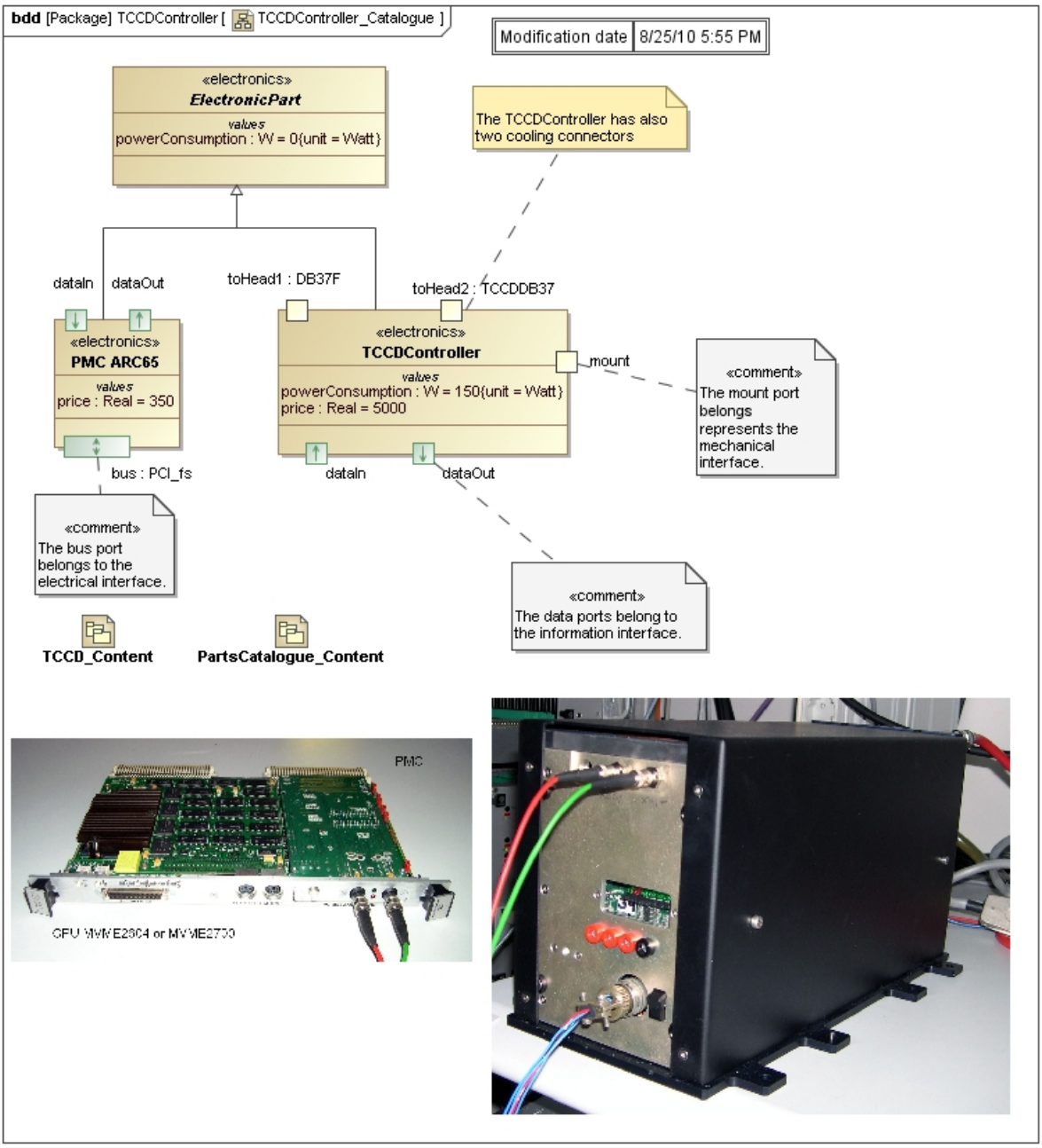


Figure 48 Catalog Definition of TCCD equipment

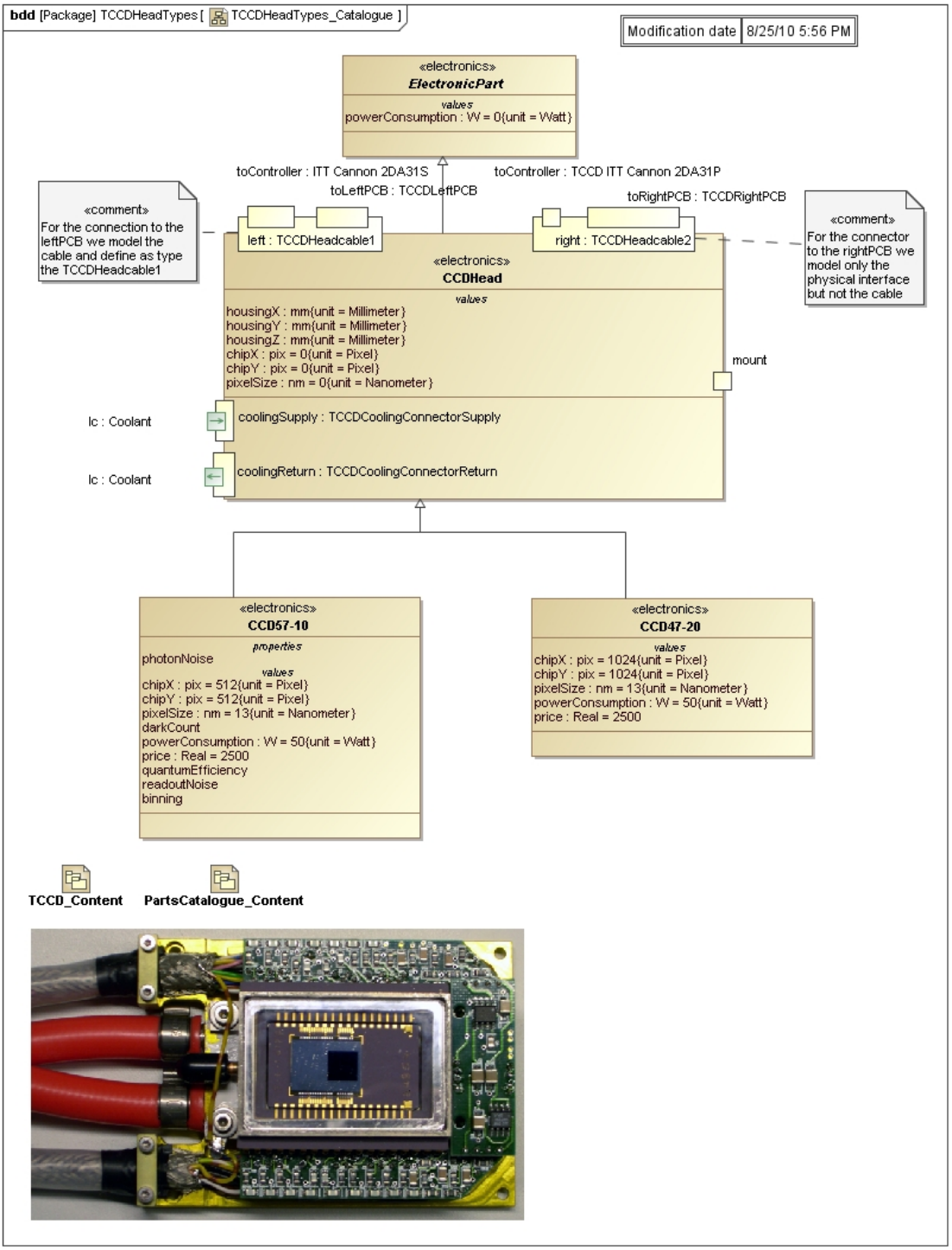


Figure 49 Catalog Definition of TCCD heads

The electronic cables are soldered to the PCB of the TCCD head. They have a plug at their end which is connected to intermediate cables, which are in turn connected to the TCCD controller.

The cables soldered to the PCB are modeled as ports of the CCDhead, typed by a block which represents the soldered cable and its plugs going to the controller.

The intermediate cables are modeled once as a simple block and once as an association block.

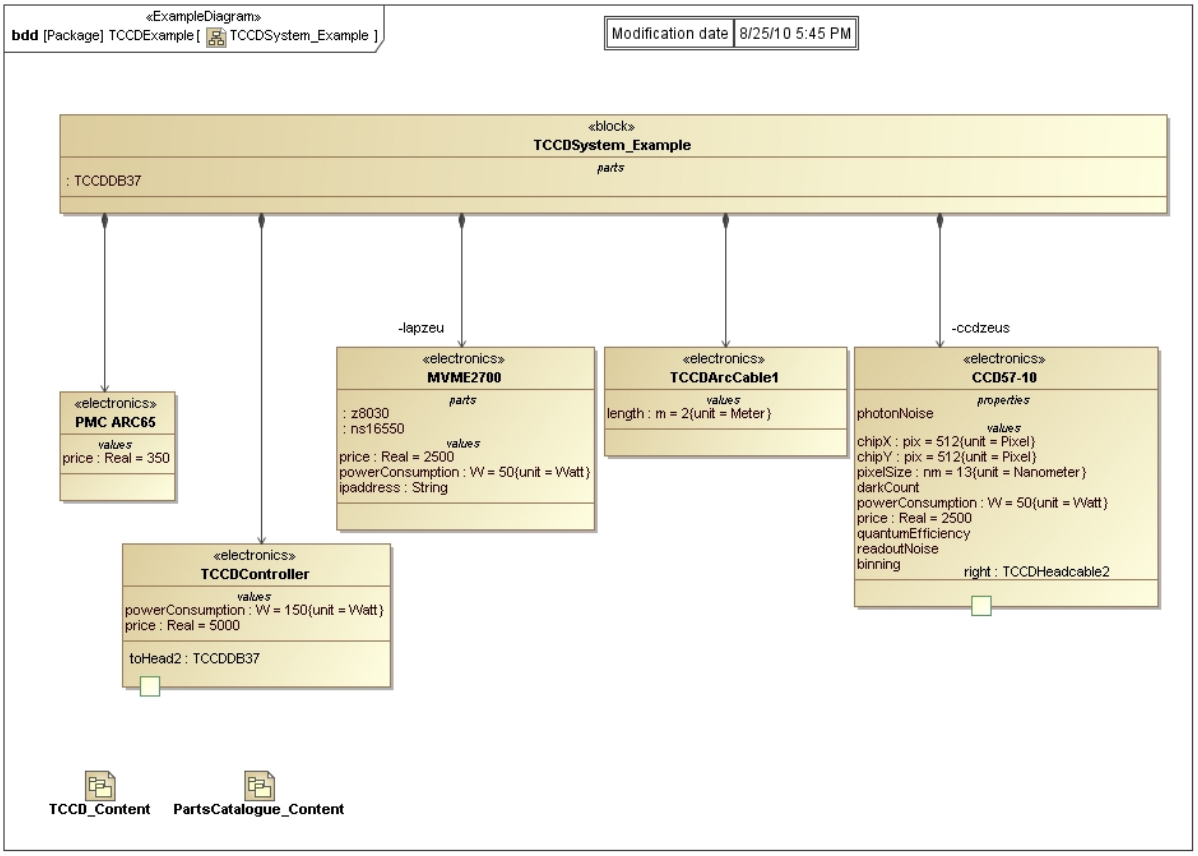


Figure 50 The Product Tree of the Example System

Cables can be modeled as simple Connectors, as Blocks, or as Association blocks, as shown in Figure 51.

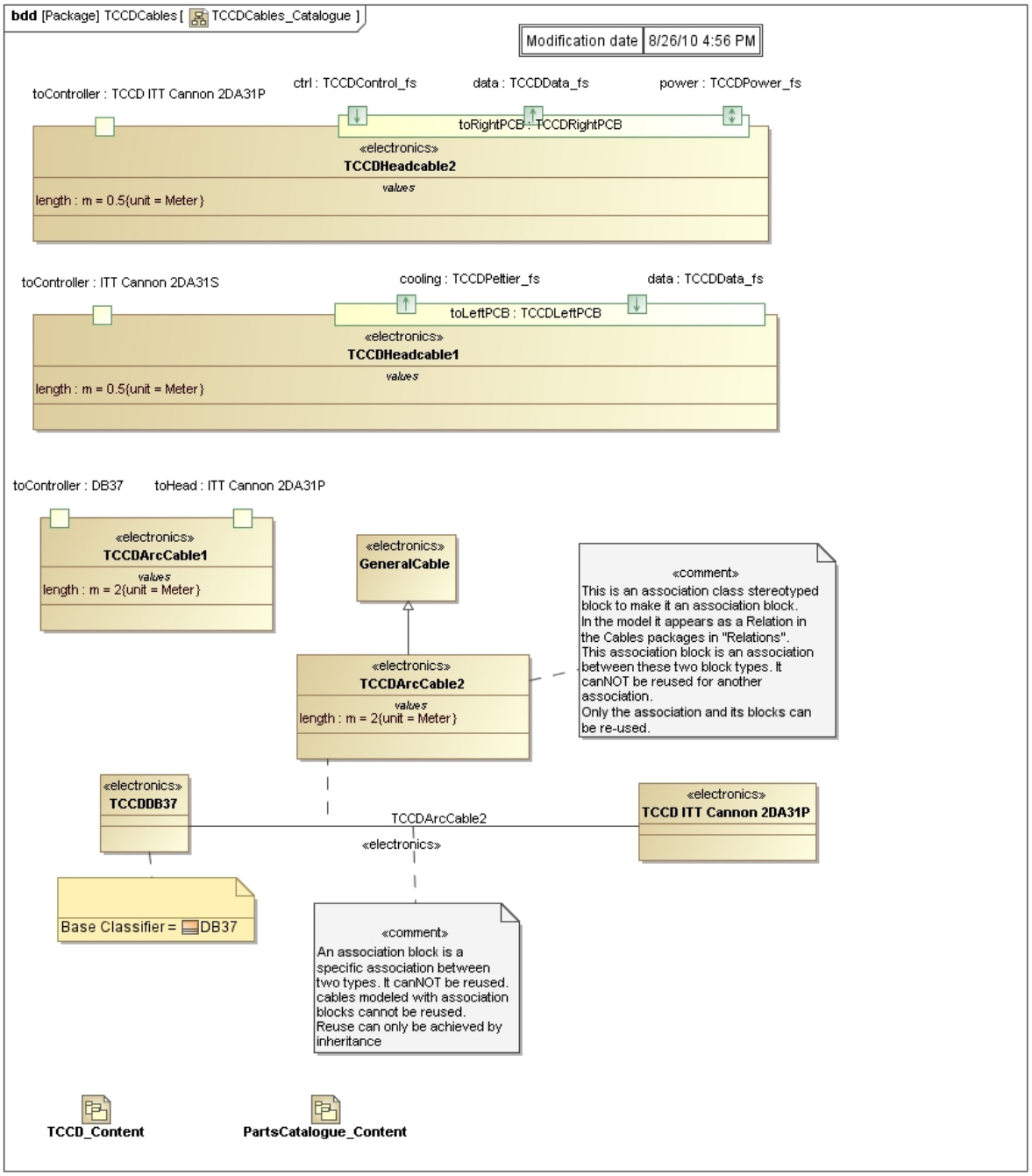


Figure 51 Models of Cables

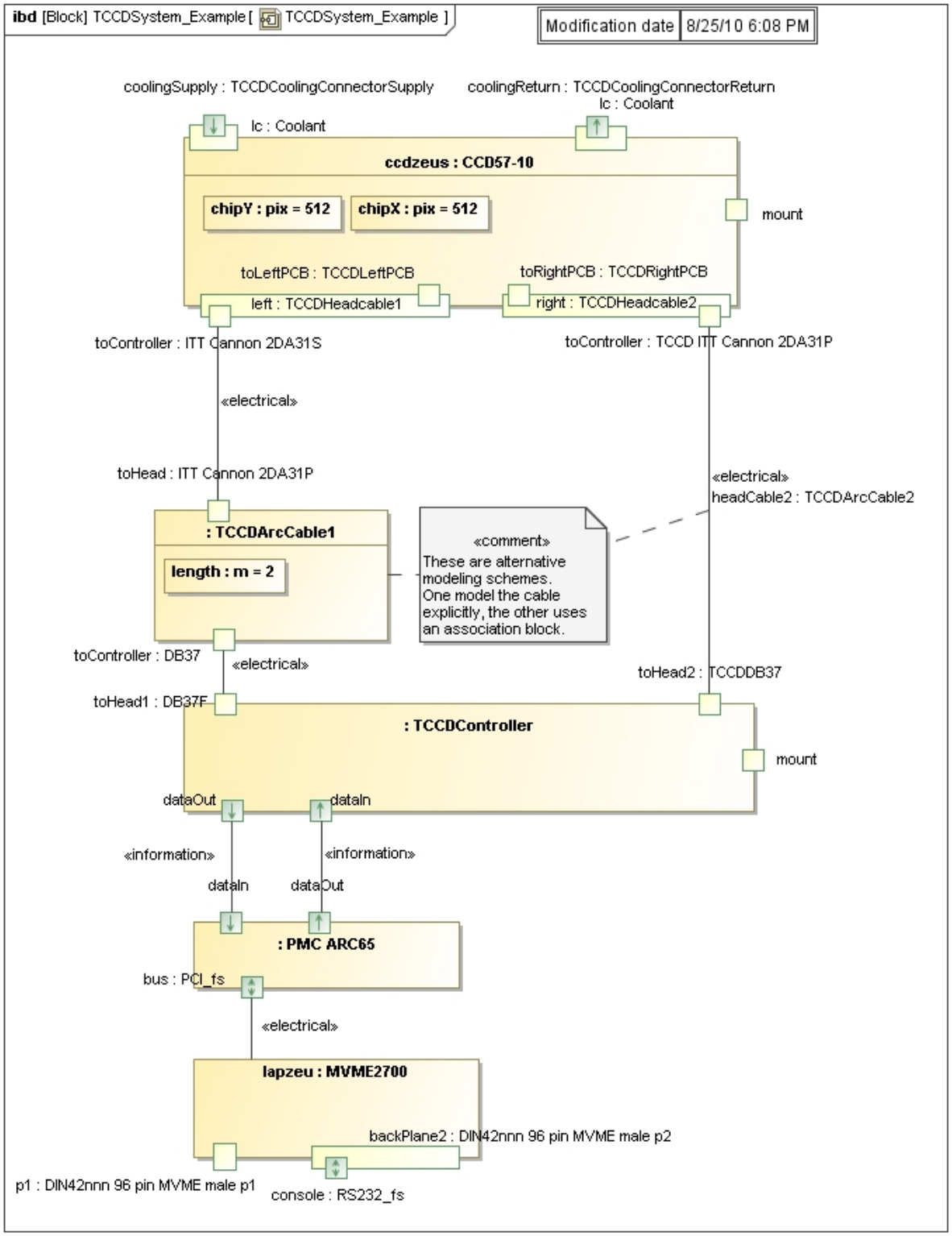


Figure 52 Assembling the parts to a system

8.5.1 Shared parts

Create a package, stereotyped <<modeling library>> for a standard parts catalogue (like motors, CPUs, etc.) to have them separate from the real project model.

Add attributes (as value properties) to further specify a part.

- references to standards, gender for sockets (male, female - with enum type), supplier id become value properties and are not defined through inheritance
- add an attribute (as a placeholder) for a rule on how to connect InterfaceTypes. e.g. only male and female of same type can be connected. This could be interpreted and verified by an engine.

In subtypes you can override properties e.g. we want to have the gender of a connector or a standard as value properties but we need different or extended standards in sub-types. In addition we need different gender of the same connector in IBDs (when taking something from a catalogue).

- use "redefine property"
  to override property default values by creating a property in the sub-type of the same name as the super-type and setting its property redefinesProperty. This is used in BDDs to create application specific types.
- use context-specific values to set values for certain attributes in IBDs.

8.6 Modeling Physical Aspects

8.6.1 Modeling physical distance between parts

Actuators and sensors might be geographically significantly apart which impacts the rest of the design. For example, the choice of network technology is driven by the physical distance.

Those locations usually come from some CAD model (the mechanical design), but they constrain the choice of technology to connect actuator and sensor, e.g. choosing GigaBit Ethernet over a serial line.

For example a <<mechanical>> connector shall have a length property.

8.6.2 Model of a magnetic field which exists between two physical entities

Since the magnetic field will have some properties, the simplest is to model the field itself.

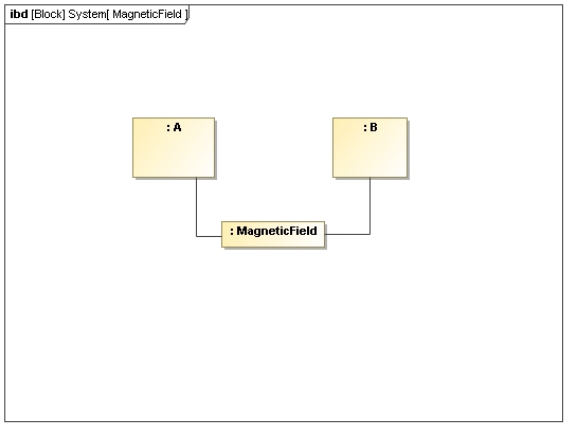


Figure 53 Model of a magnetic field

9 Interface modeling

Interfaces of all kinds are a major architectural element at system level. The goal of this chapter is to show which SysML elements are available and how they can be used to model interfaces in abstract terms and in terms of an engineering discipline as mechanical, electrical, optical, or software.

The elements available to model interfaces are:

- Ports (Standard UML Ports, Flow Ports)
- Service Interfaces (UML Interface)
- Blocks

The following chapters present different use cases for interface modeling, their goals, solutions, and problems.

9.1 Port and Flow Basics

Two types of Ports exist:

- Standard Port (aka Service Port)
- Flow Port

9.1.1 Standard Ports

A standard port is equivalent to a service port where different kinds of services are offered with defined operations and parameters, or signals.

It originates from IT/SW usage. The interfaces are defined in a BDD. Standard ports can be perceived like a service port, with provided/required interfaces (services with operations), like defined in UML 2. They correspond to some programming model, like IDL or a class interface. They describe the logical level of communication.

They are mainly used for command and control systems, and/or client/server situations. The interfaces (lollipops) specify the services that they provide/require. This clearly identifies the relationship between the parts/blocks as active and resulting in control, rather than simple data transfer. Typing directly an interface gives you only a limited form of service orientation.

It is useful as long as: you only need to use a block/class as a contract with ports, not specify the implementation (you can however delegate from a port typed by an Interface to an internal part)

Standard ports can be typed by a block, an interface, a data or value type. If a standard port realizes an interface, it must be typed by a block, which realizes the interfaces. This offers more flexibility than directly typing with an interface because you can transparently add another interface.

An interface can have a State Machine Protocol associated with it to define the method call protocol.

Having the port typed directly by an interface is only useful if you only need the port to be typed by one interface (you can't do multiple provide/require without a Block/Class type).

To promote reuse of your blocks you should:

- Define the ports and their required/provided interfaces in a BDD first, FOR EACH AND EVERY BLOCK, completely independent of any reuse context. That is a good place to document the block (alone) with comments, as well as document any interfaces specific to that block. Show operations/attributes etc. for that block.

- For a given higher level system using the defined blocks as parts with ports, "plan" your connections first in a matching BDD, ensuring that the ports to be connected do provide and require the correct interfaces. Use "display paths" to ensure that each interface is required and provided. DO NOT use associations yet to create the compositions for the top context block.

9.1.2 Flow Ports

A Flow Port specifies the input and output items that may flow between a block and its environment. Flow ports are interaction points through which data, material or energy (like current, oil, water, liquid) "CAN" enter or leave the owning block. Material, information, signals, even rats, can concurrently and bi-directionally flow between Flow Ports.

Flow ports model a continuous flow of an item.

It cannot only be of physical characteristic but also data, in case one wants to model a continuous data flow like in high performance computing. Input and output of data: a block performing a calculation may have an input and output flow port representing the input given to the calculation and the output results. Service port with getters and setters do not represent input and output - they represent provided and required services (operations). Examples are data processed with FPGAs or image processing pipelines where recipes to reduce images are used

A flow port is NOT a property of a block; therefore it cannot represent a part of a block. It always needs to be related to a part property, which uses the things that flow over the port. Distinction is made between atomic flow port and non-atomic flow ports:

Atomic flow ports relay a single usage of a block, value-type, data-type or signal. Atomic flows are one-way only where some item flows. Example: a pump may have an “in” flow port where it pumps the water into the pump and “out” flow port where the pump ejects the water out.

A non-atomic flow port relays items of several types as specified by a flow specification. Flow ports have a direction: in, out and in-out. A flow specification consists of flow properties, which are typed. Flow properties also have a direction: in, out and in-out. The direction of the flow port and its specification must be consistent. Examples are serial lines, USB, CAN-bus, Ethernet.

The distinction is made according to the flow port's type.

A flow specification with a single flow property is equivalent to an atomic flow port. The atomic flow port is a simple short-hand. It does not mean that the type of the atomic flow port flows over the port.

A non-atomic flow port can be conjugated. If it is, then all directions of the flow properties specified by the flow specification that types the flow port are relayed in the opposite direction (i.e., in flow property is treated as an out flow property by the flow port and vice-versa).

If a structured flow port is connected to another port and the ports are on the same level, one port must be conjugated where the in become out and the out become in, like the famous 2 and 3 pins of a serial line - you need a null modem.

Atomic flow ports can by definition never have a flow specification and therefore are never conjugated. If a structured flow port of a block is used in an IBD (delegation) and connected to a port of a block property the direction must be the same and not conjugated. The item flow gives the exact detail of WHAT is flowing between two ports. For example the port defines that liquid flows, whereas the item flow specifies that oil flows. Like that you can reuse the same block and ports and connect them with different connectors depending on the context. An item flow is itself again a normal block or value type with all its features like properties, operations and constraints.

9.1.3 Data flows

Data structures are created on a BDD using value types to both create message hierarchies and to then type the flow port on the IBD. Usually, this takes the form of an inheritance hierarchy with the highest level Value Type in the hierarchy typing the port. Modeling in this way means you can easily add new messages and you do not have to change any flow specification when a new message is added. This is particularly useful when modeling a system at the level of neediness and where the item flows model the information exchanges. These ports can later be allocated to the communications ports typed as Ethernet, RS-232, etc.

9.1.3.1 Sensor/actuator data

In monitor and control the system, we need to look at additional characteristics of the system, for example temperature, flow rate and so on. The systems engineer can then type this information as SI Value Types to communicate with both the software and hardware engineers, also specifying the level of precision that is needed for the telemetry used to measure the system. The telemetry can then be specified as analog, digital, pulse counters and so on, and the appropriate telemetry can be acquired that meets the job.

9.1.3.2 Input and output of events

An occurrence can be transmitted from an (out) flow port to another (in) flow port of another block. This is completely equivalent description to standard port with an interface having an event reception where one port has this interface as required and the other has this interface as provided. However using flow ports for this purpose instead of standard ports might be more intuitive since it is not relying on the complexity of standard ports, required\provided interfaces and event receptions.

Ports can be connected directly with a Connector if you do not need to specify constraints, attributes, etc. You still can use a stereotype qualify the type of connector, like mechanical, optical, etc.

If you need to describe more properties of the connection use another block to define them. For example a cluster of computers connected to the same Ethernet subnet, devices connected to a CAN-bus or a sewer where several sinks are connected require to model the medium as block where you connect. One also needs to be aware for example, of whether the different parts will be reused. Take the valve for example; typing the ports on the valve by residue or H2O means that only one type can flow through them. Creating an inheritance hierarchy of fluid, sub-typed by H2O and residue, and typing the ports by fluid means the either H2O or residue can flow through them.

9.1.4 What’s the relation port and standard UML interface?

A port can realize different interfaces. It combines several interfaces; e.g. If the port is Ethernet it represents the sum of all its protocols. E.g. it realizes UDP, TCP, etc.

9.2 Combining ports and flows to represent interfaces

9.2.1 Modeling a structural interface like a socket, screw, hole etc.

Use a standard port typed by a block that specifies the structure. We do not need yet necessarily another part property "inside" the system. The structural information is contained in the interface description. The practical advantage is that we do not need to open the box to know the structural properties.

See Figure 24 Electrical IBD of the Observatory Context

9.2.2 Modeling standards like RS232, CAN bus etc

You have several parts in the model:

- The (mechanical) interface type, like DB-25, DB-9
- The electrical signals, like Receive(tr), Transmit(tx) and Ground(gr)
- The hand-shaking, error detection protocol, etc.
- The cable
- The data which flows

Depending on the required level of detail there exist different options:

9.2.2.1 Model "everything"

- Model the mechanical connector with a block, named DB-25, DB-9
- Model the electrical signals with a flow specification, where each signal is represented by a flow property.
  Where the meaning of the flow specification is in the sense that anything that supports this interface can flow through this port.
- Create a flow port as part of your DB-25 block. This actually represents the assignment of the mechanics to signals, which may differ from one supplier to another. You need to create an application specific sub-type of your DB-25 to do the assignment. Or, you create another special interface block which owns a standard port typed by DB-25 and a flow port typed by RS-232. In any case, stereotype the interface block as <<portgroup>>.
- The actual interface driver is a component within the receiving block. If it was a computer, for example, there would be an RS-232 port on the computer which would connect to an internal part that is an RS-232 interface driver with its respective ports on it. Its ports may include the individual pins or still be abstracted as a single port. You specify what flows by the physical interface specification.
  Its behavior, e.g. the handshaking, is modeled by a state machine attached to the part property which uses the flow port.
- In the simplest version is using a connector.
- The data (or any other flowing entity) is represented by item flows. The item flows are of type value.

9.2.2.2 Modeling ONLY A FLOW of entities.

- Represent the data with flow specifications (if you have more than one property) or a value type (semantically equivalent to a flow spec with one flow property) and type the flow port with the flow spec. For example, if you want to define the packages which flow over a CANbus

See Figure 49 Catalog Definition of TCCD heads， Figure 24 Electrical IBD of the Observatory Context

9.2.3 How do I model a cable?

The cable can be modeled in various ways, depending on the detail you need:

- a simple connector
- a block if you are interested in the properties of the cable and you want to re-use it. N.B. That the cable can also have ports to represent plugs and sockets.
- an association block
  in this case you can type the connector with the association block and you get a very compact representation in the IBD.
  NOTE: it must be an association between types, e.g. the types of the ports you want to

connect. The re-usable element consists of the two types and their association - NOT the block itself.

See Figure 51 Models of Cables.

9.2.4 Combining physical connector type and flow

In APE there are a so-called Junction Boxes (JB1 and JB2) which connects the Control System Electronics to the Field Electronics. The Junction box has two interface plates. One where the cables coming from the control system are connected (the “external” interface plate) and one where the cables to the actuators on the opto-mechanical bench are connected (the internal interface plate).

Each interface plate has a group of plugs for each subsystem located on the bench, e.g. ZEUS, DIPSI, IM.

The two interface plates are modeled as nested ports and each group belonging to a subsystem is again modeled as nested port. In this case we have a double nested port as shown in Figure 54.

The Interfaces are represented by standard ports, typed by a block which is stereotyped <<portgroup>>. It serves as the specification of the port and groups together several interfaces. The Block can itself have ports and therefore several levels of nesting can be achieved.

<<portgroup>> itself is generic. There are different stereotypes to be specific about the kind of interface:

- <<eportgroup>> … electrical interfaces
- <<oportgroup>> … optical interfaces
- <<mportgroup>> .,. mechanical interfaces
- <<pportgroup>> … protocol interfaces
- <<iportgroup>> … information interfaces

The aim of grouping the interfaces is to define physical connector and flow at border of part and hide internals of a block. The main benefit is that a single type is needed to define physical connector and flow and that the interface type can be re-used. Traditionally, several unrelated ports are needed.

Different flows over a connector (e.g. pin assignment) can only be assigned via specialization of the block which types the port

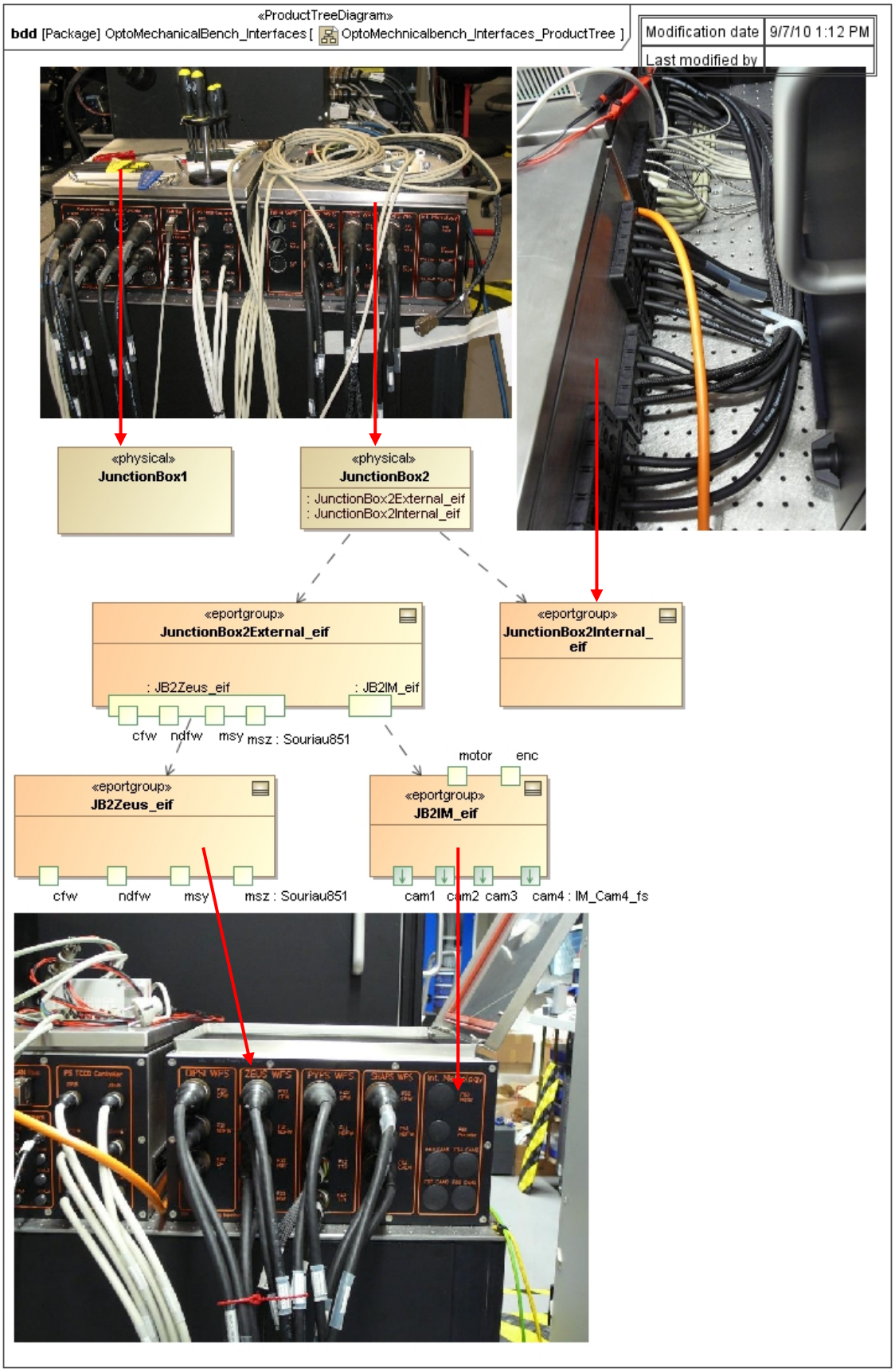


Figure 54 Grouped Interfaces of Junction Box 2

The Junction Box has an internal wiring which connects the interface plates plugs, which is shown in Figure 55. The connection between Control System, Junction Box, and Subsystem are shown in Figure 40.

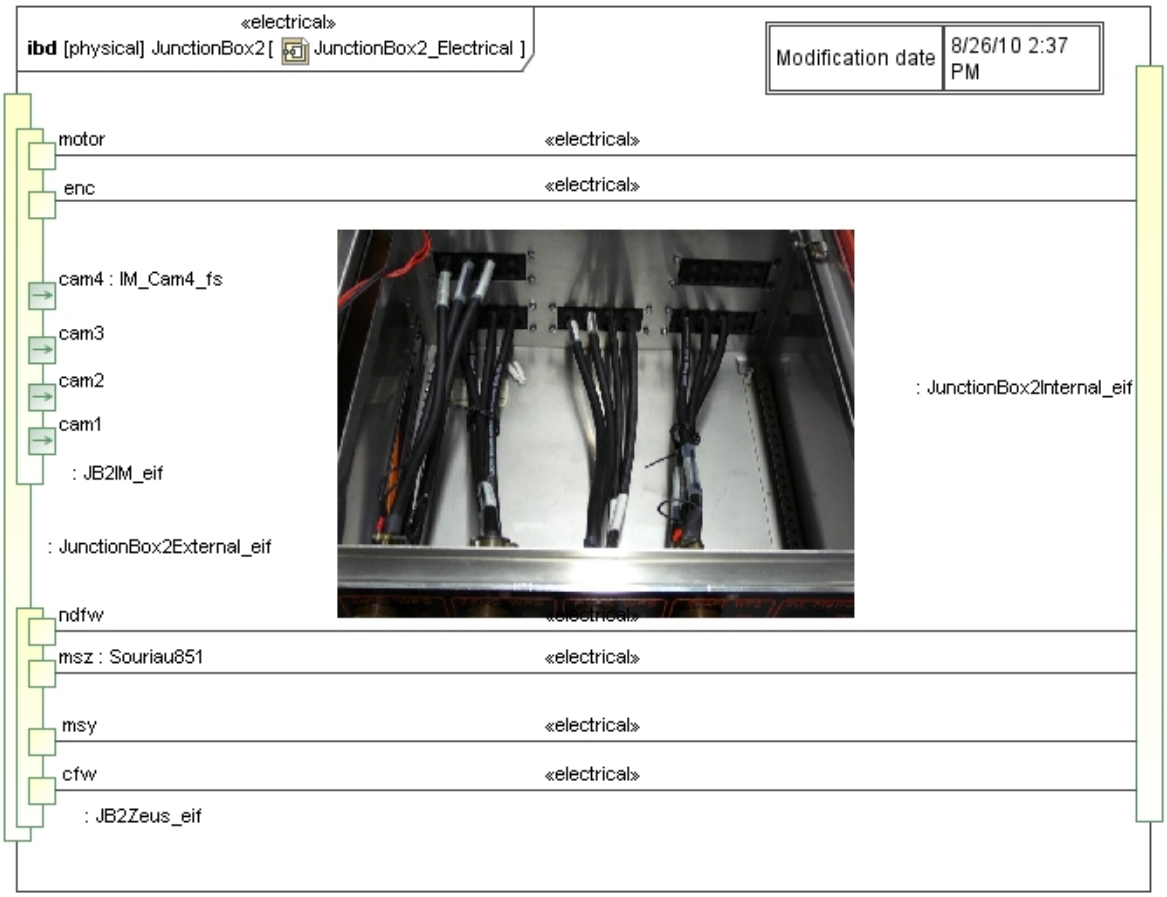


Figure 55 Internal wiring of Junction Box 2

APE uses special technical CCD heads which provide and require different interfaces. The head needs to be cooled; therefore there are interfaces to integrate it into a cooling circuit (coolingSupply, coolingReturn). The type TCCDCoolingConnectorSupply is a block, and owns a flow port lc, typed by an <<Item>> Coolant. The type TCCDCoolingConnectorSupply inherits from block "SelfSealingFluidFemale" which is a standard catalog connector for fluids. By specializing, the specific flow port for the Coolant can be added and allows combined modeling of physical structure and flowing items (Figure 56, Figure 57).

An alternative is shown for the coolingReturn interface, where a <<portgroup>> is used. The <<portgroup>> owns a flow port and a standard port for the Coolant and the physical connector. <<allocation>> is used to indicate over which physical connector the Coolant flows.

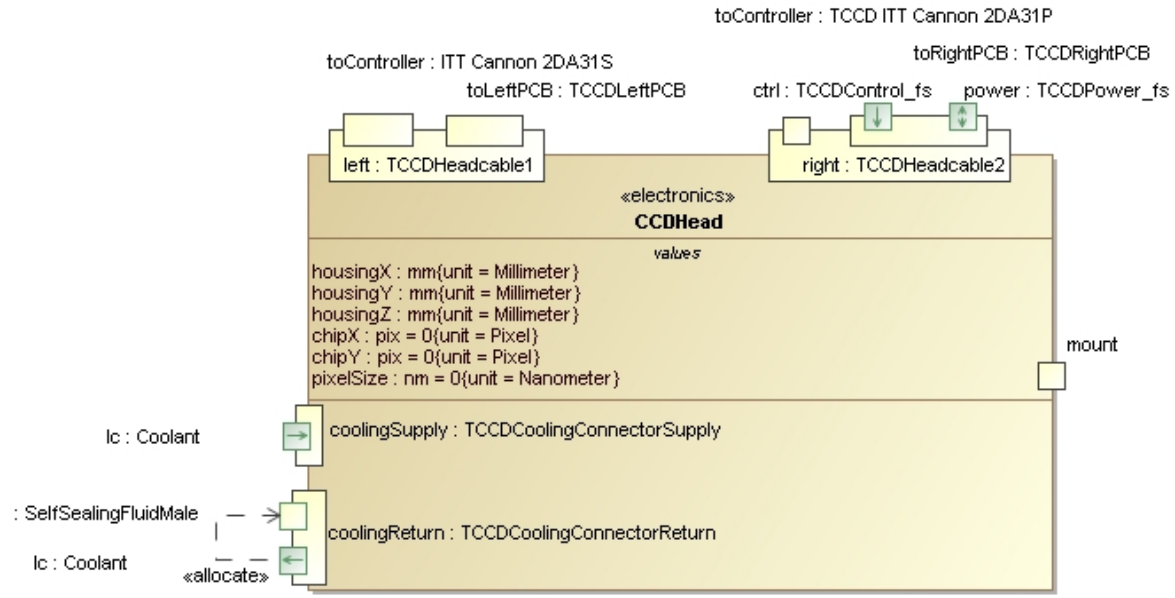


Figure 56 Interfaces of TCCD head

This example shows a CCD Head where the cables are directly soldered on the PCB. Using nested ports gives a compact representation of the block and its interfaces, which can be easily re-used.

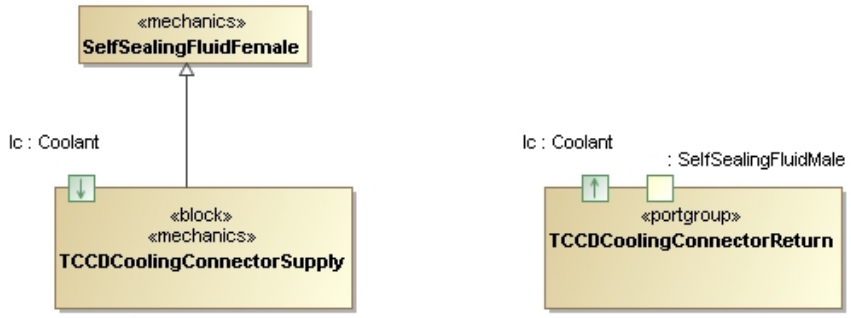


Figure 57 Definition of TCCD interface

9.3 Layered Command and Data Interfaces

9.3.1 Example

The Local Control System of the Active Segmented Mirror provides and requires command and data interfaces which run over different LAN interfaces, and use different protocols.

9.3.2 Context

Different information interfaces can use different physical interfaces, e.g. data on different LAN port, using different protocols, e.g. CORBA. Allocation of structural elements across multiple abstraction layers is needed.

9.3.3 Problem

Traditional SysML modeling way would use several unrelated flow and standard ports which make re-use more difficult and creates cluttered structures.

9.3.4 Solution

Define Command and Data interfaces in one Block which enables grouping of interfaces which have a high coupling, re-use, extendibility, and consistency.

- Aggregated information, electrical, and protocol specifications for ports
- <<Allocate>> information ports to physical ports and protocol ports
- Profile with stereotypes for interfaces types
- Special port types for better readability (cluttered diagram by stereotypes)

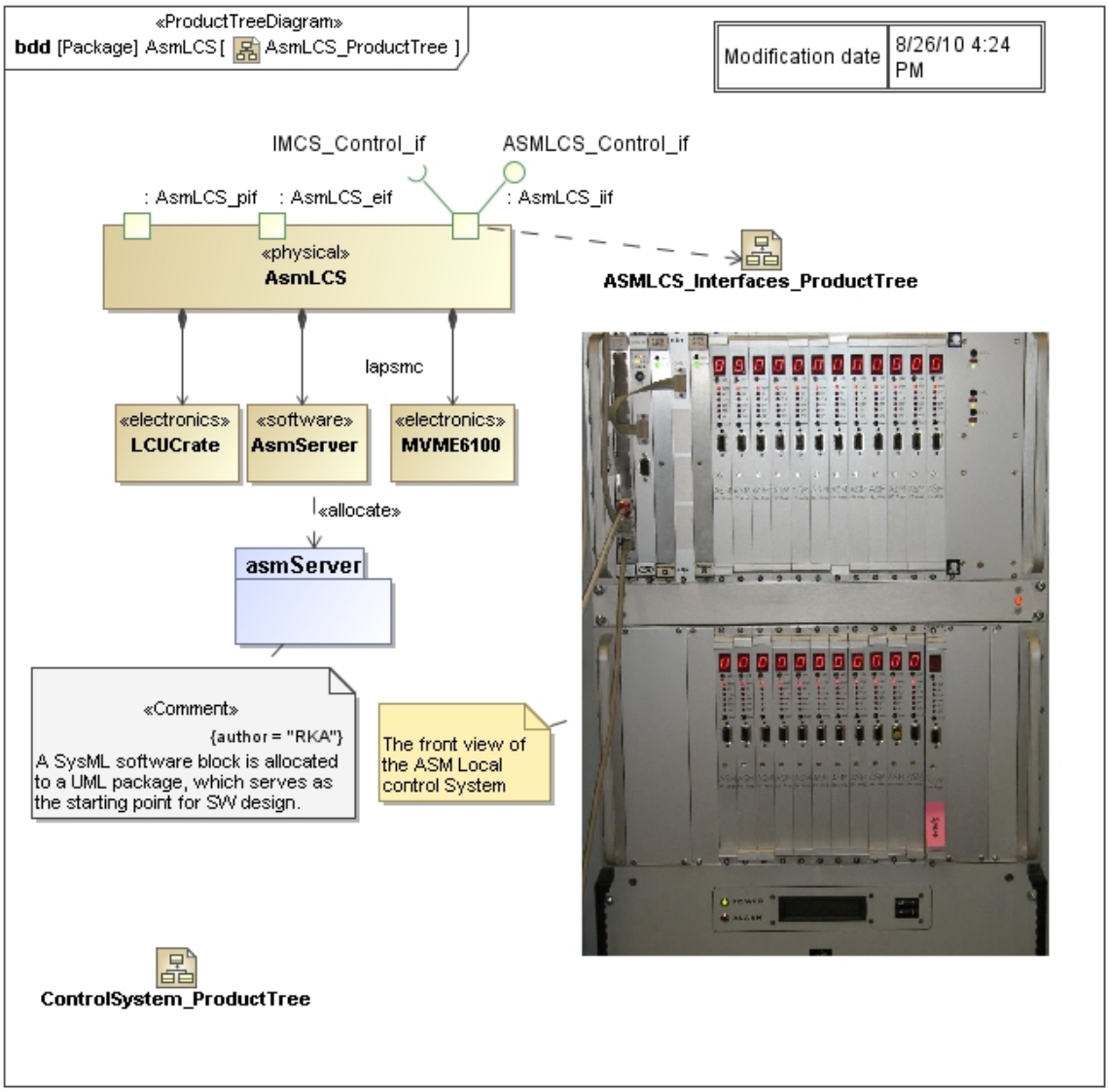


Figure 58 Product Tree of ASM Local Control System

Figure 58 shows the data and command interface. It is specified by an <<information>> <<portgroup>> which <<uses>> and <<realizes>> standard UML interfaces. The Data interface is modeled with a flow port which is typed by a <<ValueType>>, representing the data which flows.

The required command interface and the data interface run over a TCP/IP protocol and a Ethernet 100 base T network. The provided command interface runs over a proprietary protocol which is based on TCP/IP, and another LAN port.

Add ports for protocols or use properties.

Defining a property of the logical interface defines the protocol for the whole interface. This is not what we intend here. The proper way is to add protocol ports for each protocol (a DDS port, a CORBA port). The logical ports are then allocated to both, the protocol ports AND the physical ports. Multiple allocation is possible. Which protocol is used on which port, can be derived from the two allocations. The implementer of the control system and/or control software has to take care of the proper allocation.

Since the diagram gets cluttered, not all allocations should appear in the diagram but a dependency matrix should be created.

Why not define the protocol stack by tags, like in WSDL?

Before a value can be assigned to a tag the port would have to stereotyped. The properties of the stereotype become the tags. There is a stereotype <<protocol>>.

However:

- you need more clicks
- you cannot create a dependency matrix which shows the allocation
- you could not show it in the diagram because there would be too many stereotypes. Would be useful only in a document generator.
- which port should get the tag? the logical? the physical? We would lose a clear separation.

Allocation constraints can be defined to constraint the supplier and client of the allocation relationship

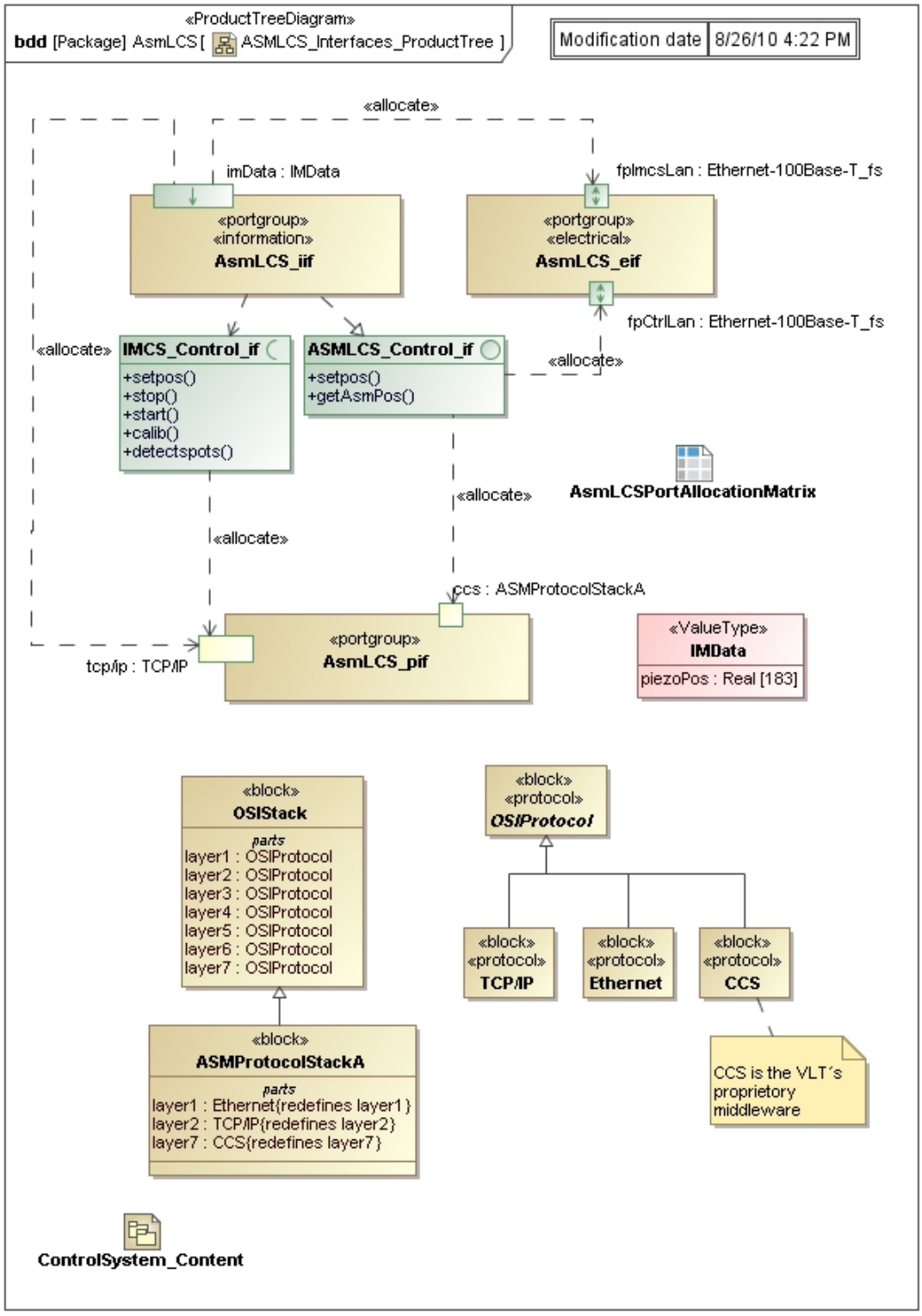


Figure 59 Command and Data Interface of ASM LCS

The Protocol Stack is modeled according to the ISO/OSI stack model.

The allocation matrix shows how the command and data interfaces are allocated to protocols and LAN ports.

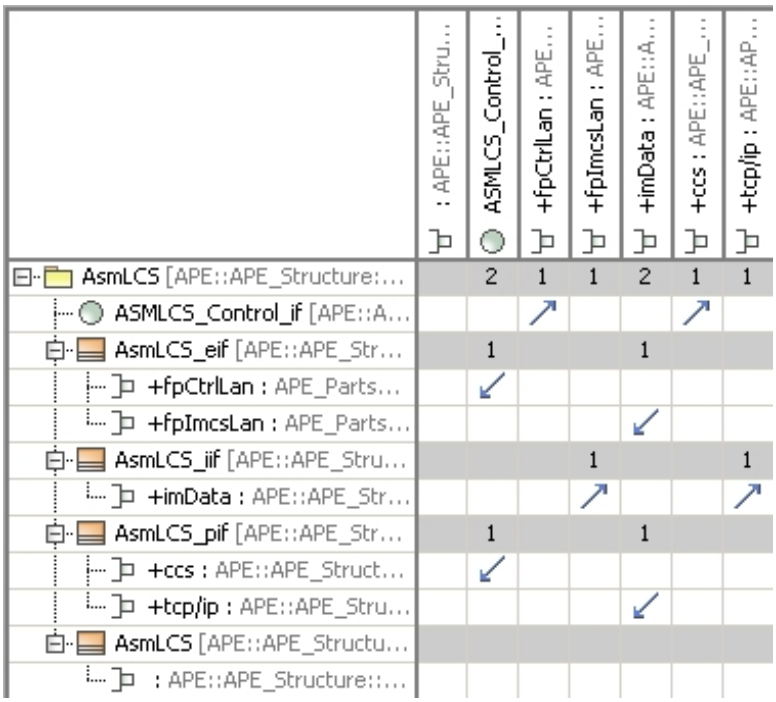


Figure 60 Port Allocation matrix

The <<software>> block AsmServer provides/requires the information interface and the IBD shows how it is connected. It could be different software blocks for each information interface.

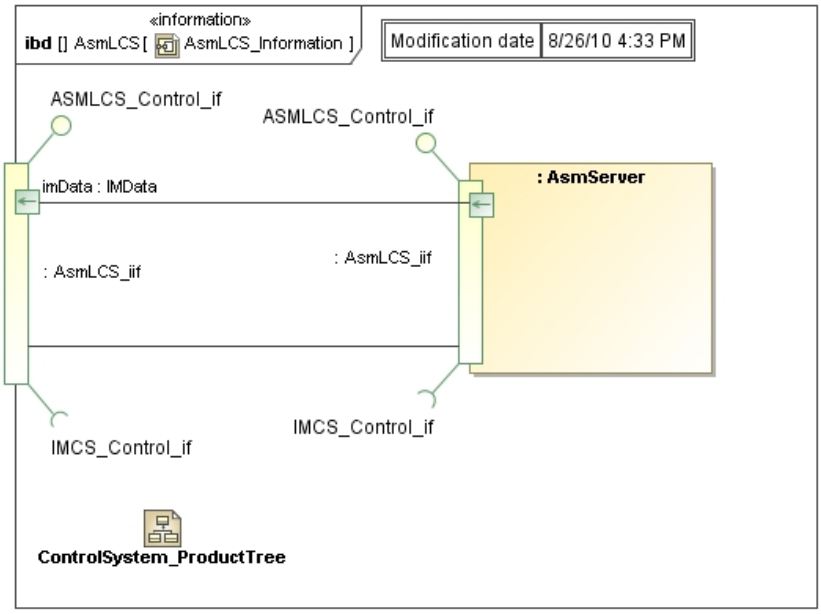


Figure 61 LCS internal information interface connection to Software Block AsmServer

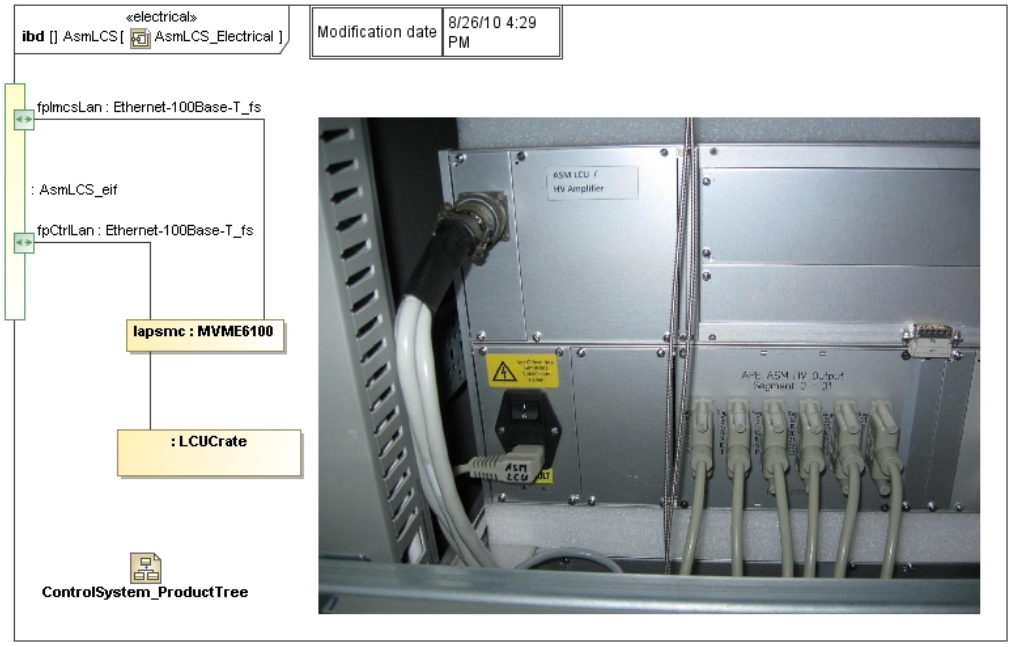


Figure 62 Internal electrical view of ASM LCS

9.3.5 SysML status

There are no plans to support discipline specific interfaces types. That would be contradictory to the unified approach of SysML. It is a task for the stereotypes mechanism.

Allocation is a stereotype of UML abstraction and the semantics (i.e. the exact mapping) of allocate are not defined in SysML. The mapping is to be defined. For practical reasons use a Note.

9.3.6 Allocation of a nested block

Allocation is a stereotype of UML abstraction and the semantics (i.e. the exact mapping) of allocate are not defined in SysML. Therefore allocation of the top most port does not necessarily mean that all nested ports are also allocated.

This makes it possible to allocate d1, d2 to lan1, lan2 and the port which realizes the control commands to yet another physical port. The interface itself cannot be allocated because it might be realized by different ports.

9.4 Flow Properties vs. Flow Ports

9.4.1 Example

A video camera provides analog and digital video streams which are models as flow ports.

9.4.2 Context

The flows which are the visible interface of a block (the camera) are delegated to nested flows, internal to block.

9.4.3 Problem

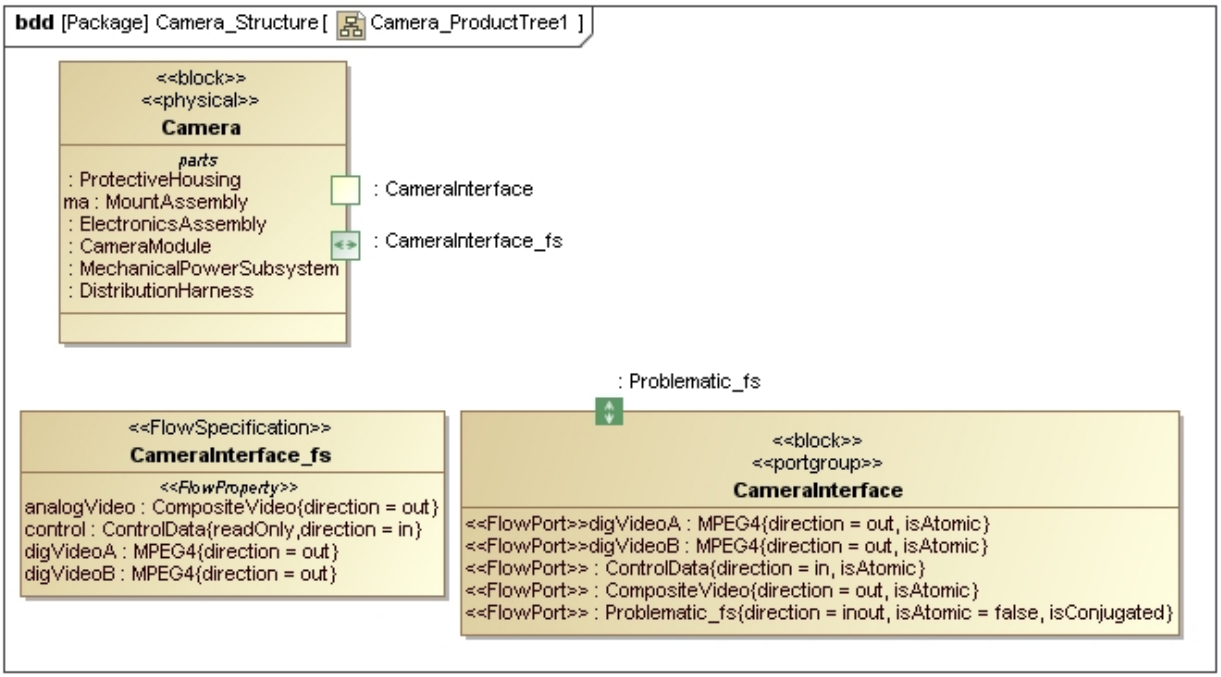


Figure 63 Definition Block and its Interfaces

When connecting the ports to the internal ports the flow port typed by the flow specification has some disadvantages. Its flow properties are not visible, therefore it is unknown how the flow properties digVideoA and digVideoB are connected to the internal ports a and b.

Flow specs the diagram doesn't tell you what's inside the port on the diagram.

9.4.4 Solution

Using a nested port with nested flow ports (which correspond one to one to the flow properties of the flow spec), the individual ports can be connected.

The example describes a camera block with two interfaces. One modeled with a flow port which is typed by the flow specification. Another is modeled with a <<portgroup>>, using nested ports.

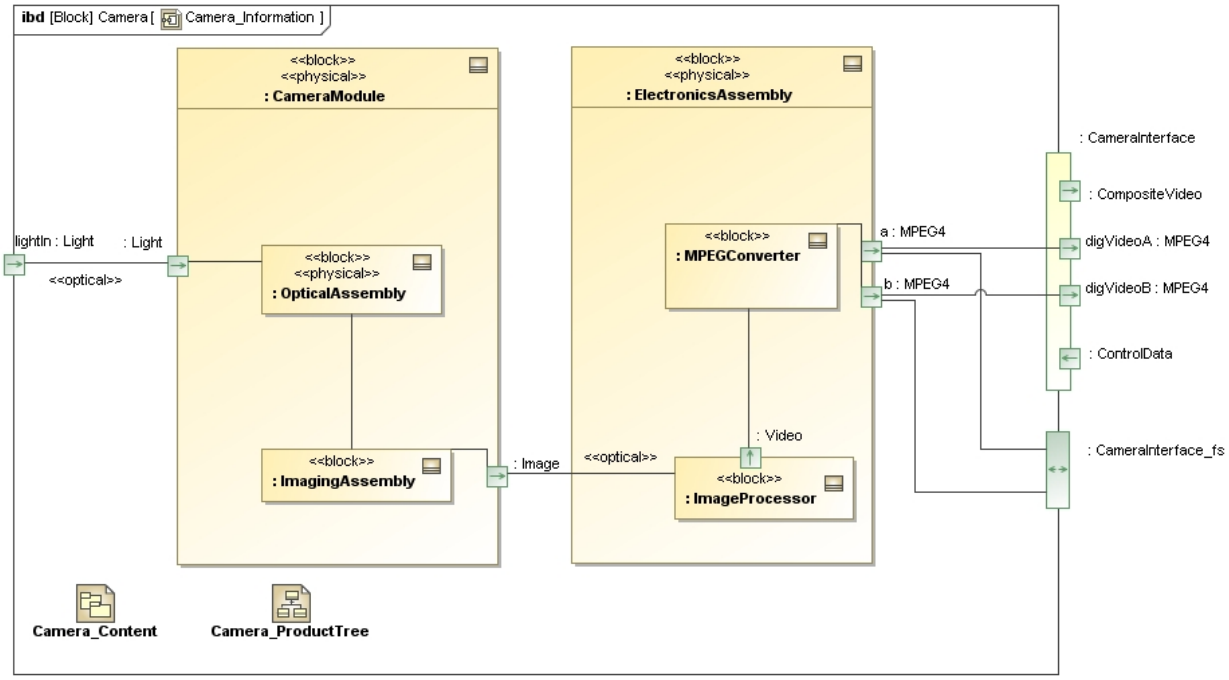


Figure 64 Internal Block Diagram of the Camera Block

9.5 Modeling interfaces which are represented by a document (e.g. ICD - Interface Control Document)

If an interface is already specified in an ICD document it makes no sense to complete model it again, but reference it..

The documents are represented by value types, stereotyped <<icd>>. They are value types because they represent a uniform type of information. Its name is the document number or title.

The connector between them is stereotyped <<icd>>. Depending on the level of detail you require you can simply use ICDs or model parts of it using ports and flows.

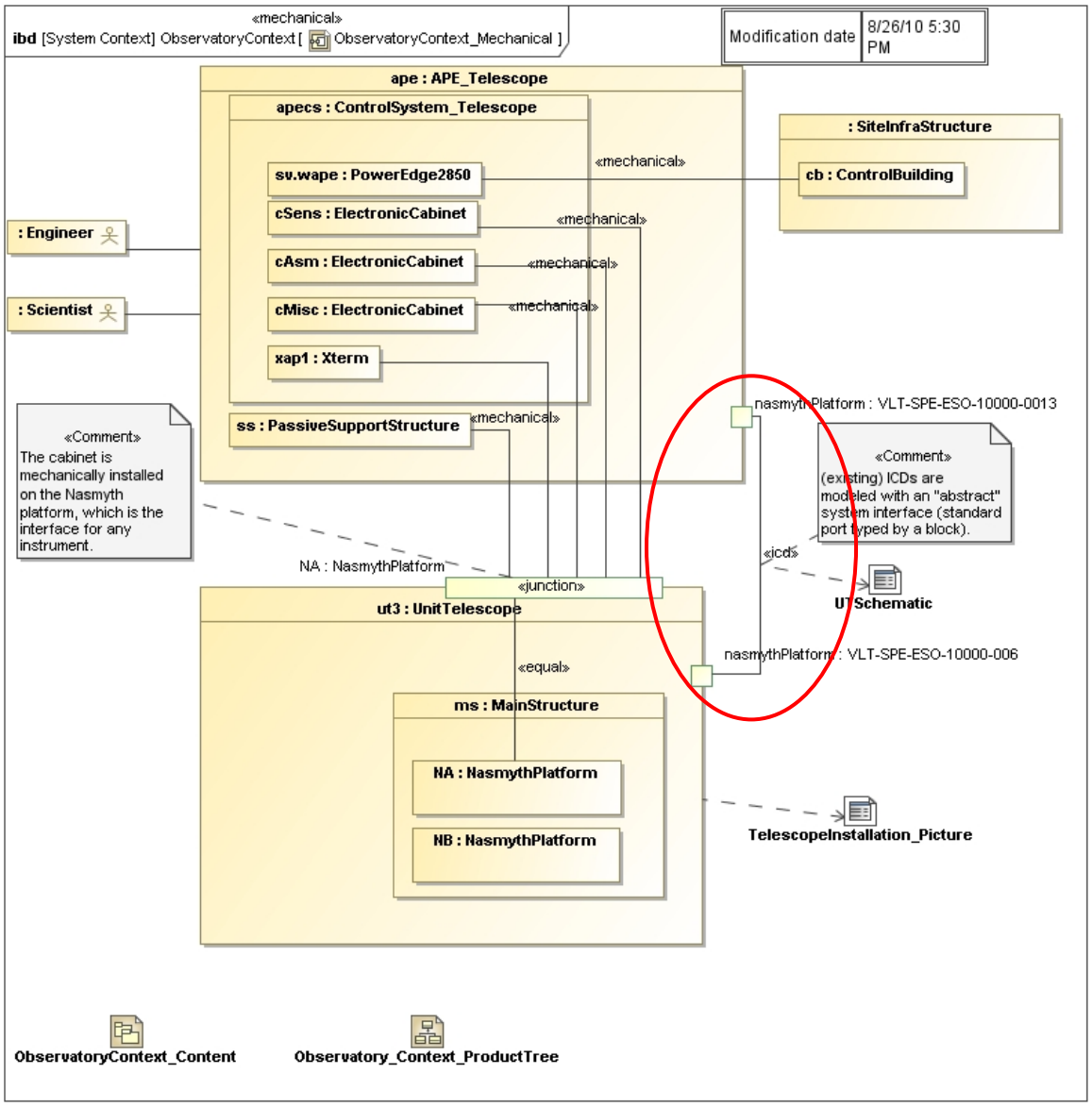


Figure 65 Mechnical Context Diagram with ICD

9.6 Relations between Interfaces

9.6.1 How can I type a connector between ports?

Connectors are typed by associations, although they are often left untyped. It should be an association between PORT TYPES.[9]

Stereotypes and types are different things. A stereotype introduces a new model element by specializing an existing model element, e.g. physical connectors.

[9] In MagicDraw you should drop these two types into a BDD diagram and draw an association. Or you could open the specification of one port, navigate to specification of type, go to Relations and create new Association directly in the model.

9.6.2 How/When do I use realize with Ports?

Realize is only used with standard interfaces, i.e. when something provides a service. As a consequence only standard ports can be used with a realize relationship. Only blocks can realize and/or use more than one interface. Therefore a port must be typed with a block before it can realize/use an interface.

You can either type the port directly with the interface or go through realization. The latter is more flexible because you can later on easily add more interfaces and realize them without changing the type of the port.

N.B.: Realize relationships exist also between Use Cases and Test Cases or other Use Case realizations.

9.7 Flows

9.7.1 Model that something flows in or out

Use a flow port (atomic, conjugated, simple, etc.). The flow port is typed by a flow spec or a Block/Signal/ValueType (atomic) to specify what flows.

- To model that the block provides or requires some services, e.g. a software API ➔ use standard port with interfaces.
- To model a combination like structure plus flow specification ➔ use a complex port: standard port typed by a block that specifies the structure and owns a flow port. The flow port is typed by a flow spec or a block/signal/valuetype (atomic) to specify what flows.
  See 9.2, Combining ports and flows to represent interfaces

- Telescope SCP: the CEE plugs or the coolant supply/return connectors are described by the standard port typed by a block. The description of what flows is described in the flow spec. The coolant is defined by a block and the properties of the coolant (temp, pressure, glycol, etc.) as value types. This block is used either as a type of the flow property (in case we have one flow port with two flow properties) or as the type of the flow port (in case we have a flow port for each connector and therefore an atomic flow port).

9.7.2 Should I use direction on flow ports?

"Trust the port direction" rather than indicate like thingIn and thingOut: also DO type ports. Although throughout nearly every previous systems engineering model you will see the direction (in/out/inout_ kind of flow ports indicated in the (contrived) flow port name, this is no longer necessary.

For atomic flow ports DO instead trust the flow port direction indicator.(And for complex port DO trust the indication of conjugation.)

The directional information CAN be gleaned from the SysML model. You will avoid errors, can change port directions WITHOUT changing names, and your diagrams will be easier to read.

9.7.3 Is the flow specification describing the physical layout of a medium or the items which flow?

The flow specification defines the kinds of things that can flow through this interaction point on a part or block. If a more logical layer is allocated to a physical layer, appropriate flow specifications on both layers are valid, e.g. describing data structures on the logical layer and current on the physical layer.

9.7.4 Do I put the specification for an image flow on the port or as item on the connector?

The type of the port can define the image format such as Digital Video, where as the thing that flows may define the content of the image, such as ”target image“. This would indicate that any Digital Video can flow through this port, but this connector conveys a Target Image. This is only one way to characterize the port and the item flow, but there are others.

9.7.5 What’s the difference between item flow and information flow?

9.8 Overview of Interfaces modeled with Flows and Ports

A ItemFlow offers the possibility to specify concrete rates or flow properties by itemProperty. The following table (Table 2) list a number of interface elements for different interaction media, connectors, isolators, and converters and the interacting elements.

Table 2 Interface Elements and their SysML representation

Type	*Electrical*	*Mechanical, Hydraulic, Optical, Thermal*	*Human-Machine*	*Data*
Interaction Medium	<<connector>> Item Flow = <<Item>> Current Flow defined by <<flow spec>> and <<flow port>>, <<association block>> for cables (in connection with their connectors)	<<connector>> Item Flow = << Item >> Force, Fluid, Photons, Heat Flow defined by <<flow spec>> and <<flow port>> <<association block>> for pipes, fibers,	<<connector>> Item Flow = << Item >>information (e.g. audio, visual, finger print, iris), mechanical force Flow defined by <<flow spec>> and <<flow port>>	<<connector>> Item Flow = <<value type>>
Connector	<<standard port>> typed by a block. e.g. DB25, RJ45	<<standard port>> typed by a block e.g. Joint coupling, flange, Valve, fiber optic connectors, e.g. metallic foil bundle	<<standard port>> typed by a block e.g. Display or a separate <<block>>	<<standard port>> typed by a block, realizing interfaces or <<flow port>> for data flows. e.g. data I/O items
Isolator	<<block>> , <<standard port>> typed by a block e.g. RF shield insulator	<<block>>, <<standard port>> typed by a block e.g. Shock mount bearing, Seal, Shutter, air	<<block>>,<<standard port>> typed by a block e.g. cover window	n/a
Converter	<<block>> e.g. Antenna A/D converter	<<block>> e.g. Gear Train Piston, Reducing valve Pump, Lens	<<block>> e.g. Keyboard, lever, loudspeaker, steering	<<block>> e.g. FPGA

		group, Peltier	wheel, touch screen	
Protocol	<<flow port>> and <<Flow Spec>> E.g. RS232, USB, CAN, Ethernet	n/a	n/a	<<standard port>>, typed by a block e.g. CORBA, DDS, TCP/IP, OSIStack

10 Behavior modeling

Many projects model only the system structure and interfaces. However, missing to specify the system behavior, using behavior modeling, typically results in serious integration problems.

Therefore we highly recommend capturing the system behavior in the system model using SysML activities, state charts and sequence diagrams.

10.1 Modeling Activities

Activities define the workflow of actions to perform, the input and output of the actions and the decisions/condition-dependent sequence of the actions.

The model shows at the same time the physical effect of a system (like distortion of wave front) as well as sensing, actuating actions and control flows.

We need to describe the wave front control scheme of APE, the relationships among internal/external disturbances, opto-mechanical effects, and control decisions, to understand the context of those decisions and to refine the control use cases. The wave front control schemes are derived by analyzing the system requirements and the opto-mechanical system architecture. From this fairly static view of dependencies, a wealth of information can be derived, like interfaces among components, communication network dimensions, synchronization requirements and required sensors and actuators.

Figure 69 shows the top level behavior of APE; i.e. the evaluation of the phasing techniques.

The model of the Wave front control becomes the central piece for further activities. The modeling element of choice is an activity diagram, using the SysML specific add-ons for systems modeling (rate, continuous flows, etc.). This prescriptive model maps the relevant information to activity elements (e.g. disturbances to object nodes, opto-mechanical effects to actions) and all the relevant information is kept in one diagram, thus enabling proper effects and relationship analysis.

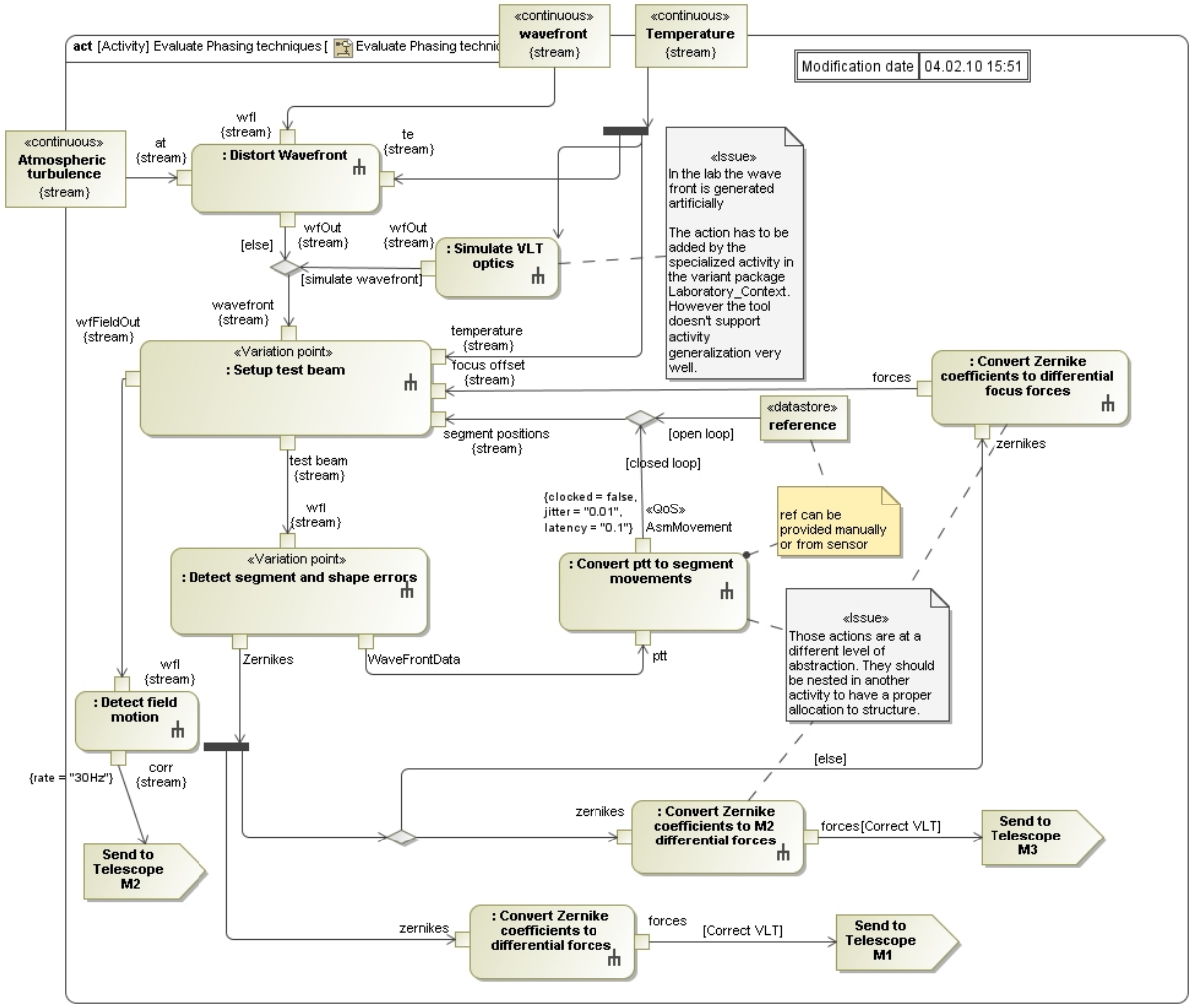
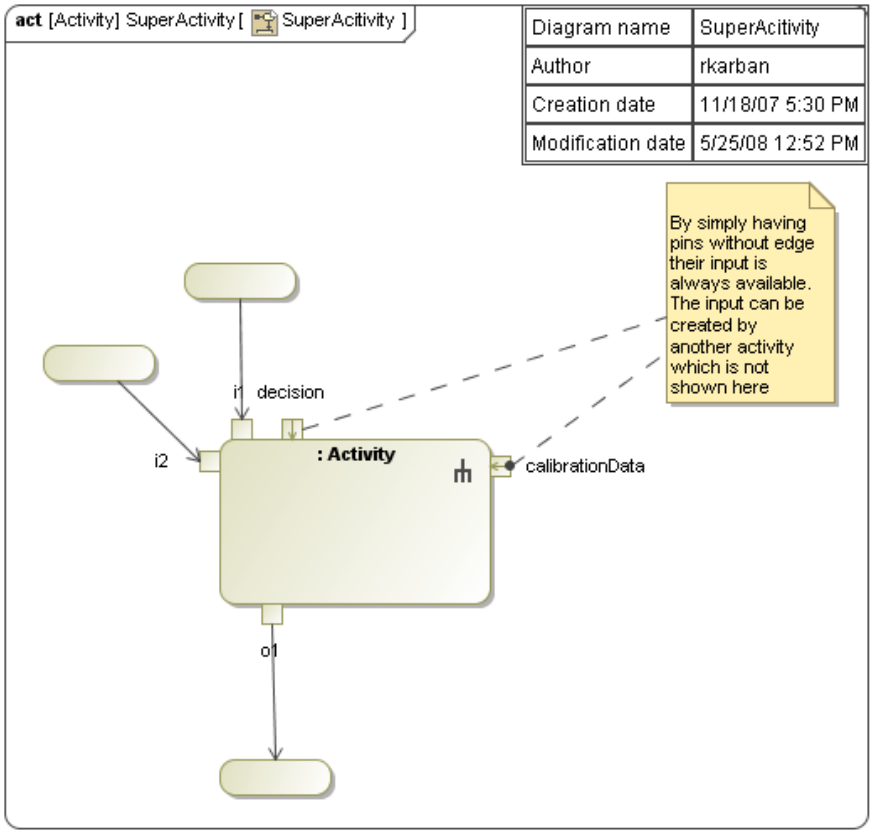


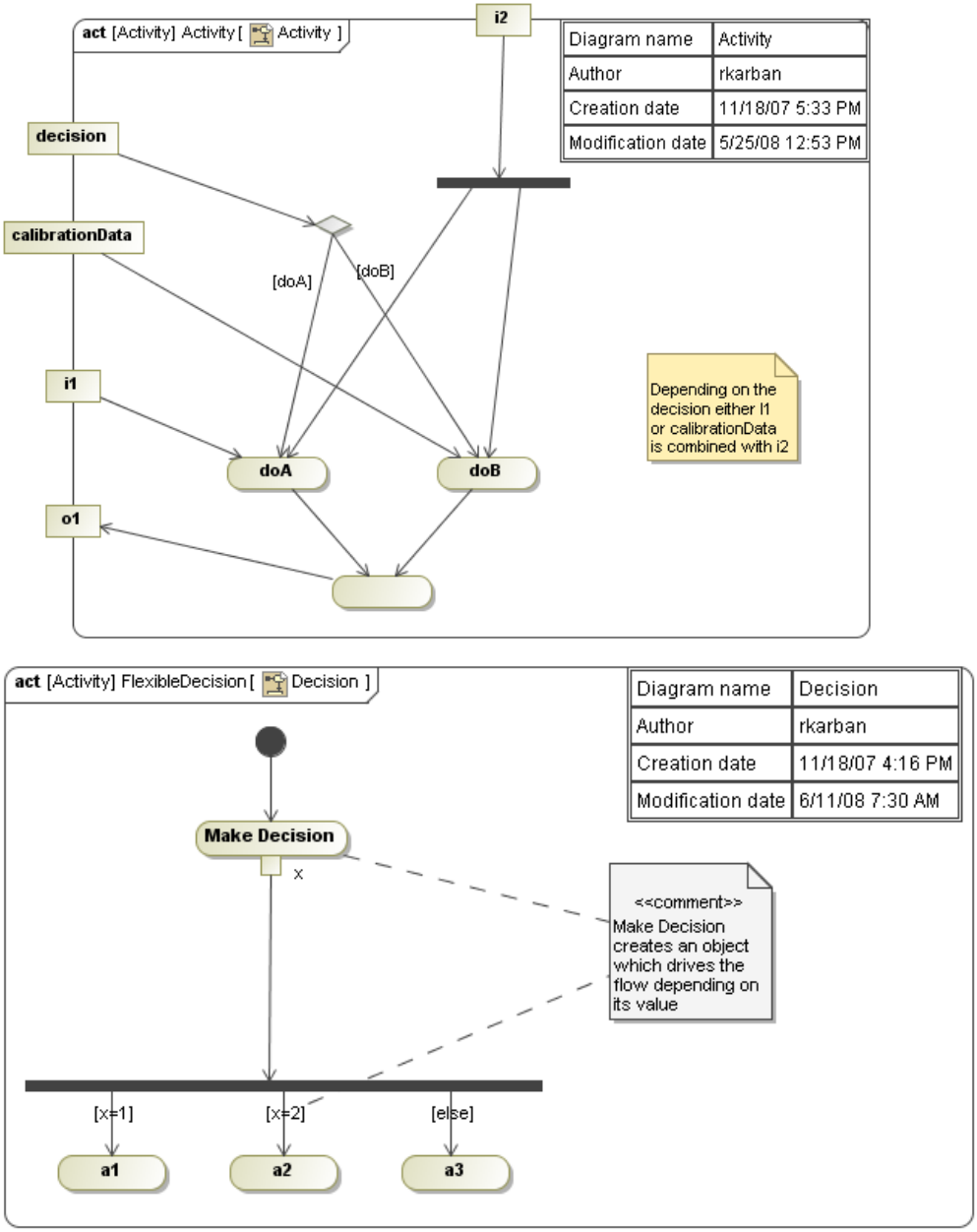
Figure 69 Top Level Behavior of APE

10.1.1 What is the relationship of Activity, Activity diagram, Action, CallBehaviorAction?

An action is never actually defined through an activity diagram. If an action is a usage of an Activity (within another activity) then the Activity that types the action is defined through an activity diagram.

10.1.2 How can I model a decision in an activity which is taken asynchronously (like an operator decision)?





10.1.3 When should I use <<discrete>> or <<continuous>> in activity diagrams?

On a philosophical basis, we would expect things that are defined by their <<rate>> to be continuous, while items which have discrete properties have sudden steps in rate.

For example, when modeling some infra-red detectors one needs to consider (count) photons. They arrive randomly and have a distribution (typically Poisson). However light, as mentioned below is often thought of as continuous.

The choice between <<continuous>> / <<discrete>> is a critical modeling assumption and is an important contextual decision. To get it 'wrong' constrains the modeling.

Additionally this include the decision about <<continuous>> or <<discrete>> time, that is, can we resolve the (potential) step changes in rate.

You should treat air, light, liquid as <<continuous>> object flows, where the object is e.g. photons, etc.

Information is a normal object flow. You can define an interruptible region with a timeout to create ”timed“ flows. In this region you could define an action which creates a <<continuous>> flow you process later on. Or, you use a control operator with the control value enable/disable which enables/disables the action which produces light. In Model-based Systems Engineering, CRC Press, 1995, A. Wayne Wymore described quite rigorously the transformation from discrete to continuous and back.

10.1.4 How do I represent control loops?

Use <<clocked>> activity diagrams with streaming and non streaming activities. The following shows an integrator.

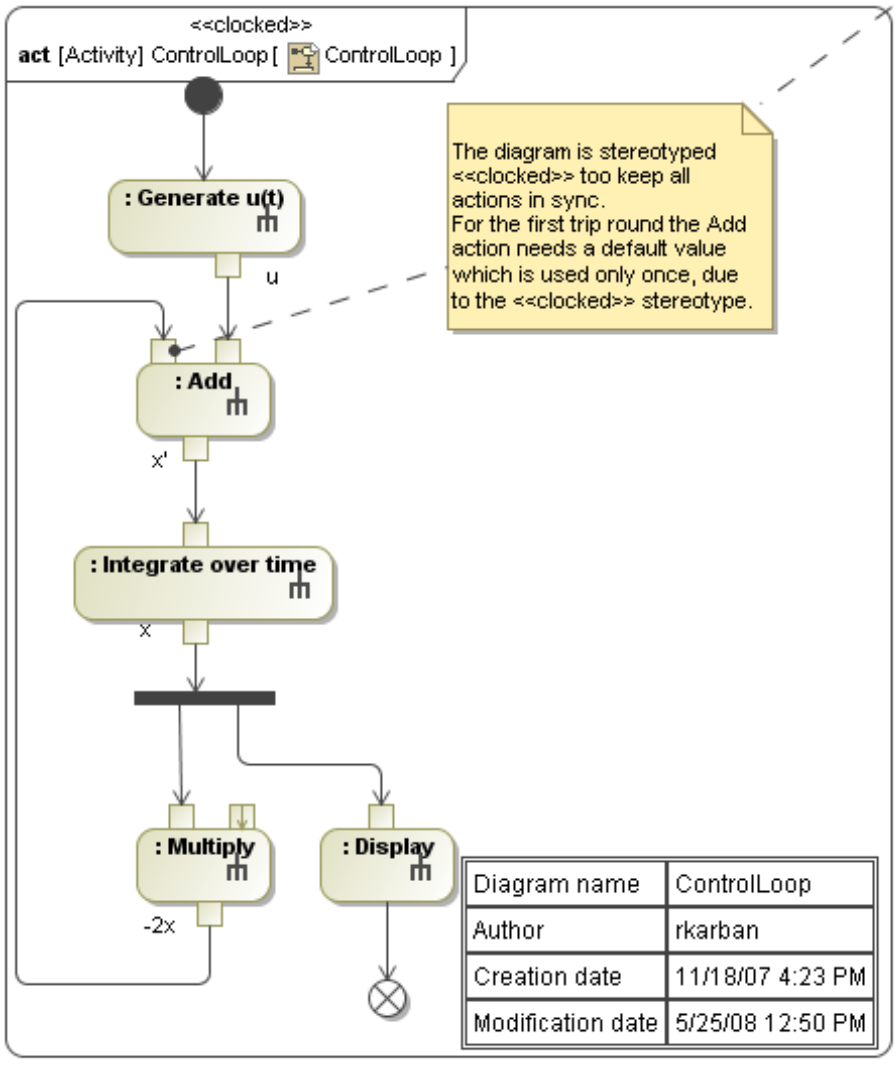


Figure 70 A simple, integrating control loop

11 Guidelines for Modeling Non-Functional Aspects

11.1 Quality of Service

11.1.1 How do I define Quality of Service?

SysML activity diagrams offer only a rate to define details of a pin. Often more QoS are needed, like latency, jitter, clocked.

The solution is to define a stereotype Qos with the properties clocked, jitter, latency, which can have different values for every Pin. If the QoS is valid for both ends of the edge, the edge itself is stereotyped, as suggested already by C.Bock.

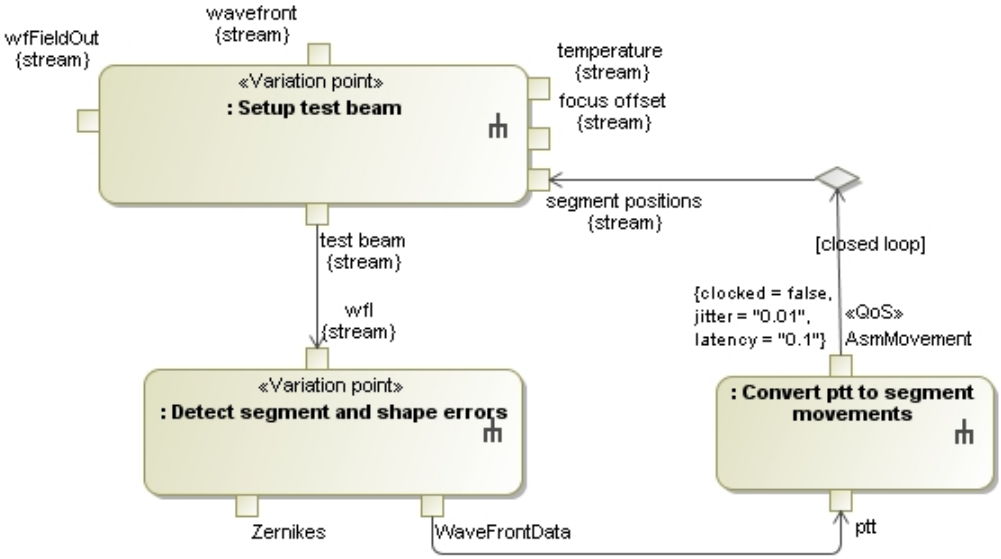


Figure 71 Quality of Service modeled in the Behavioral View

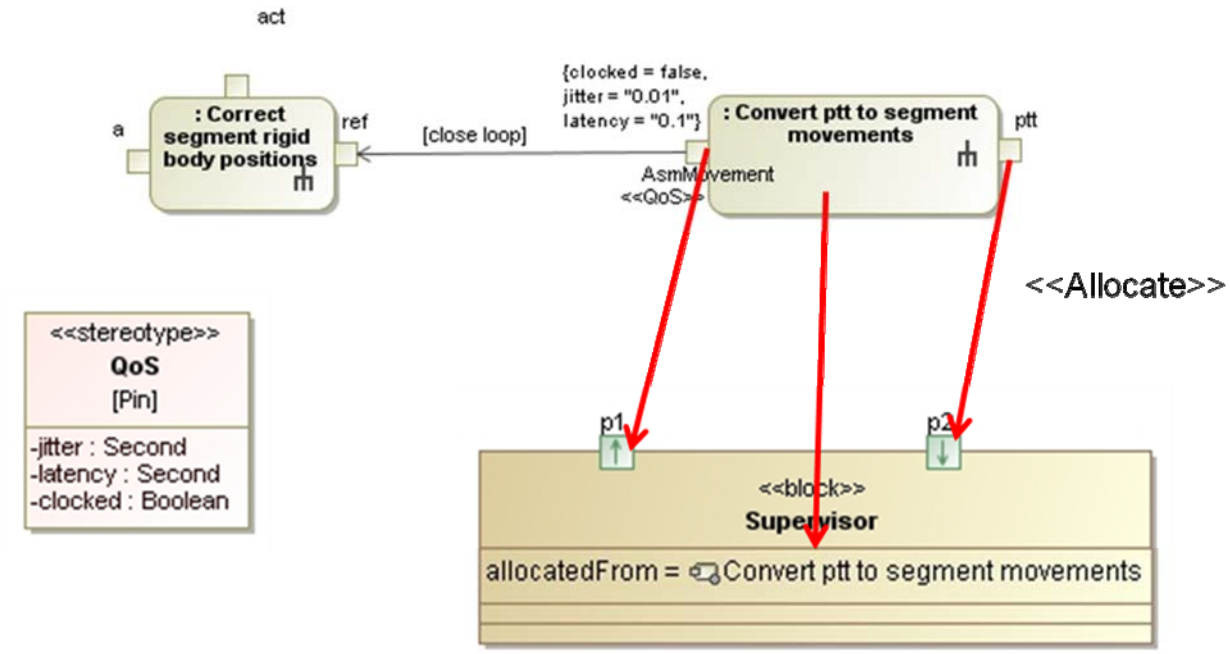


Figure 72 Allocation Scheme Pin to Port

The main point of discussion is, if the pin of the action or the parameter of the activity shall be stereotyped. The correct approach seems to stereotype the parameter and the tool shall propagate it to the associated pin -.

SysML status

- SysML only provides only <<rate>> stereotype which extends Activity Edge and Parameter.
- Allocation of Ports to Pins not addressed in SysML standard 1.1[10]
- Synchronization of Parameter and Pin is tool-dependent.
- UML Profile for Modeling Quality of Service and Fault Tolerance Characteristics and Mechanisms

11.1.2 How does it relate to Parts and Ports?

Activities are as usual allocated to parts or blocks. Each pin can be allocated to a flow port. In case pins are bundled on a port they are allocated to the same port. The allocation of pins to ports is optional. If there is a one to one mapping the data type of the flow port and the object node have to be the same.

Allocation ObjectFlow to ItemFlow

The ObjectFlow (Edge) describes that in the context of an Activity the output of one Action is bound to the input of another action. In the context of a block a item flow describes the flow of an object from one part or port to the connected part or port. The allocation of the ObjectFlow to an ItemFlow defines which ObjectFlow corresponds to which ItemFlow in a given context. Supplier and producer and context need always be defined.

Allocation Pin to Port (not addressed in SysML standard 1.1)

The pin defines which objects flows in/out of an action from a functional point of view. The port defines which object flows in/out of a block from a structural point of view. The allocation of pin to port defines the mapping of functional to structural view, independent of a context. The supplier and producer need to be known, e.g. when certain data flows over an Ethernet port but it is irrelevant who is connected to it.

- Activities are allocated to blocks if the allocation is true for all parts of this block
- Actions are allocated to parts if the activity is only relevant for a particular part.
- Block operations to parts
  This is particularly the case when sequence diagrams are used to describe behavior rather than activity diagrams. Operations of a block (the whole) in a sequence diagram can be allocated to its parts, it is composed of.

12 Ontologies

When creating a model it is of utmost important that the semantics of the model elements and their relationships is properly defined. A correct definition of the semantics allows validating models and forces the modelers to model similar things in similar ways, called conceptual integrity. In large multi-user projects a consistent model structure and organization is the foundation on which modeling can take place. Apart from the model structure and organization also the modeling patterns must be defined, e.g. how interfaces are modeled. All this is required to guarantee readability, navigability, and consistent representation of information.

An ontology defines formally terms, concepts, and their relationships.

[10] MagicDraw extends these stereotypes to ObjectNode for applications like this

There can be general purpose Ontologies to define something like model structure and very domain specific Ontologies like the conceptual elements of a telescope or space craft.

The most formal way is to define an Ontology in an ontology language like OWL (Web Ontology Language) and apply model transformation to create a profile with SysML stereotypes, representing those concepts and extend UML meta classes or specialize SysML stereotypes.

Most recipes and patterns in this Cookbook are based on Ontologies, e.g. Project Ontology, Variant Ontology, Interface Ontology, Product Tree Ontology, etc.

They are defined as a Class model in the SE2Profile. The Classes are allocated to a stereotype model. This is a less rigorous, yet worthwhile exercise to formalize modeling.

Knowing the Ontology, its allocation to stereotypes, and the mapping to SysML model elements allows in principle to validate the model against the Ontology and check it for consistency; i.e. determine, whether the representation of the model is consistent with the ontology.

Eventually, **every** model element must have a stereotype applied and its meaning properly defined in an Ontology.

In the following some examples are shown. The complete ontology and mapping is defined in the APE model.

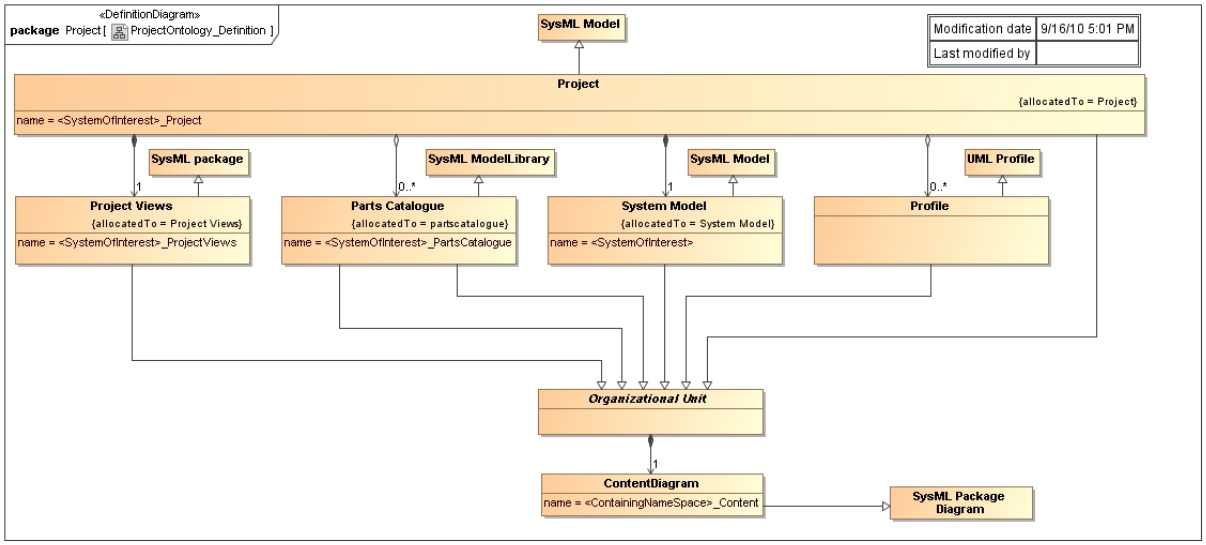


Figure 73 Project Ontology

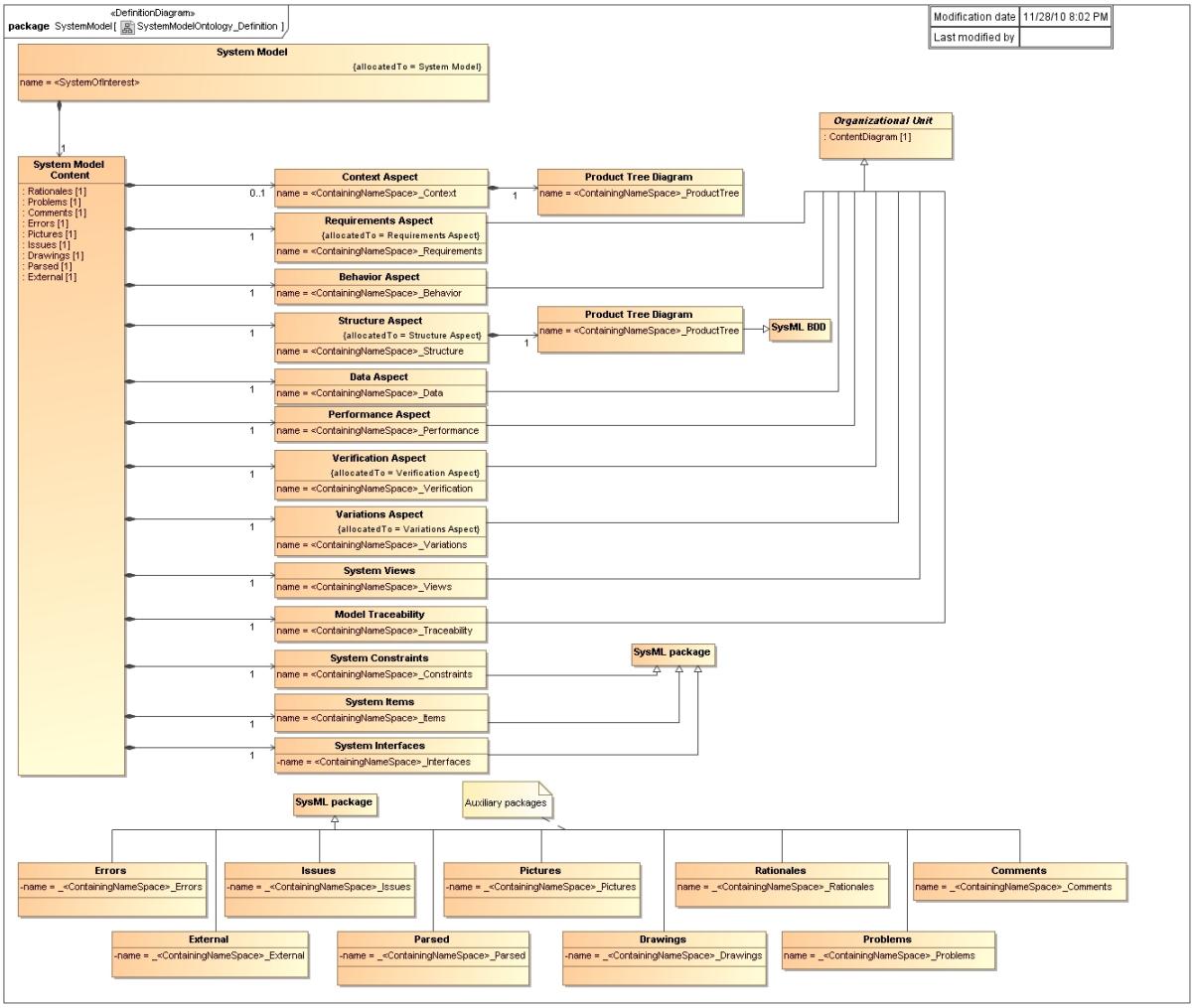


Figure 74 System Model Ontology

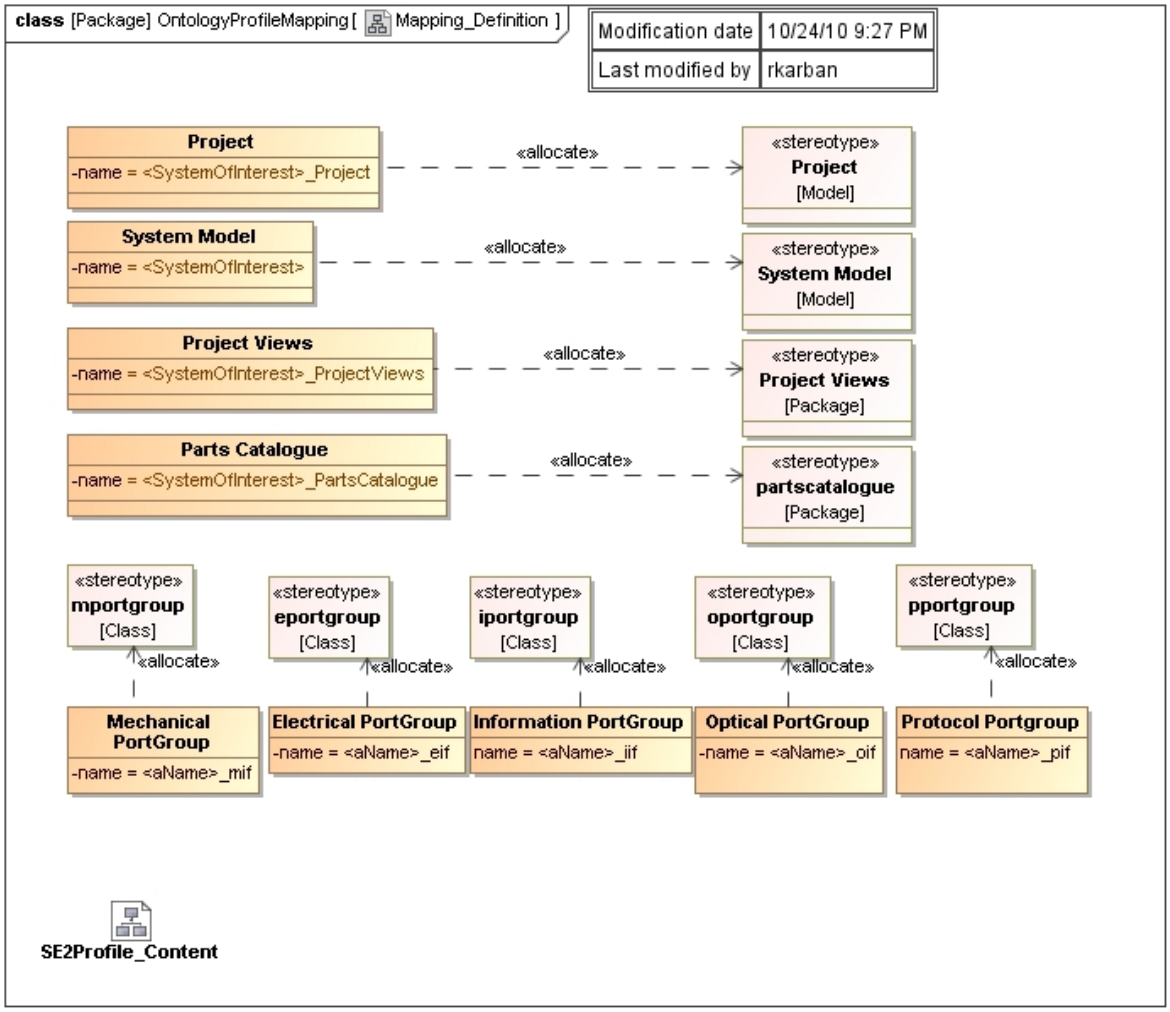


Figure 75 Mapping of Ontology Classes to Stereotypes

13 Integration with other disciplines

This chapter describes the integration of system engineering modeling with other disciplines.

13.1 Transition to UML for software

How can a system model be used to seamlessly start software engineering?

Notion

- Seamless transitions from SysML <<system>> and <<software>> blocks to UML classes, mapping also ports and interfaces

How to

- <<allocate>> block to package
- Alternative I: <<allocate>> SysML ports to UML ports and <<realize>> the same interfaces. Use interfaces for information access to map flow ports.
- Alternative II: create a UML „part class“ representing the SysML block and create connectors for SysML ports to UML ports in IBD and class diagram

SysML status

- <<allocation>> implies dependency of System to SW or vice versa.
- Classes are excluded from SysML

The main problem is how to trace SysML ports/interfaces to UML ports/interfaces. Interfaces are easy, they are simply realized by some classes.

We present two options to do the transition:

Define a "part-class" of the SW block which represents the SW in the SysML model

The UML class is then referenced in the UML SW package and has associations with the other classes of the SW

- Pro
  - The ports and interfaces can be seamlessly connected from the top (control system) to the class
  - strong coupling of SysML and UML
- Con
  - Classes are excluded from SysML (add to SysML status)
  - strong coupling of SysML and UML
  - Flow ports do not exist in UML
  - depends on development process
  - depends if tool supports having UML and SysML at the same time available

Allocate class ports to ports

- Pro
  - Only the SW block appears in the SysML model. The cut between the models is done at SW block level.
  - System service ports are connected to the SW block ports (there can be more than one software block) -> strong coupling
  - The SW developer defines how UML elements are allocated to the SysML elements by allocating them.
- Con
  - usage of allocation requires anyway a mixed language approach like in option one because allocate has to be used.
  - If you want to show how SysML interfaces are implemented in SW you need allocate.

Only those flow ports are interesting to SW, which are not physical; i.e. information flow ports (DDS like). Define one SW interface for information access. All flow items of the flow spec of the flow port can be mapped to subclasses of the abstract data class; i.e. each concrete data class has a dependency to the flow item.

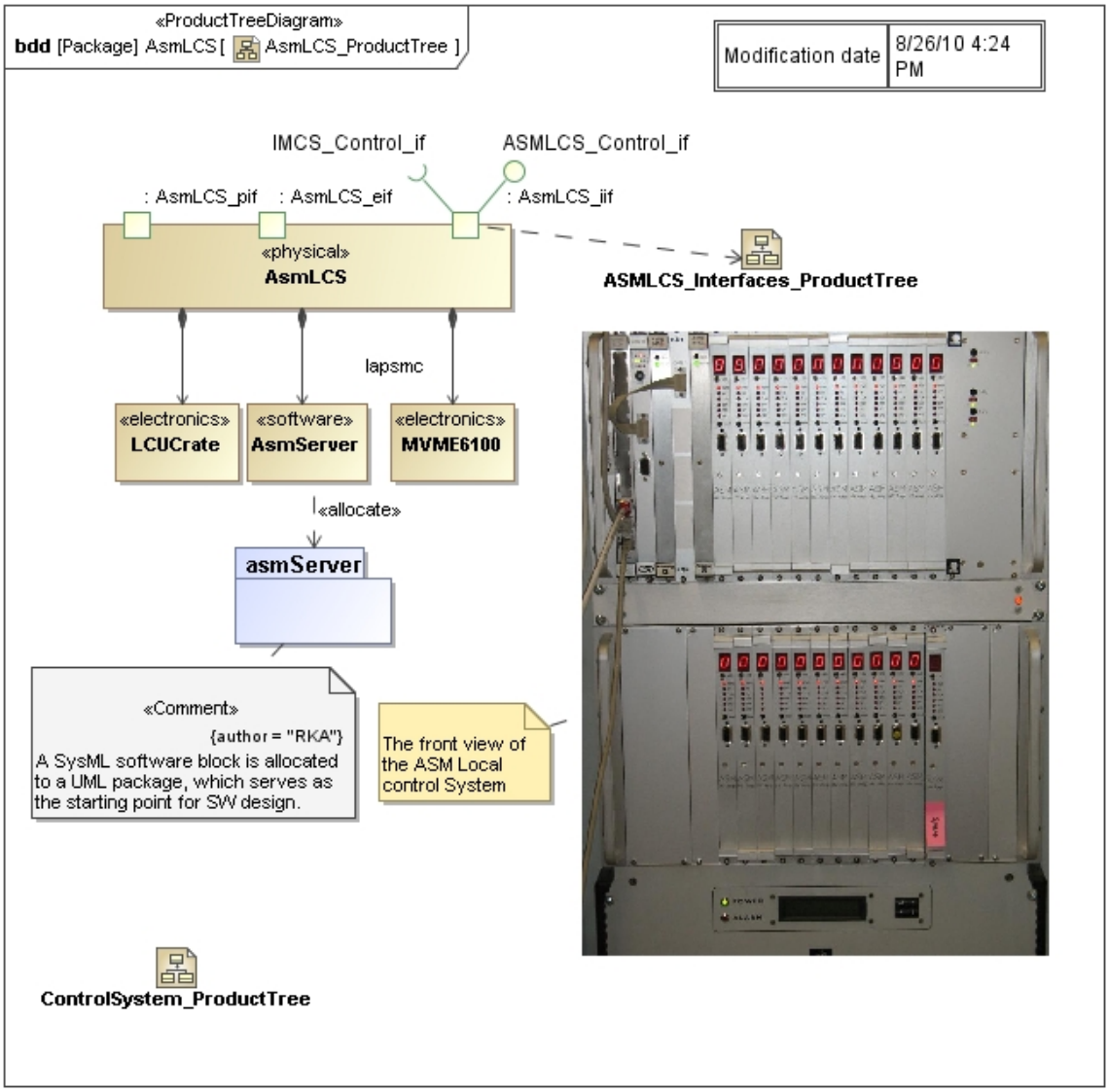


Figure 76 Product Tree of ASM Local Control System

In general a software block shall be allocated to **ONE** package and there shall be no detailed SW design, like creating different blocks for interfaces, control or entity as suggested by other authors. We think the detailed design should be left to the SW developer. The developer gets a block with defined logical data and command interfaces, available (allocated) physical interfaces (like LAN ports), possibly defined protocols, and allocated functions.

This allocation is the minimum step necessary. If further detail is needed a mixed language approach is needed.

The logical interface at a higher abstraction level, like control system or system, shall be replicated on SW block level, to have a proper tracing.

In the IBD of the next higher abstraction level the ports of the higher level are connected to the ports of the SW block(s). Here starts the cut between System and Software (Figure 77).

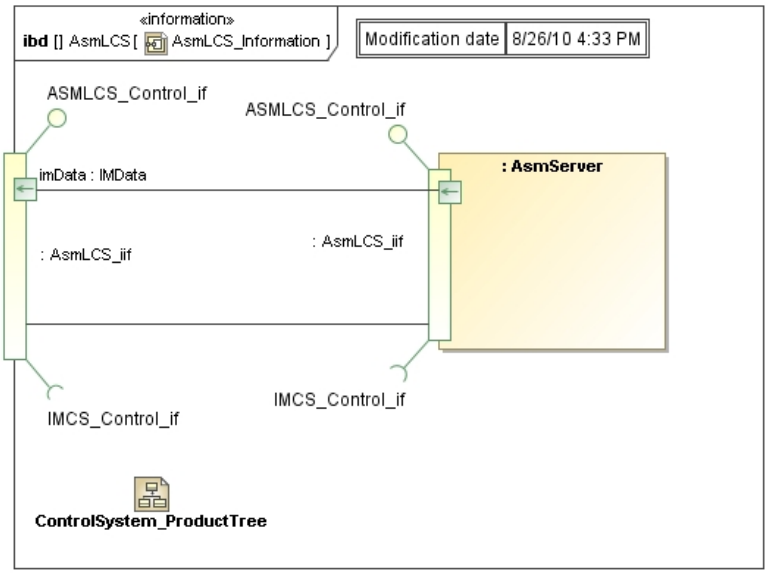


Figure 77 Information View of ASM Local Control System

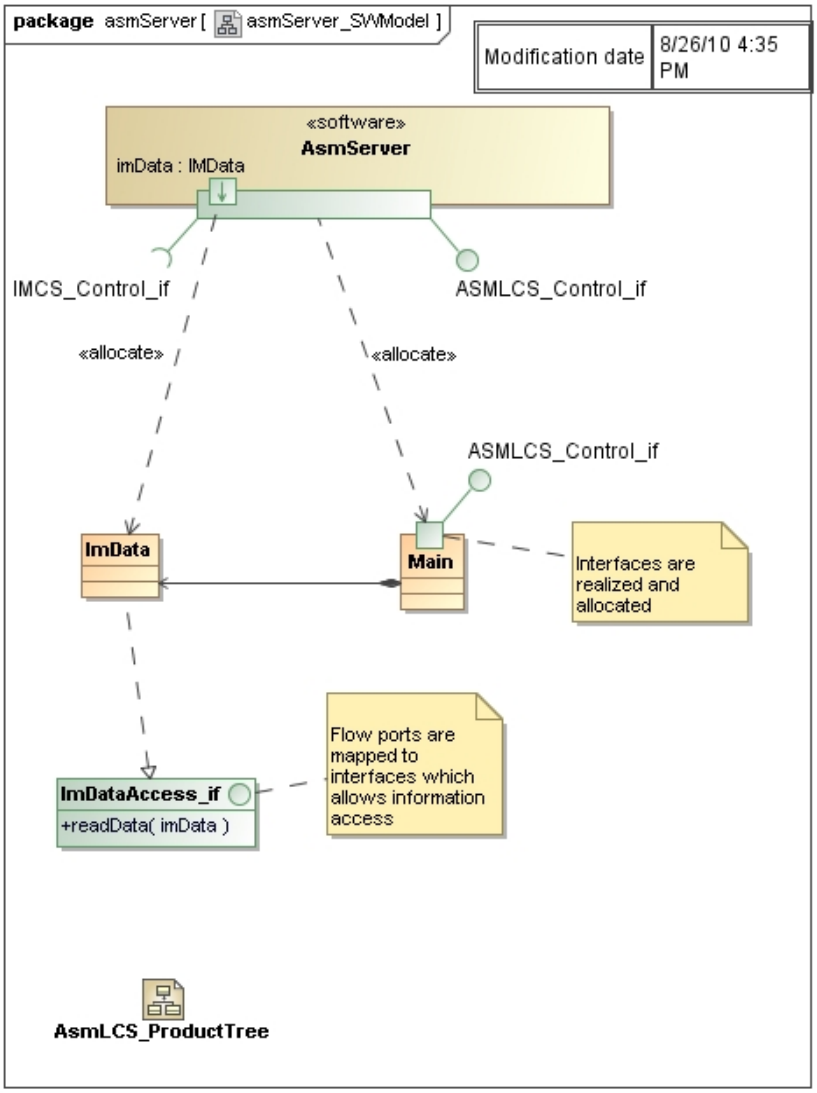


Figure 78 Relating SysML to UML for <<software>> Blocks

The SysML model does not include the discipline specific models like UML. The UML model uses information from SysML, i.e. the SysML SW block with it's interfaces is the system class in the UML model. The correct way would be to transform the SysML block to the UML class. The pragmatic way is to use the same model element, i.e. the SysML SW block is the same as the UML system class.

But it is not necessary a one-to-one mapping. A SysML software block could be mapped to one or more classes. Also several SysML <<software>> blocks could be mapped to one single UML class. Important is the direction: the SysML model doesn't include the UML model, but the UML model uses information from the SysML model. There should be no UML elements in the SysML model. In theory a generator/mapping creates elements in the UML model from the SysML model. In practice we have no big gap between both models, since we could stay in the same model.

13.2 Interdisciplinary analyses and trade off

It is useful to note that while a parametric expression can be evaluated, it is not a behavior. A behavior describes a computational algorithm that evaluates in a specific sequence. A parametric equation is different in that binding any n-1 parameters of a parametric relation allows use to define the remaining one. Thus, parametric relations are not behaviors; they are statements of the relationship of quantifiable properties of a set of items.

A parametric relationship states how the value of one property impacts the value of other properties

- Used for Engineering analysis
- Mechanism to integrate engineering analysis (performance, reliability models) with SysML assemblies
- Let user create network of constraints among properties of a system, built using basic mathematical operators.
- Can be used to support tradeoff analysis by representing evaluation function, can be used jointly to probability modeling available from the Auxiliary Chapter
- Not defined to be executable/simulatable Time

The following example shows a parametric diagram, describing relations between environment properties, optical system properties, and electrical system properties.

The environmental property is the flux of the star in photons/s/m2. The optical properties are light transmissions, and the electrical properties are quantum efficiency.

Each element in an optical system will not transmit 100% of the light passing through it, e.g. a fraction of the light will be absorbed by the mirrors, lenses, filters, etc. It is important to quantify the amount of light lost in an optical system and, in general, to minimize the loss.

If there is too little light, one can then evaluate the CCD characteristics: integration time, binning, etc. and also determine the specifications of the CCD like the readout noise, the dark noise, etc.

It can also happen that a star is too bright, and it is then important to know the amount of light on the detector in order to not saturate it.

The original photon flux is influenced by the optical elements in the light path, whereas the final flux arriving at the detector (ZEUS), is influencing together with the detector’s quantum efficiency the signal to noise ratio.

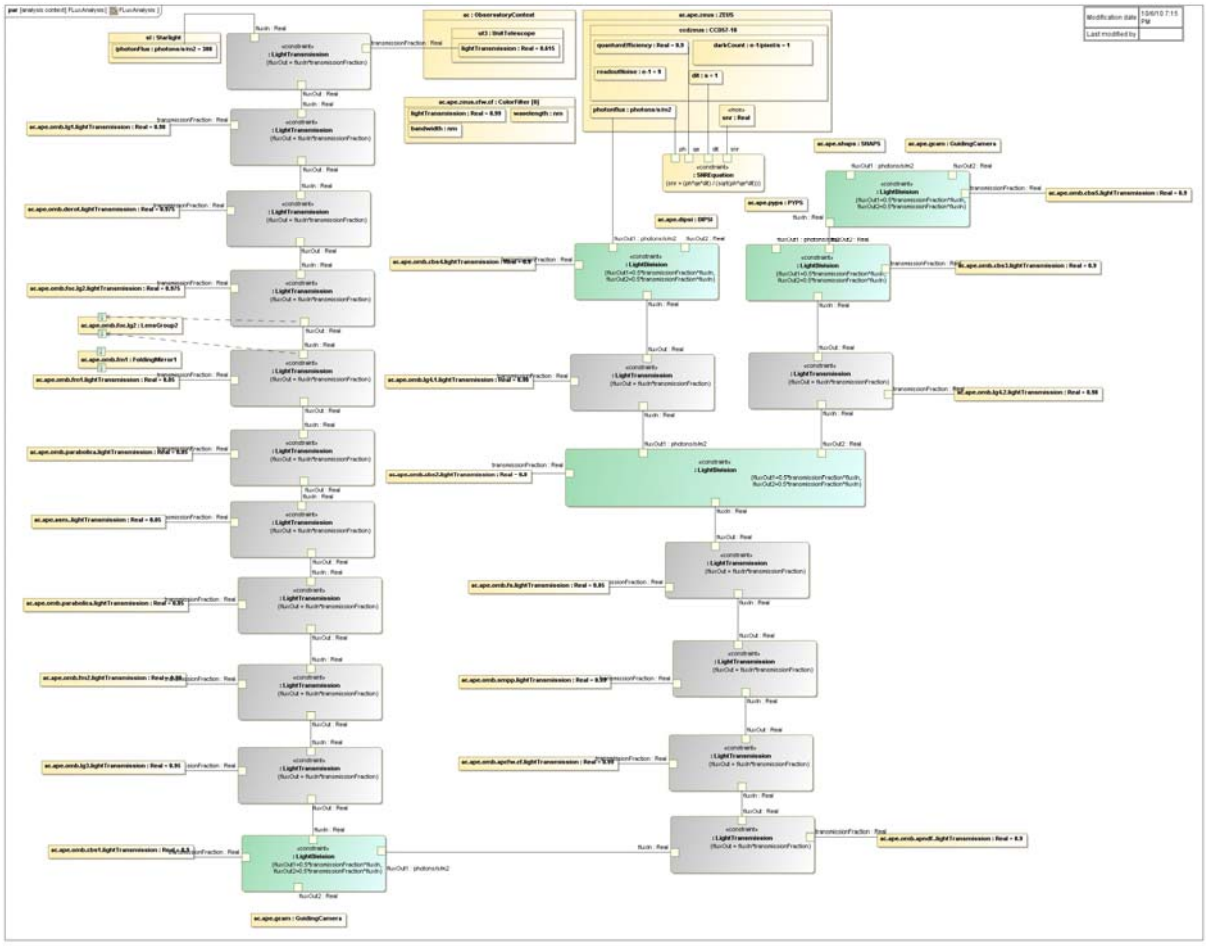


Figure 79 Complete parametric diagram for Flux Analysis

.

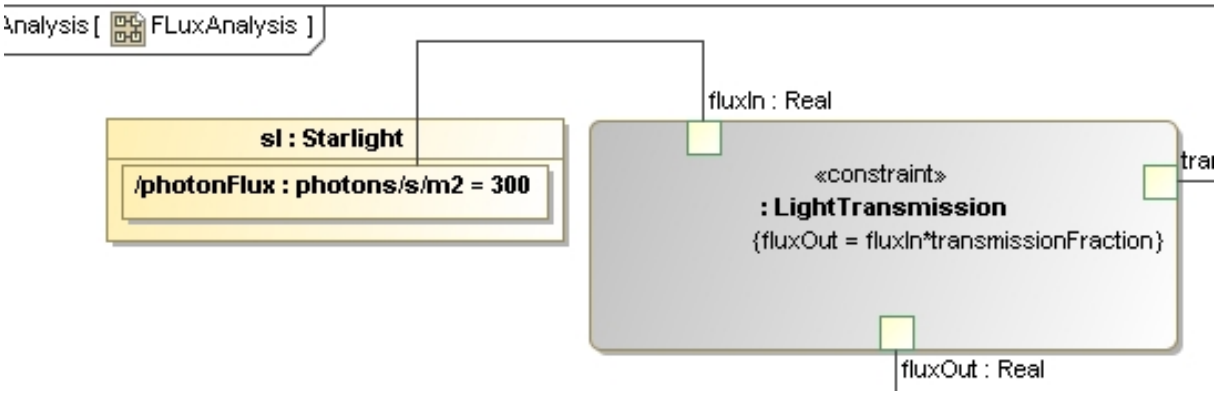


Figure 80 Flux received from Environment - the star itself

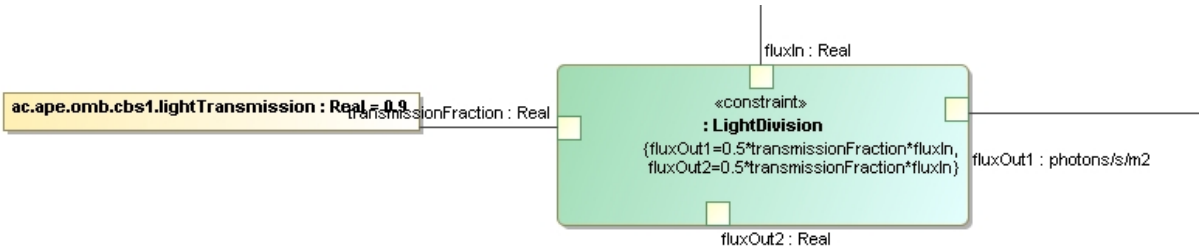


Figure 81 FLux is reduced by beam splitters and transmmission factor fo optical elements

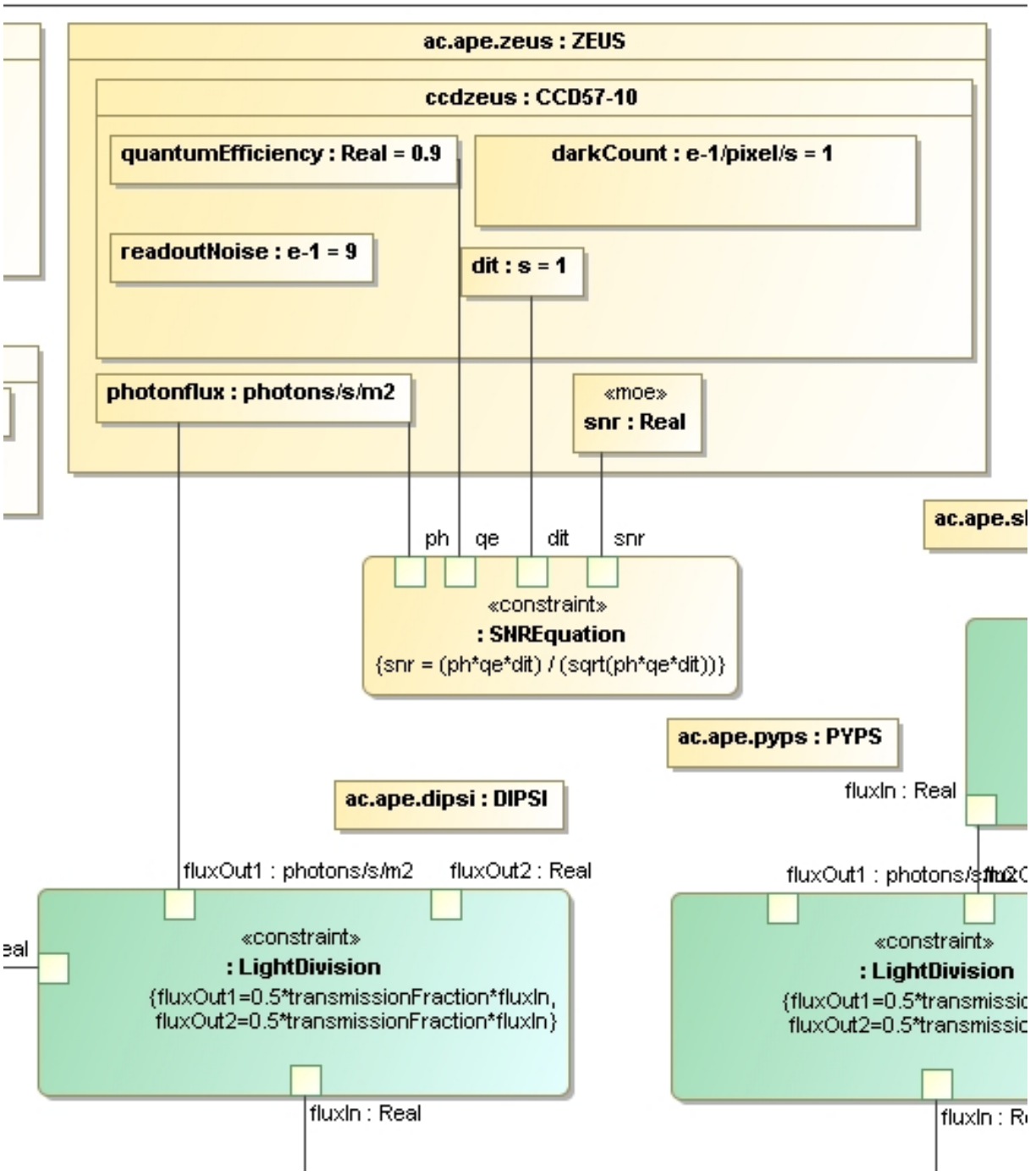


Figure 82 Signal to noise ratio at ZEUS detector

14 Variant modeling

The modeling of system variants is a core technique for model based systems engineering. You need to model variants

- for analysing design alternatives,
- for evaluating variants via trade-offs,
- for modeling of product families,

and for the separation of a logical and a physical architecture.The challenge is to separate the variant from the common part and to manage the dependencies.

14.1 Definitions

A **variation** contains a set of variants that have a common discriminator.

A **variant** is a complete set of variant elements that varies the system according to the variation discriminator.

A variation point marks a core element as a docking point for a variant element.

A variant element is an element in a variant package.

A core element is an element that is valid for all variants.

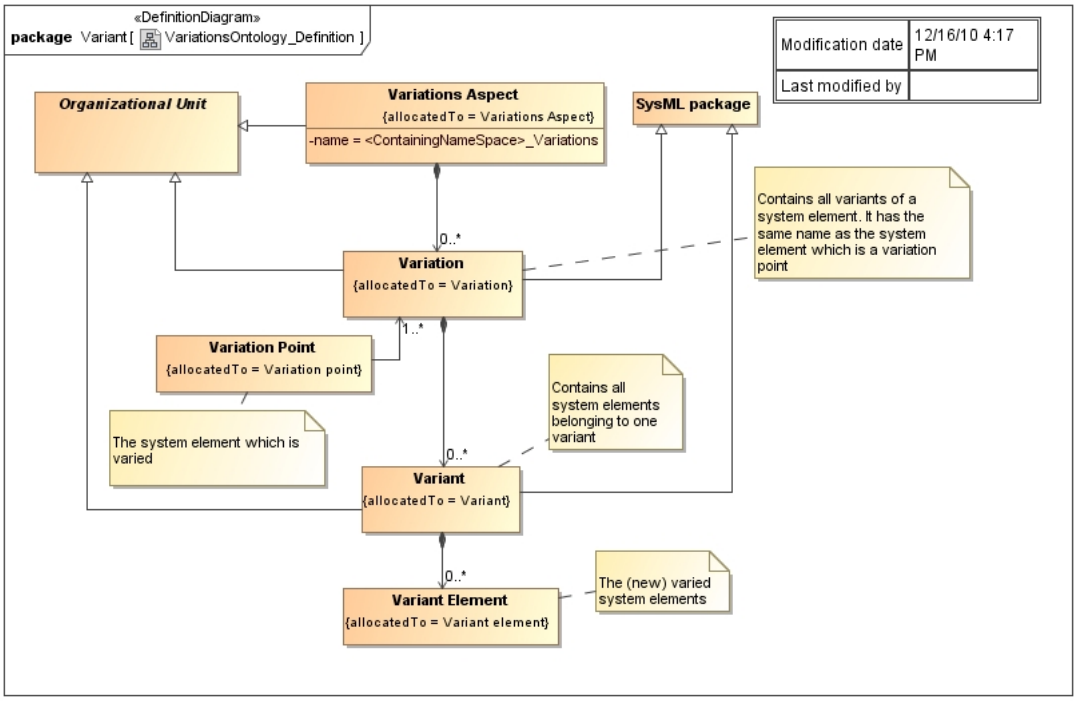


Figure 83 Variant ontology

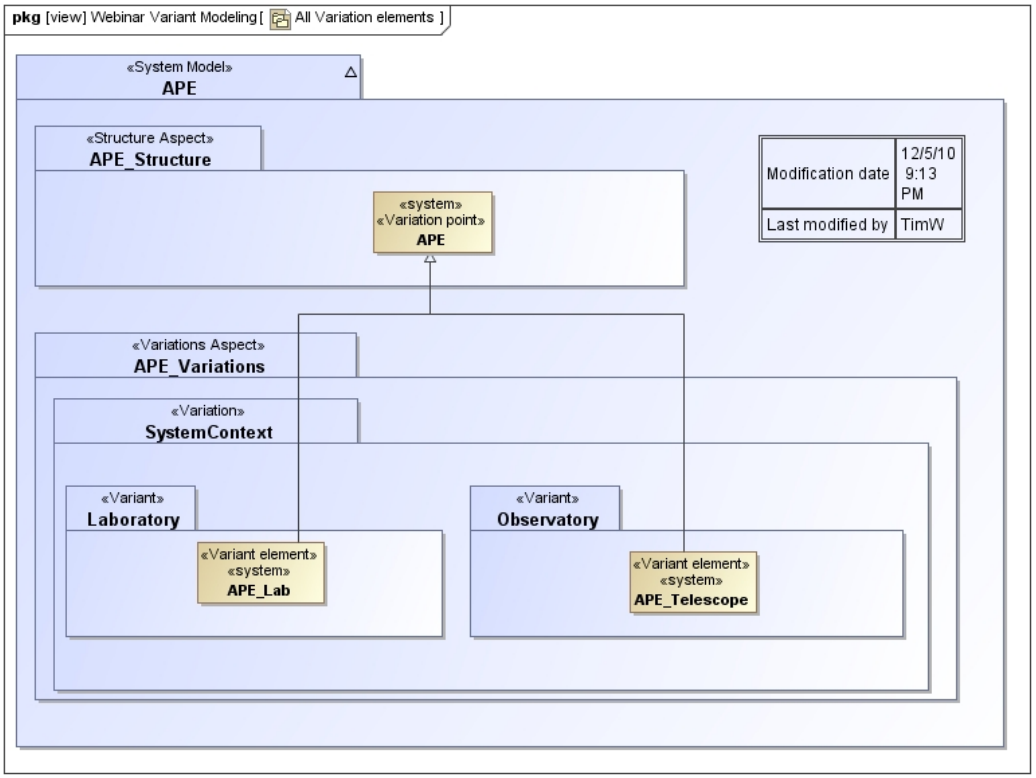


Figure 84 Example for variant terms

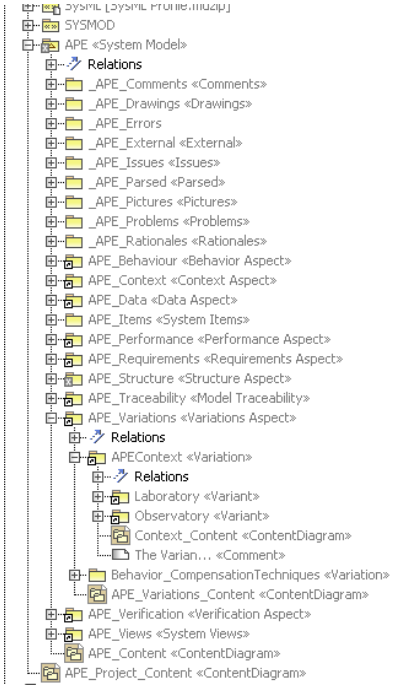


Figure 85 Separation of concerns: core and variations

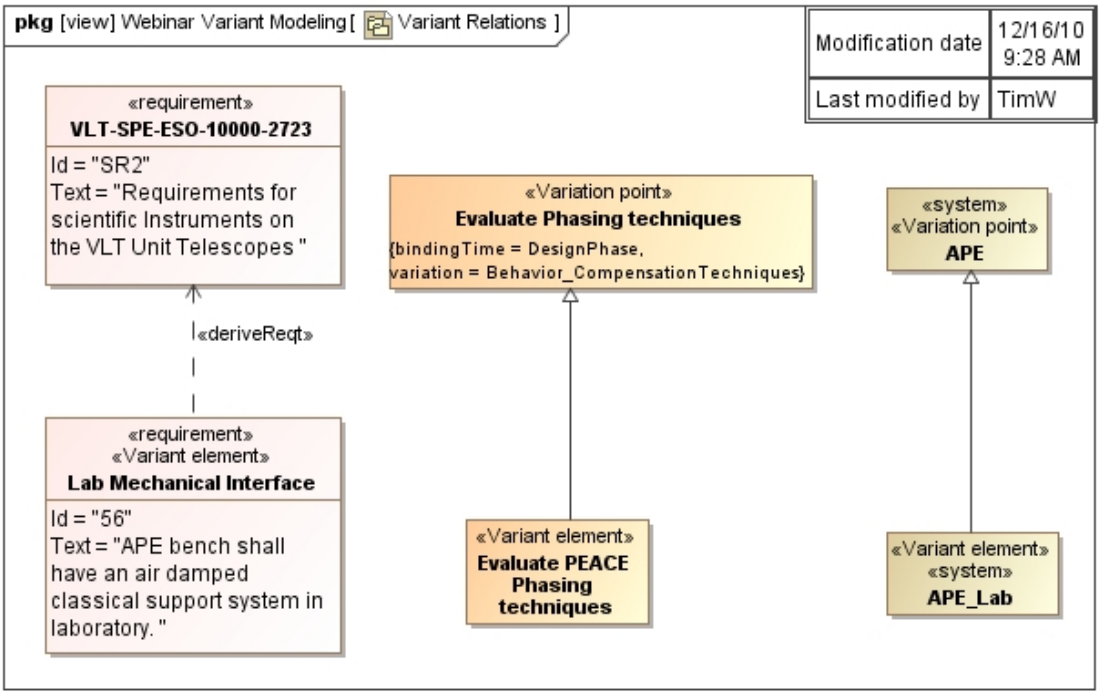


Figure 86 Relationship between core and variant elements

14.2 SYSMOD Variant Profile

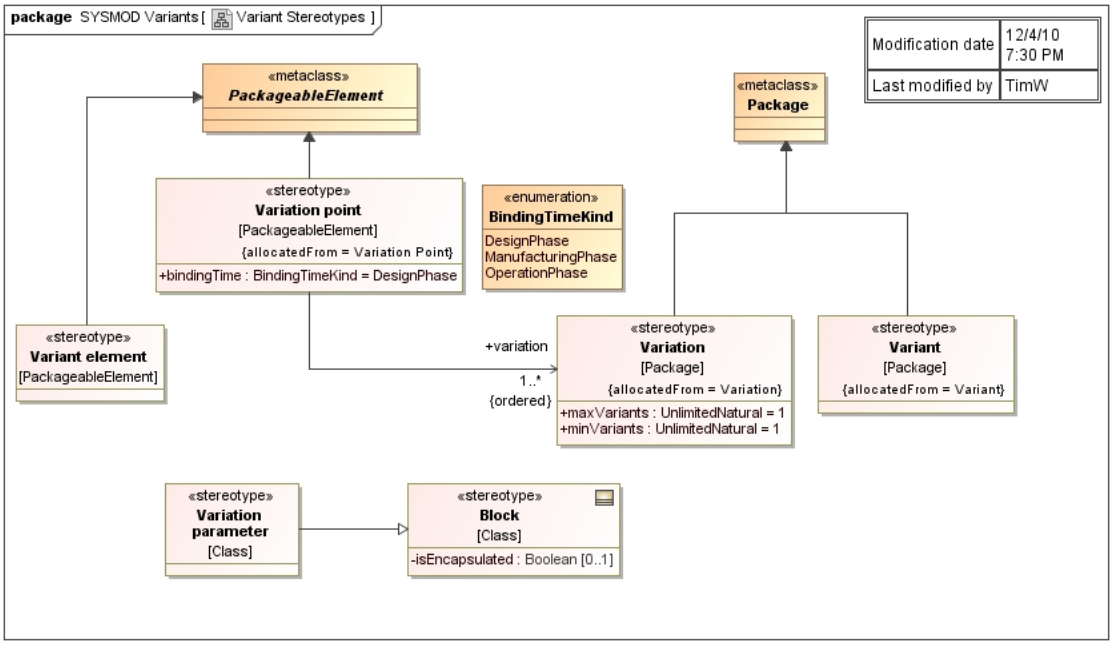


Figure 87 SYSMOD variant profile

14.3 Variant configurations

The Featured Oriented Domain Analysis (FODA) is a modeling method, which allows to describe features (variants) of a specific product. In Figure 88 an FODA example feature tree of a car is provided.

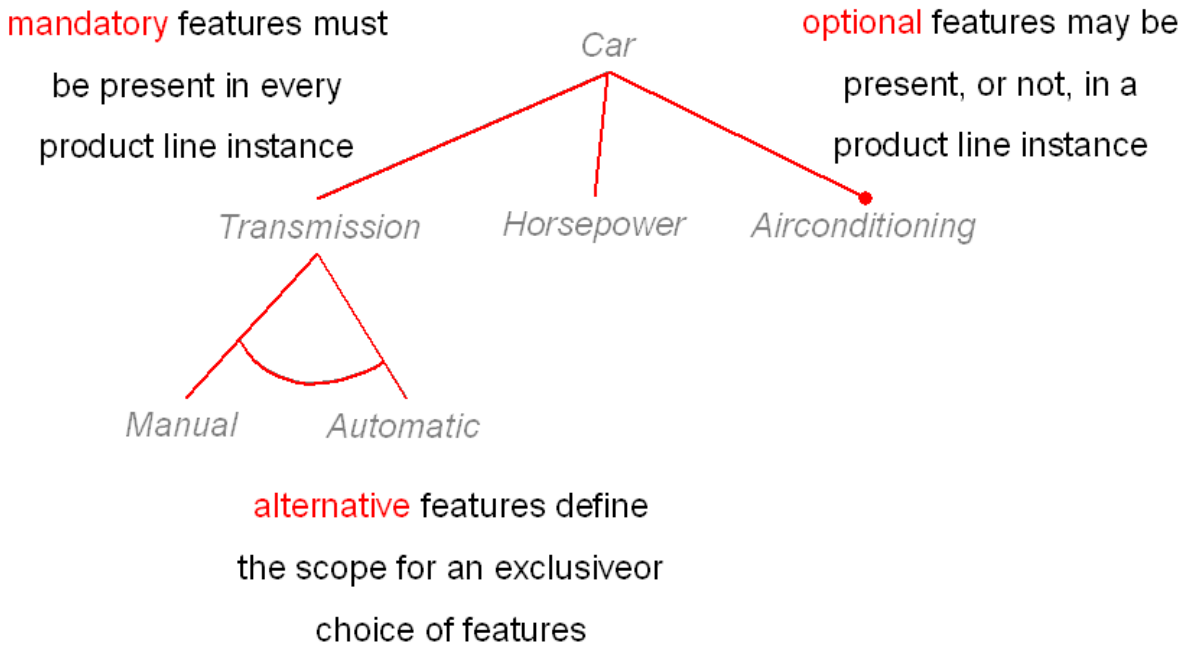


Figure 88 FODA example(Source: Myra Cohen, Matthew Dwyer: Software Product Line Testing Part II : Variability Modeling)

The above example could also expressed with SysML and the different variant stereotypes:

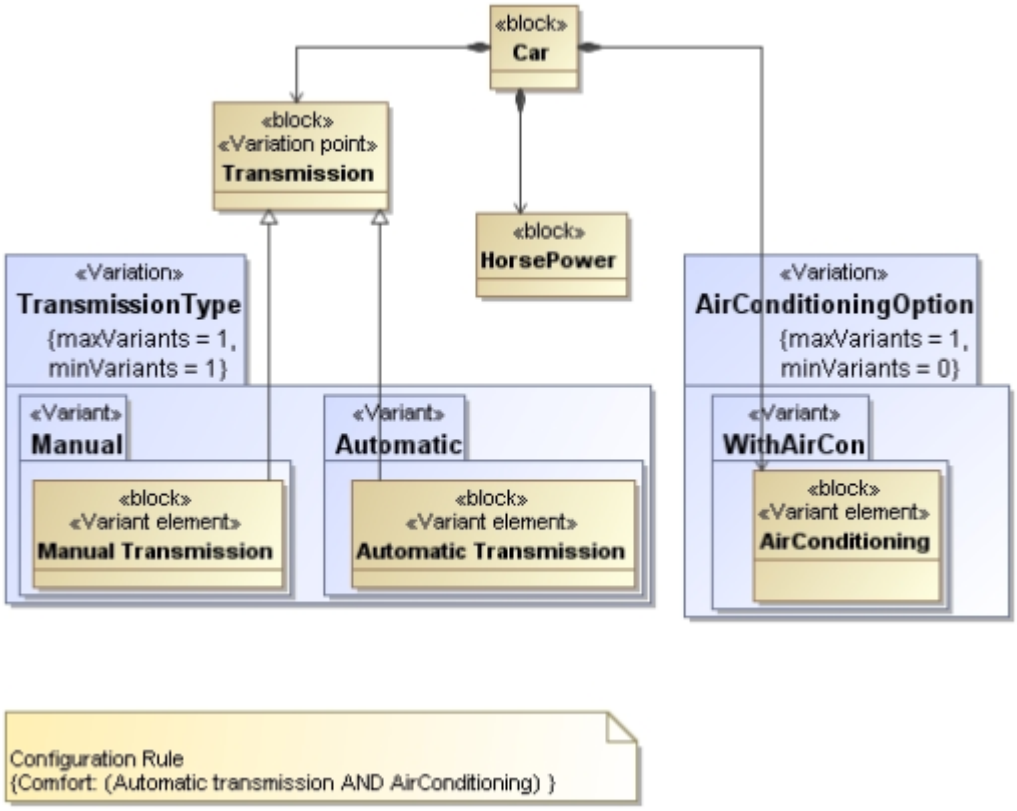


Figure 89 Car variants

Rules formulated in a textual DSL and embedded in UML constraints are defining the variation possibilities. In Figure 89 Car variants, the “Comfort” option of a car is defined by the rule, that the car has automatic transmission and air conditioning on board. The TransmissionType variation is AirConditioningOption is optional, so the stereotype tag minVariant is zero.

14.4 Model transformations

Even simple variations are resulting into complex configuration spaces. It is necessary to have a simple view for a selected configuration. This view could be produced by a M2M-Transformation (M2M=Model to Model).

Three variations are spanning a three-dimensional configuration space (see Figure 90 3D configuration space) and eventually many more possible configurations. A configuration is one point in the configuration space.

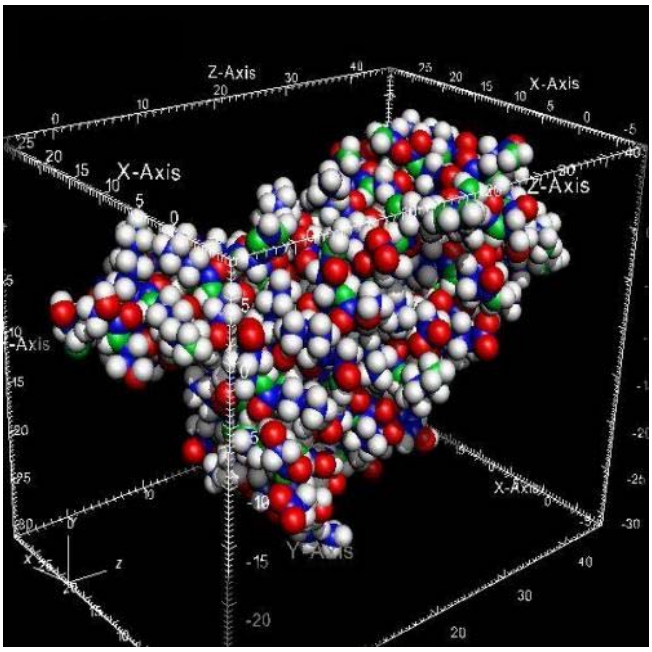


Figure 90 3D configuration space

The aims of the model transformation are:

- Face-out of irrelevant details.
- Creation of a product model out of a product family model.
- Elimination of non-existing variants and closure of variants because of superfluous abstractions.

The following categories of M2M transformation exist:

- **View- vs. Copy-Strategy:**
    - View: The transformation creates a view in the source model.
      -> Advantage: Seperation of Product Line Engineering and Product Engineering
    - Copy: The transformation creates a new model
      -> Effect: Discard of variants during the development phase.
- **Filter vs. Refactoring-Strategy:**
    - Filter: No more required model elements will be deleted (from the view or the copy)) by the transformation
      -> Easy to apply, but some „ballast“ remains

- Model-Refactoring: There exists not „the one and only“ transformation, but a set of adequate refactorings, with a corresponding non-trivial transformation
  -> Efect: best possible reduction of complexity, but hard to implement

An example of the simple filtering M2M approach is shown in Figure 91Filter approach:

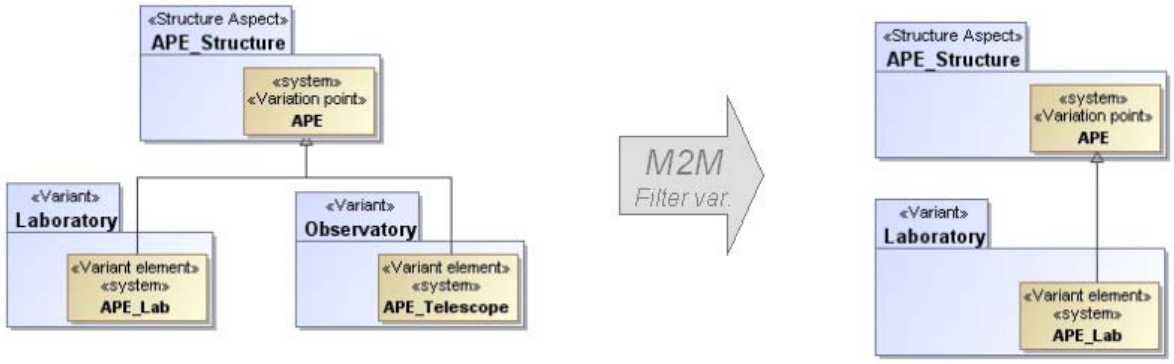


Figure 91Filter approach

The elements of the laboratory variant are presented. All other elements of the observatory variant are filtered out. But inheritance superclasses, used to derive variations, are still available in the model.

An example of the refactoring M2M approach is shown in Figure 92Refactoring approach:

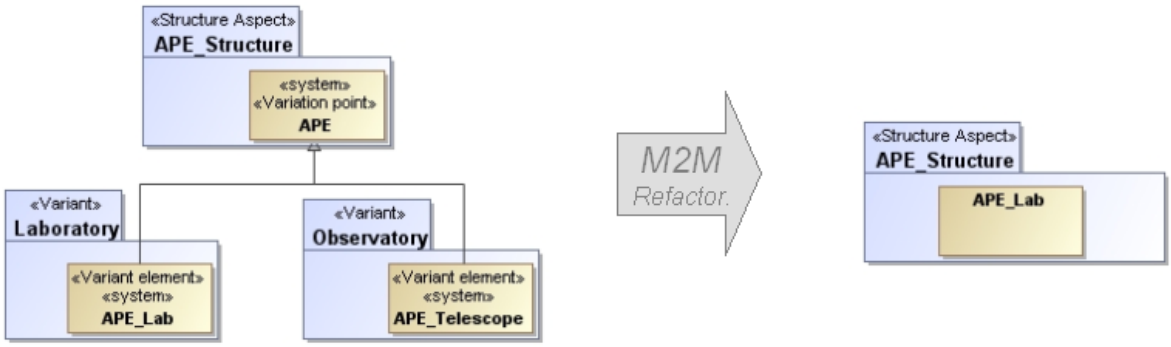


Figure 92Refactoring approach

Here the resulting model after the transformation, only contains the elements of the laboratory variant, the inheritance superclasses for deriving the variants, are also refactored out of the model.

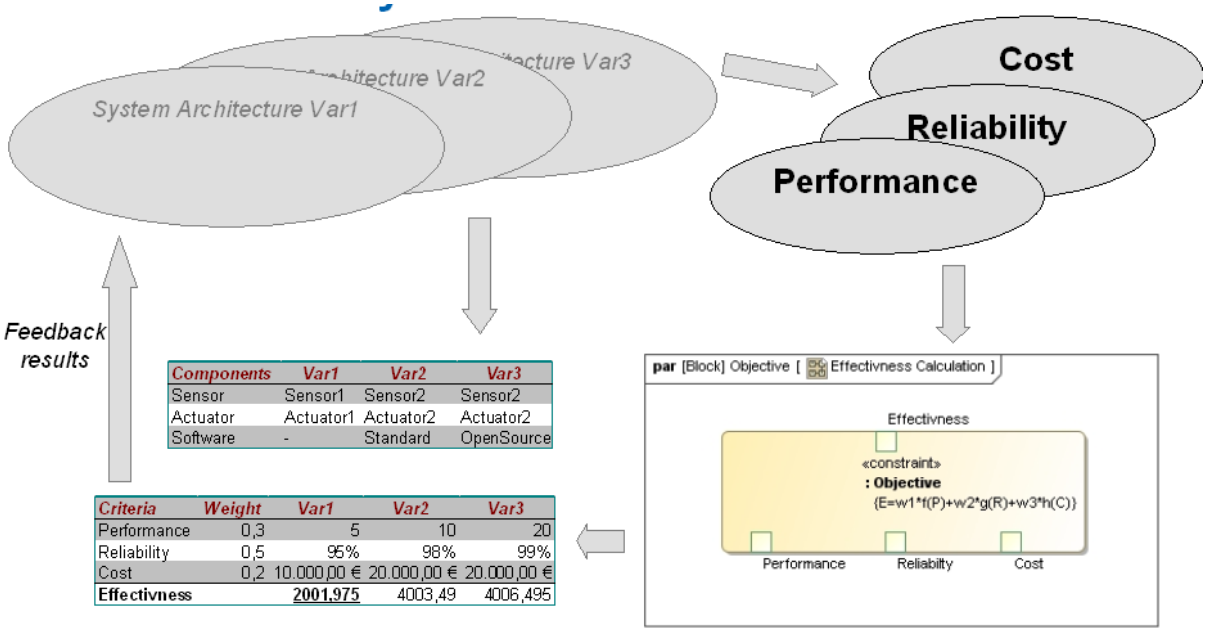
14.4.1 Open issues

There are open issues concerning M2M transformations:

- Until now model transformations are only manually applied in the telescope model.
- Simple approach could be easily implemented:
  E.g. MagicDraw offers the Module concept. This could be used to hide all other variants and present only the elements belonging to that module/variant.
- Automatic model transformation shall be evaluated by using transformation frameworks like OpenArchitectureWare, which is now part of the Eclipse Modeling Project
  http://www.eclipse.org/modeling/

14.5 Trade-Off analysis

Different alternatives/variants could be evaluated/weighted by applying trade-off studies. In Figure 93 Trade-Off Analysis shows the trade-off analysis process for three different variants. The performance indicators cost, reliability and performance are calculated and weighted by a effectiveness function defined as a parametric constraint. The “most effective” variant is the result of the trade-off.



Components	Var1	Var2	Var3
Sensor	Sensor1	Sensor2	Sensor2
Actuator	Actuator1	Actuator2	Actuator2
Software	-	Standard	OpenSource

Criteria	Weight	Var1	Var2	Var3
Performance	0,3	5	10	20
Reliability	0,5	95%	98%	99%
Cost	0,2	10.000,00 €	20.000,00 €	20.000,00 €
Effectivness		**2001,975**	4003,49	4006,495

Figure 93 Trade-Off Analysis (Source: Sanford Friedenthal:, Advancing Systems Engineering Practice Using Model Based Systems Development)

15 Cross-cutting the model and traceability

15.1 Guidelines for allocations

15.1.1 Can the same element be allocated to different blocks?

In principle yes. The spec says: a single «allocate» dependency shall have only one supplier (from), but may have one or many clients (to). (15.3.2.1 Allocate (from Allocations) – constraints).

Allocations of activities are a bit different. There an allocation is always a 100% allocation. If you have to allocate an action to more than one component you miss some information and you need more granularity in the activity diagram. Multiple allocation of activities is effectively a copy to different blocks, like executing the same action in parallel.

15.1.2 Should I allocate to part properties or to blocks?

Consistent allocation at same abstraction level is often not possible. Allocate at same level and then refine model by allocating functions to next lower level of structure.

If a part is owned by one block and referenced by another <<allocate>> has to be used to indicate that they are effectively the same part in the system.

15.1.3 How do I map an information port/connector to a physical one?

For a control system you need (at least) 2 perspectives:

- the information one, where I define standard ports realizing interfaces, resp. flow ports defining data flows. They are connected by <<information>> connectors
- the physical one, meaning the transport layer. i.e. the information (commands, data, etc) is transported over CANbus, ethernet, rs232, etc.
- Start with a information perspective where you simply specify components and their ports. At that point you do not know yet how they are physically connected. You might only know that one port runs over a low speed connection, another over a very high speed one, etc.
- Later on, they are allocated to some hardware.
- The information view defines what information is flowing; the electrical view defines how it is physically flowing.

<<allocate>> the information port to the physical and/or information connector to physical.

This scheme can be used to model data which flow in one IBD and allocate those information flow ports to a CANbus port in another IBD.

16 Domain Specific Model Extensions

16.1 Additional stereotypes

- Blocks which are used as a context for parametrics are stereotypes analysis context to distinguish them properly from normal blocks. otherwise there is always <<analysis context>> in the name of the block
- blocks which are used to type standard ports in order to realize interfaces and group ports, and represent a collection of interfaces are stereotyped <<portgroup>>
- blocks which act as a grouping mechanism of a system which is distributed within another system (e.g. an entertainment system in a car) but has its own lifecycle and product tree, yet is not necessarily co-located is stereotyped <<system group>>.

16.1.1 Where do I put (new) domain specific model elements, like stereotypes?

Create a Profile package.

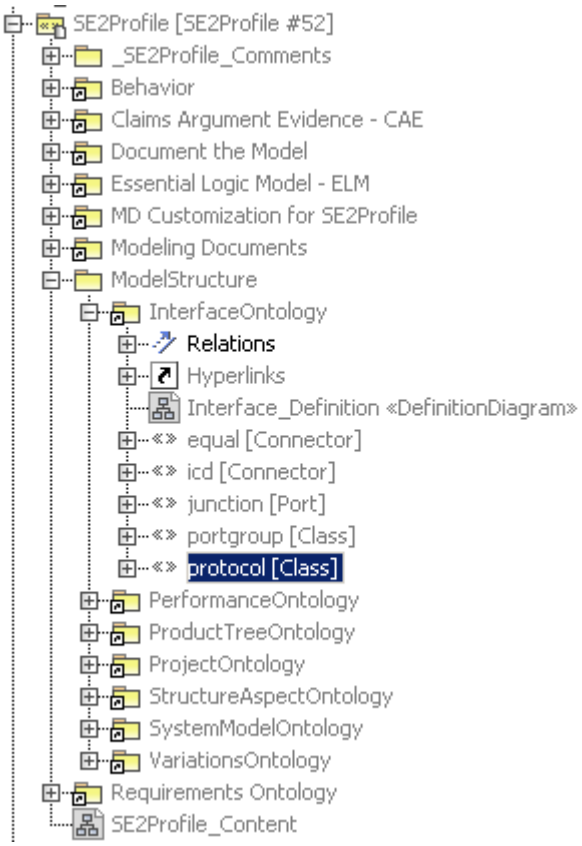


Figure 94 Containment tree of SE2 profile

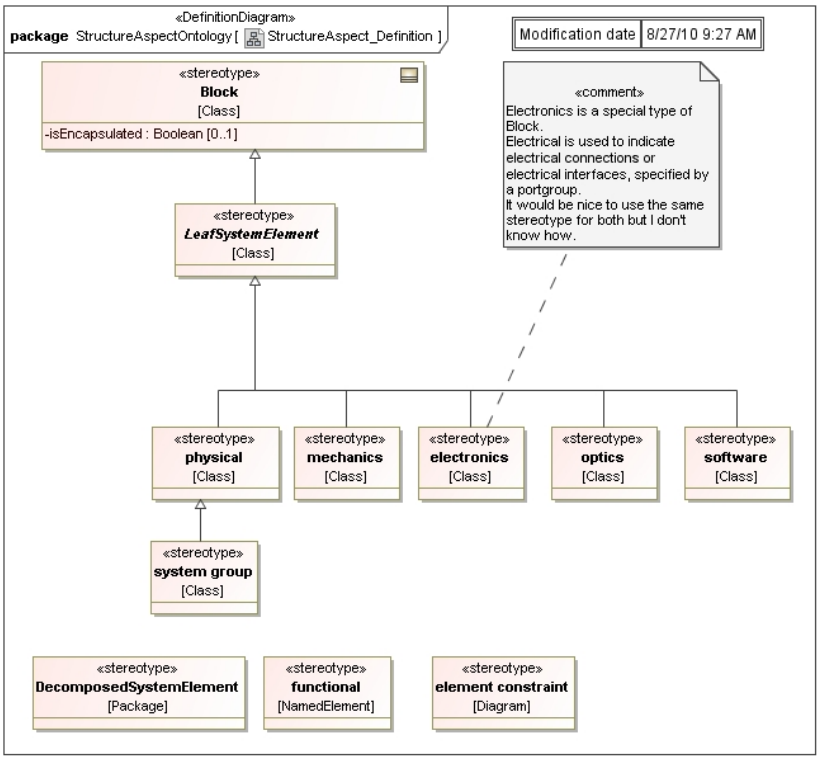


Figure 95 Domain specific stereotypes

16.2 Modeling domain specific Quantities, Units, and Values Types

Create a package, stereotyped <<modeling library>> for domain specific value types.

If you define your domain specific units based on the QUDV and SI Value Type ontology and profile, e.g. Jansky.

You have to use the QUDV, SI Value Type libraries.

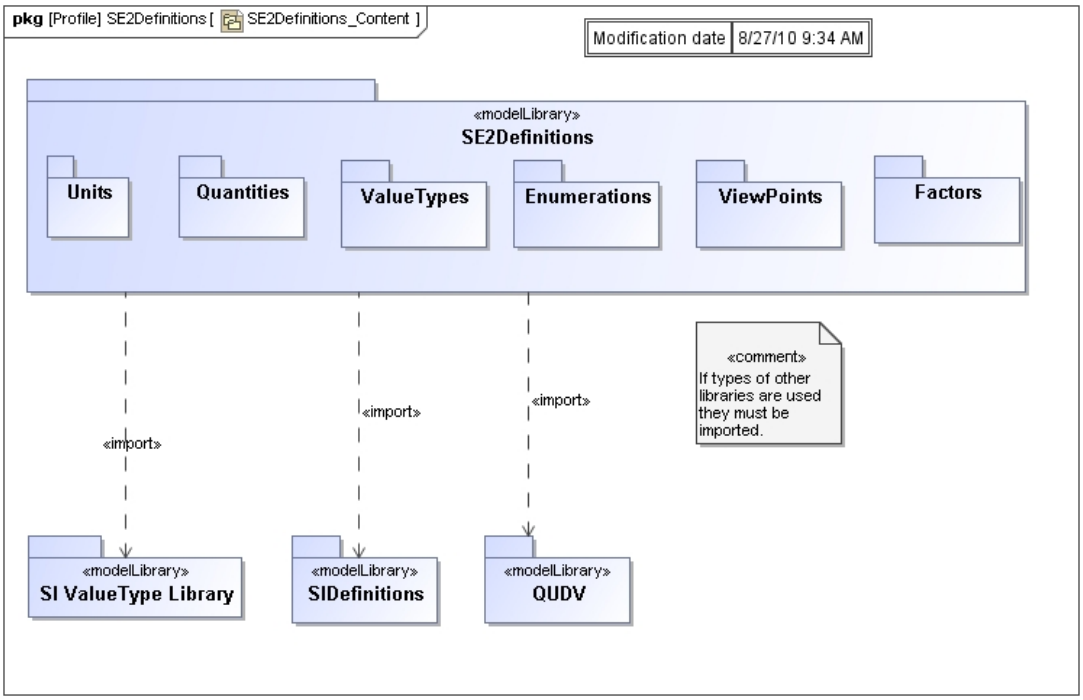


Figure 96 Package Structure of Doman Specific Definitions

In the package Factors you find four factors for the quantities and units.

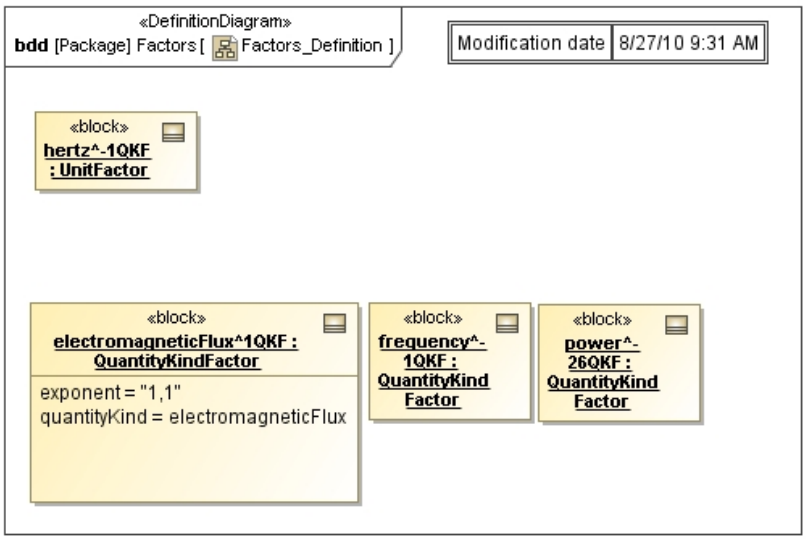


Figure 97 Instance Specifications of QUDV factors

In the package Quantities you find w derived quantities.

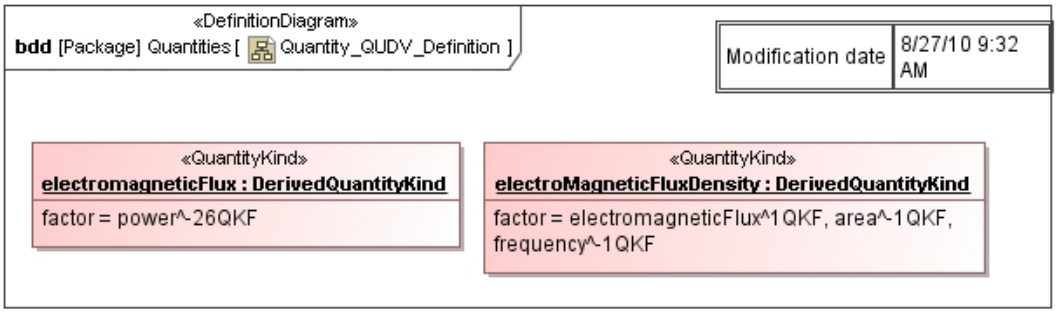


Figure 98 QuantityKinds according to QUDV

In the package Units you find Jansky as DerivedUnit.

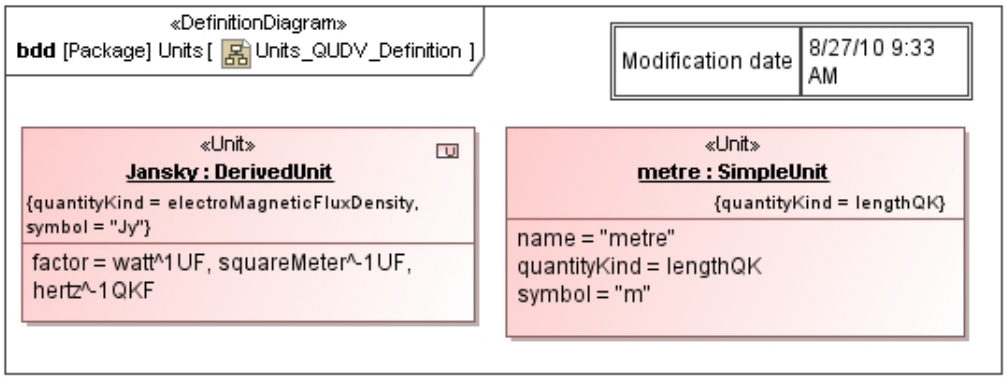


Figure 99 Units according to QUDV

17 Challenges of SysML deployment in an organization

- Best practices
  - Mentor and SysML/Tool confident person
  - Extend gradually the range, define modeling goals, guidelines, and standards
  - “Just use it!” (Do not talk about modeling and SysML too much as it raises fear of waste of time)
- Observations
  - (no) support/commitment from management but a necessity for engineering
  - How is presented to management? How do they see a gain? There is no immediate real-life artifact (no LED blinking, no tangible objects)
  - Under pressure people fall back to techniques they know
  - People are often lazy to learn/apply something new

- Not modeling means often not understanding and therefore underestimating the problem.
- Modeling reveals complexity and people get scared
- Contractual problems with models – only text is understood by lawyers

18 Tool (MagicDraw) related guidelines

18.1 Style and Layout

18.1.1 Remove stereotype <<block>> of parts in IBDs to increase readability

Parts in IBDs show by default the stereotype <<block>>. This clutters the diagrams and does not add any useful information. Hide the stereotype (it makes the diagram more compact) unless it adds value.

18.2 Navigation

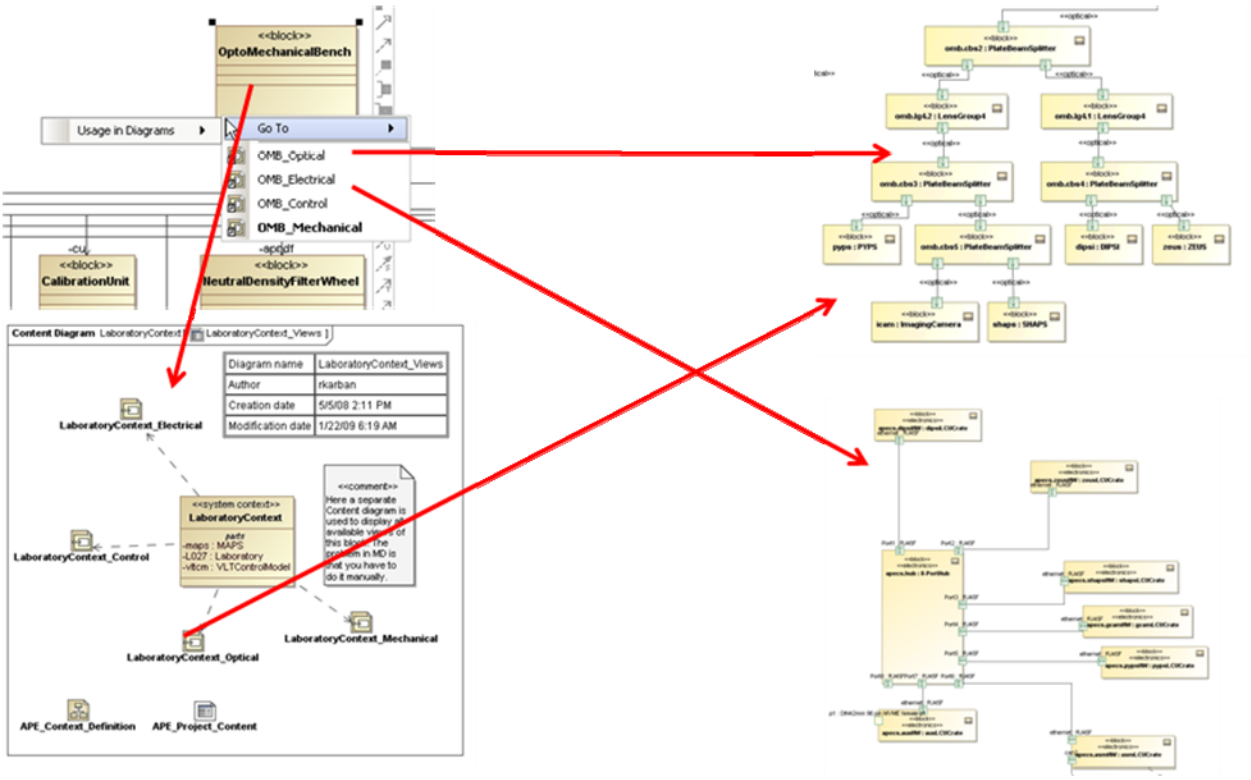


Figure 100 Hyper linking a Model for Navigation

- As soon as you create a new element's symbol, ask yourself: "What can I hyperlink it to ?"[11].
- Hyperlink every single model or package to a SysML Package Diagram (or SysML Block Definition Diagram)
- Hyperlink every assembly Block to its Internal Block Diagram (IBD)[12]
- Place at least one Block Definition Diagram (BDD) diagram icon on every Internal Block Diagram (IBD)

[11] In MagicDraw drag a diagram icon onto it
[12] If you use MagicDraw SysML's StructuredBlock menu that is done automatically for you.

- Drag the Internal Block Diagram (IBD) icon of the Type of a Property onto that Property in an IBD so that you can open up a part into its matching IBD.
- Hyperlink your top-level SysML ‘system’ and/or ‘system context’ to their IBD or BDD and place them on every diagram possible throughout your project. However, be aware that this can prevent modularization.

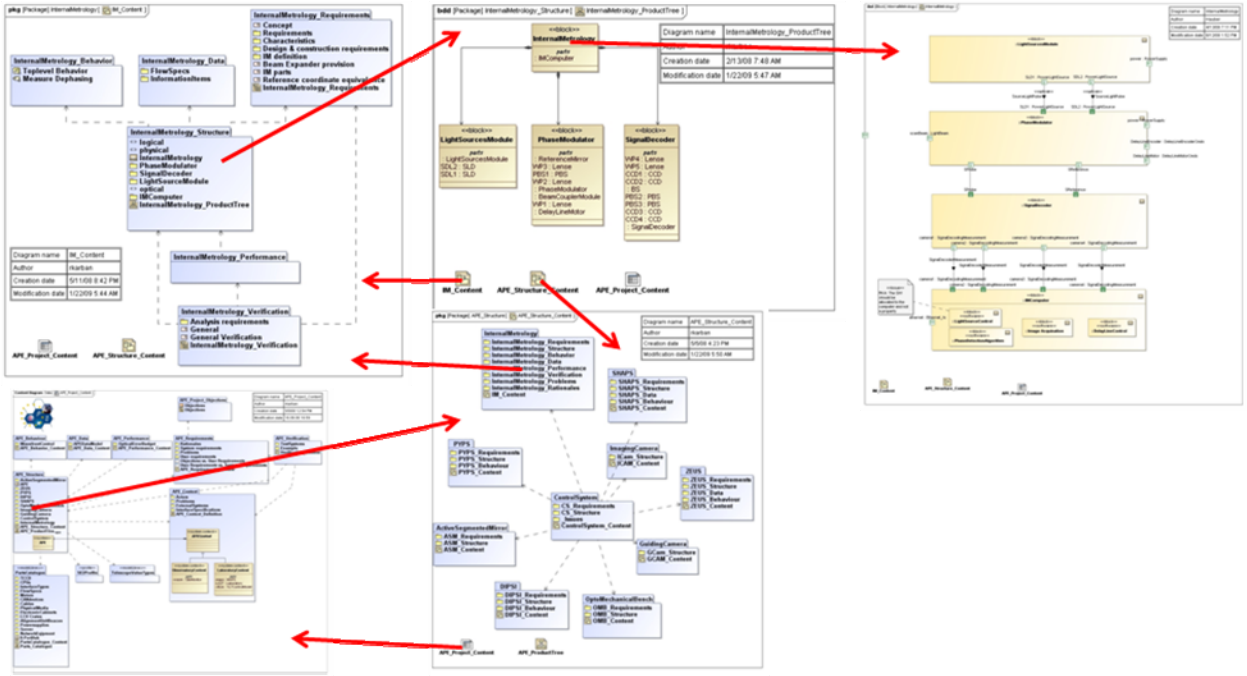


Figure 101 Navigation with hyper links

Navigate on elements.

Navigate very little via the browser. You need to make you project completely navigable ON THE ELEMENTS and also ON THE PACKAGES. It is a basic systems engineering idiom. One needs to be able to OPEN UP packages and OPEN UP systems and blocks.[13]

Use hyperlinked packages with contents list and dependencies between packages.

You can also show (possibly stereotyped) dependencies between packages better to reinforce the sense of systems engineering, You don't have to be too fancy, just reflect the basic sense or process.

You need a clearly stated <<system>> (APE)

Show BOTH a <<system>> and a <<system context>> at the very top level. (You needn't show the parts and properties, however you might like to.) Also, you should link your Context to a diagram (like Context Definition).

The hyperlinks to a block lead you to its Content and structure diagrams

A block, representing a complete sub-system, is hyperlinked to its _Content diagram and to its IBDs.

[13] In MagicDraw: All you need to do is create package diagrams for your packages and drag the package diagram icon from the browser onto the package symbol in a diagram.