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Software Engineering for Embedded Systems

An introduction to the Systems Modeling Language

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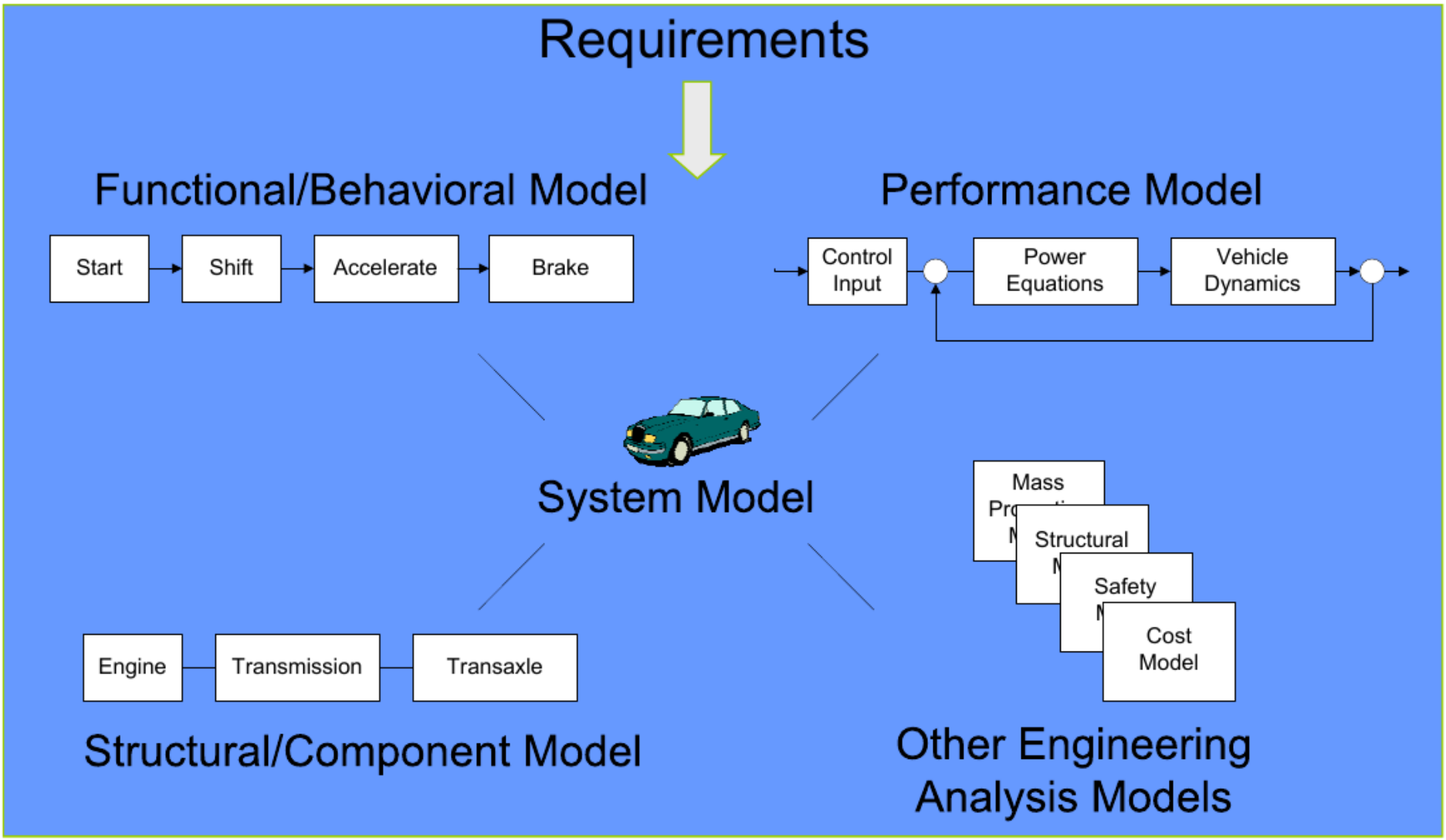
Outline

Systems Modeling Language

What is Systems Engineering?

- Systems Engineering is a discipline that concentrates on the design and application of the **whole (system)** as distinct from the parts. It involves looking at the problem in its entirety, taking into account all the facets and all the variables. (*Federal Aviation Agency FAA-USA, Systems Engineering Manual, Definition by Simon Ramo, 2006*)
- Systems Engineering is an iterative process of top-down synthesis, development and operation of a **real-world system** that satisfies, in a near-optimal manner, the full range of requirements for the system. (*Definition by Howard Eisner, Essentials of Project and Systems Engineering Management, Wiley, 2002*)

System modeling



Benefits of model-based Systems Engineering

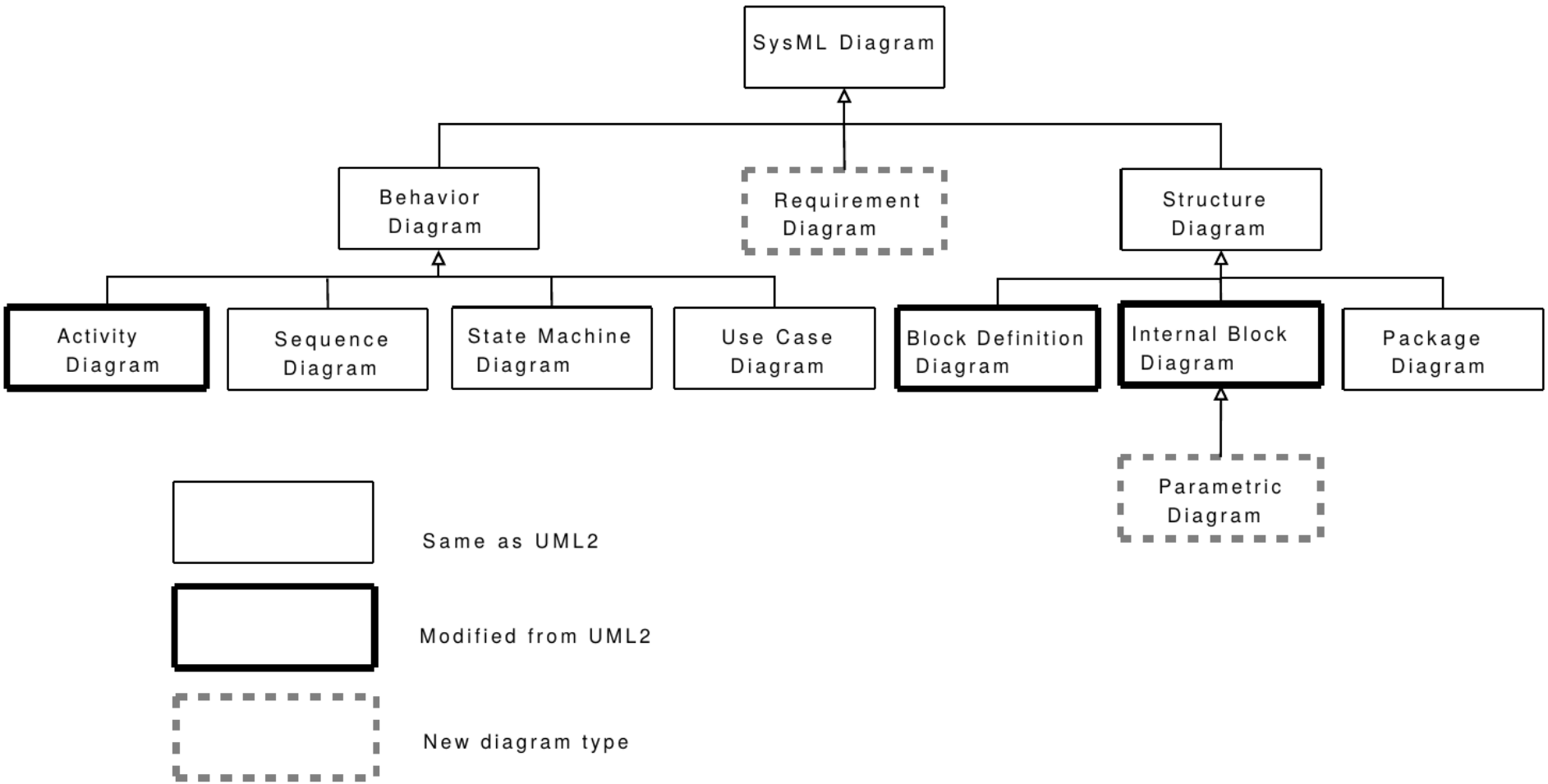
- Shared understanding of system requirements and design
  - Validation of requirements
  - Common basis for analysis and design
  - Facilitates identification of risks
- Assists in managing complex system development
  - Separation of concerns via multiple views of integrated model
  - Supports traceability through hierarchical system models
  - Facilitates impact analysis of requirements and design changes
  - Supports incremental development & evolutionary acquisition
- Improved design quality
  - Reduced errors and ambiguity
  - More complete representation
- Supports early and on-going verification & validation to reduce risk
- Provides value through life cycle (e.g., training)
- Enhances knowledge capture

Systems Modeling Language (SysML)

- Is a graphical modeling language adopted by the OMG in 2006
- Supports specification, analysis, design, verification, and validation of systems that include hardware, software, data, personnel, procedures, and facilities
- Is a visual modeling language that provides
  - Semantics = meaning, connected to a metamodel
    (rules governing the creation and the structure of models)
  - Notation = representation of meaning, graphical or textual
- Is not a methodology or a tool (SysML is methodology and tool independent)
- Extends a subset of UML2
  - The Unified Modeling Language (UML) is a general-purpose, developmental, modeling language for software-intensive applications (**software engineering**)

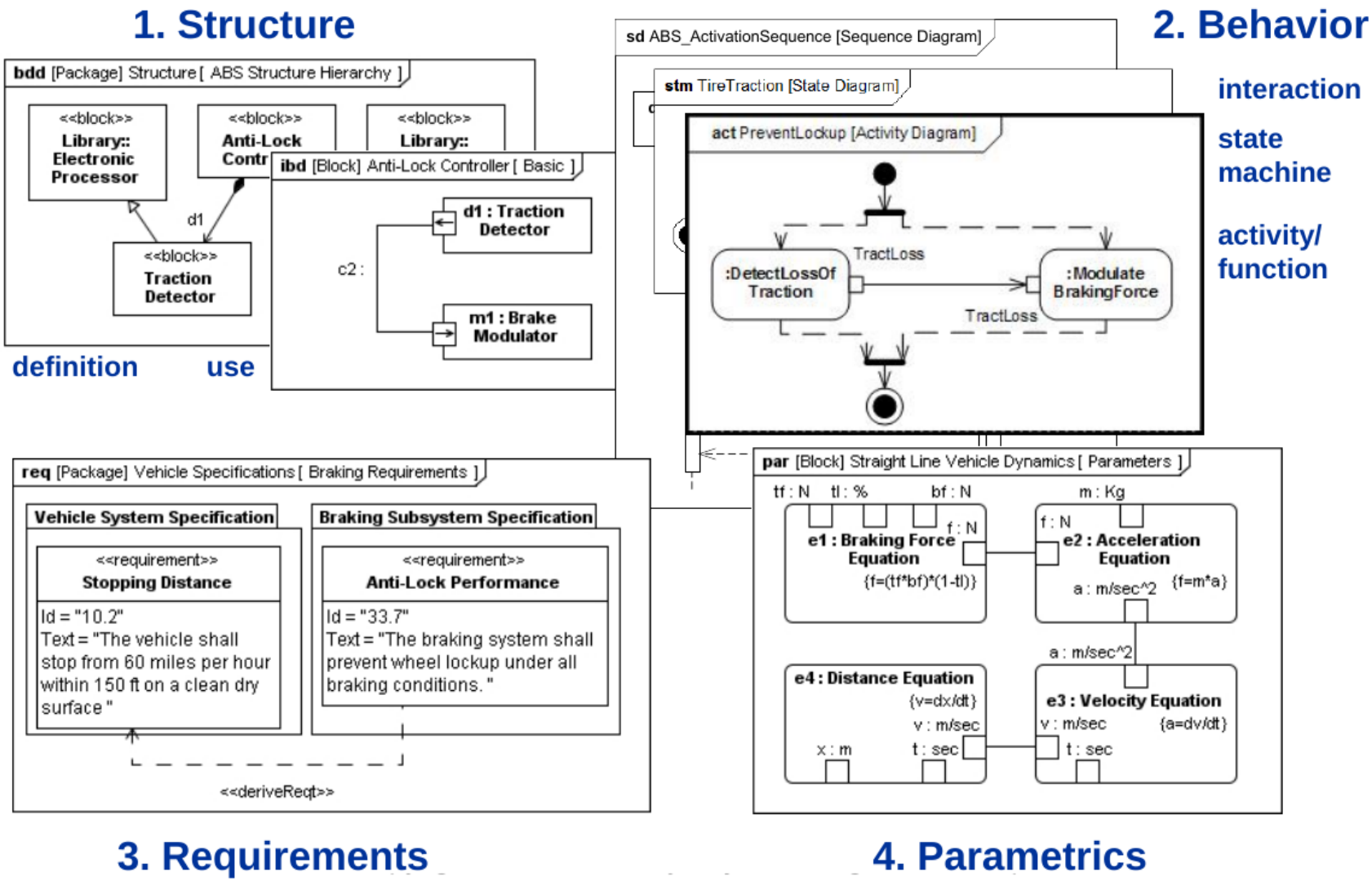
SysML vs UML

- SysML diagrams

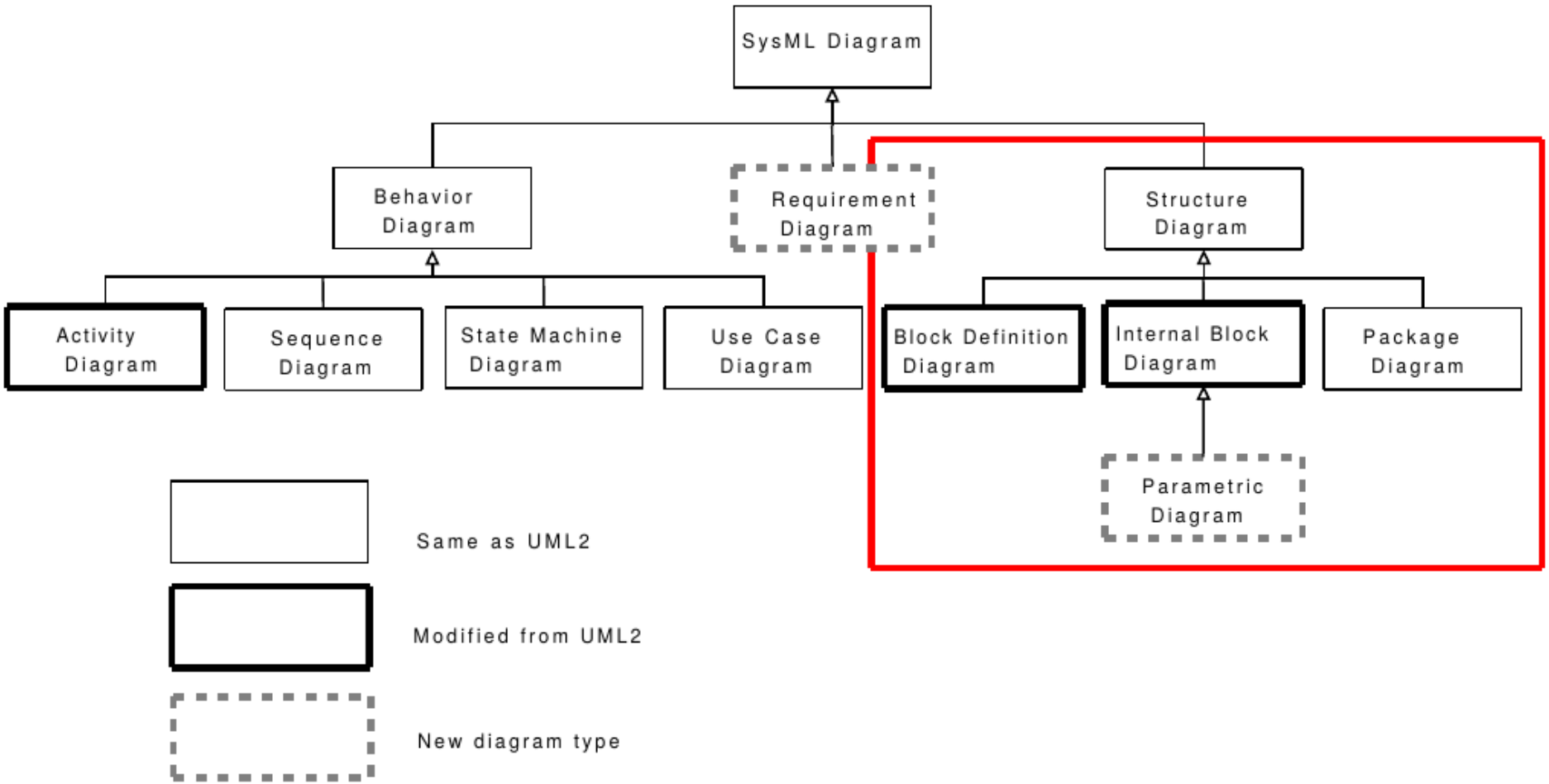


4 pillars of SysML

- Example of modeling of an ABS system



Structural diagrams



Package diagrams

- Same as in UML2
- Used to organize the model
  - Groups model elements into a name space
  - Often represented in tool browser
  - Support model configuration management (check-in/out)
- The model can be organized in multiple ways
  - By System hierarchy (e.g., enterprise, system, component)
  - By diagram kine (e.g., requirements, use cases, behavior)
  - Use viewpoints to augment model organization

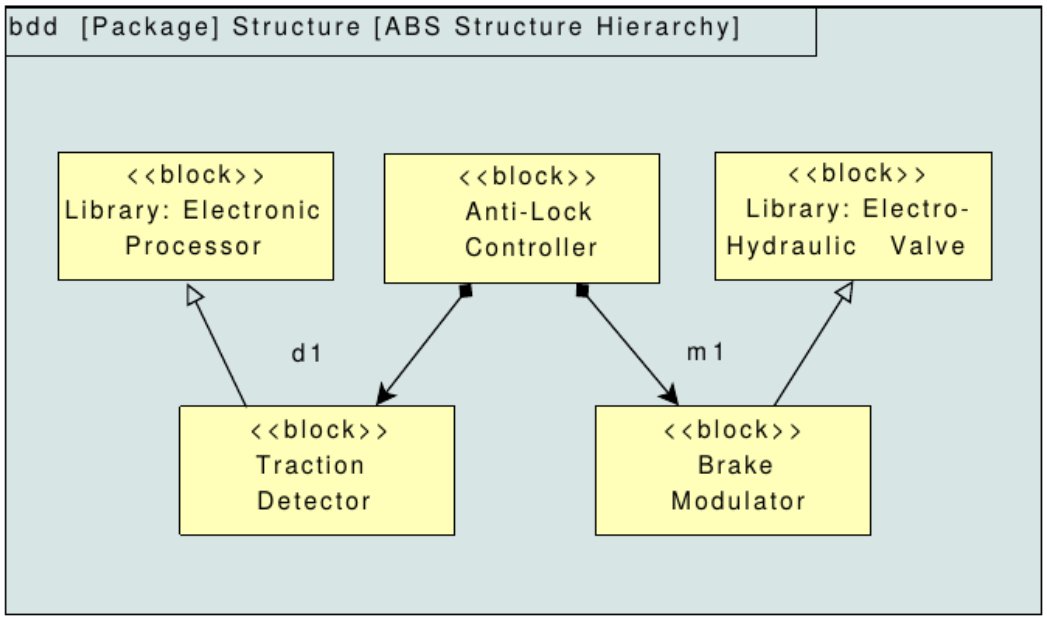
Block

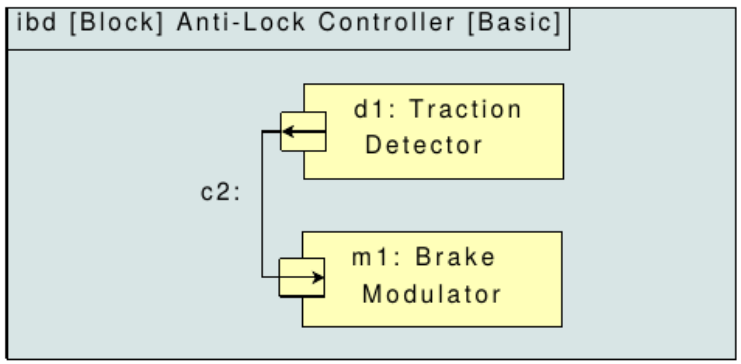
- Is a basic structural element
- Defines a set of structural and functional features to describe an element or system (software, hardware, data, procedures, . . .)
- Used during both physical and logical design
- Its characteristics can be described by multiple standard compartments
  - Properties (parts, references, values, ports)
  - Operations
  - Constraints
  - Allocations from/to other model elements (e.g., activities)
  - Requirements the block satisfies
  - User defined compartments
- Can be used to specify hierarchies and interconnection

Block Definition Diagrams and Internal Block Diagrams (1/2)

- A Block Definition Diagram (BDD) described the relationships among blocks (e.g., composition, association, specialization)
  - Same as a type definition (corresponds to a UML class diagram)
  - Reused in multiple contexts
  - Cannot define completely the communication dependencies and the composition structure (no topology)
- An Internal Block Diagram (IBD) describes the internal structure of a block in terms of its properties and connectors
  - Part is the usage of a block in the context of a composing block (also known as role)
  - Internal structure and communication & signalling topology become explicit
- Ports specify interaction points on blocks and parts
  - Integrate behavior with structure
  - Standard (UML) Ports specify required or provided operations and/or signals (used for software components)
  - Flow Ports specify what can flow in/out of a block/part (used for signals and physical flows)

Block Definition Diagrams and Internal Block Diagrams (2/2)

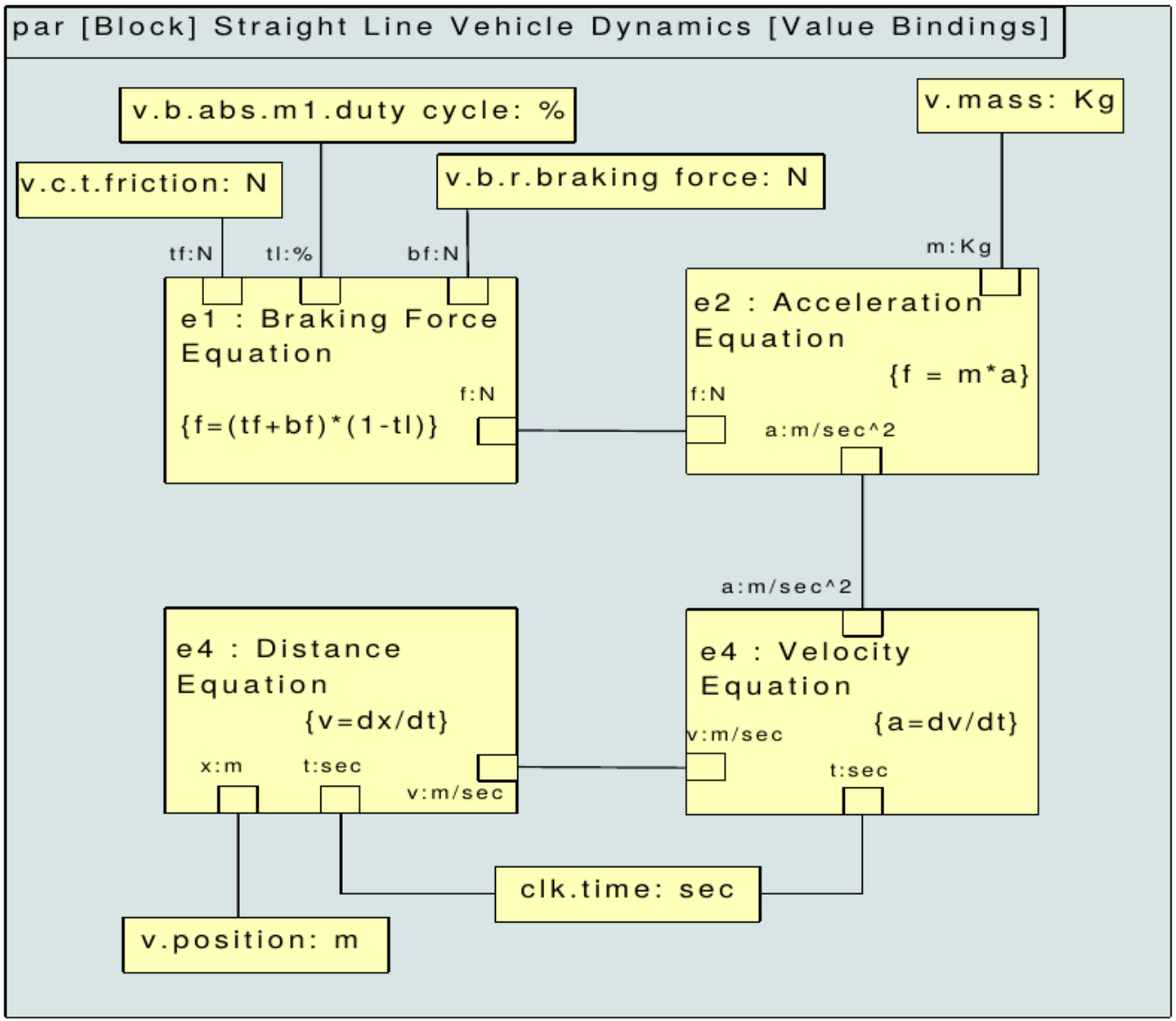




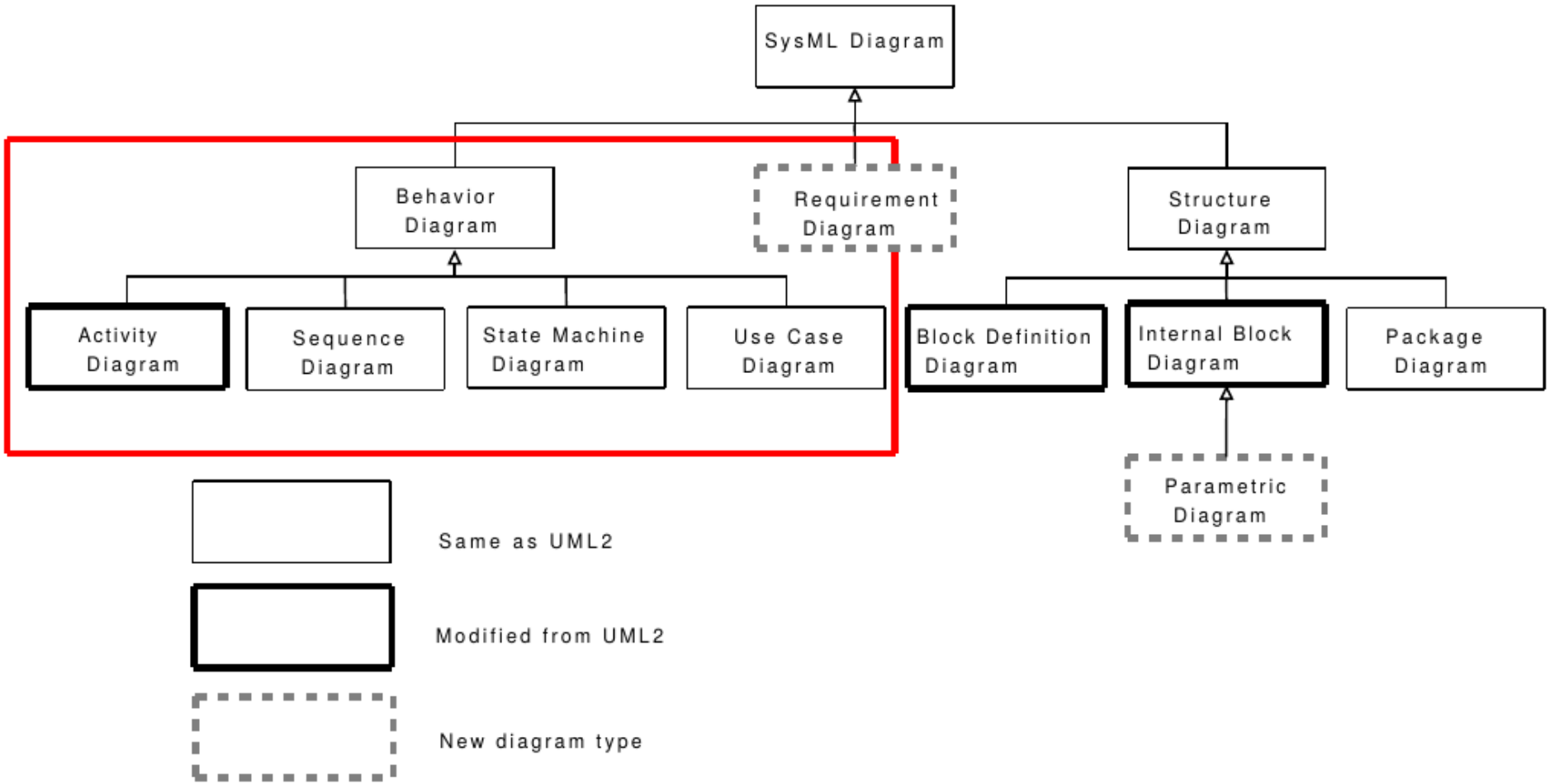
Parametric Diagram (1/2)

- Used to express constraints (equations) between value properties
  - Provides support for engineering analysis (e.g., performance, reliability)
  - Facilitates identification of critical performance properties
- Represents the usage of constraints in an analysis context
  - Constraints are defined by constraint blocks capturing equations
  - Expression language can be formal or informal
  - Computational engine is provided by applicable analysis tool and not by SysML
  - Binding of constraint parameters to value properties of blocks

Parametric Diagram (2/2)



Behavioral diagrams



Activity Diagrams

- Specify transformation of inputs to outputs through a controlled sequence of actions
- Similar to dataflows with enhancements that allow the representation of a more general semantics, including modeling of continuous physical flows
- Secondary constructs show responsibilities for the activities using activity partitions (i.e., swimlanes)
  - SysML adds support for continuous flow modeling (modeling of continuous-time systems)
  - Alignment of activities with classical systems engineering techniques, e.g., Enhanced Functional Flow Block Diagrams (EFFBDs)

Sequence Diagrams

- Provide representations of message based behavior
  - Represent flow of control
  - Describe interactions between parts
- Provide mechanisms for representing complex scenarios
  - Reference sequences
  - Control logic
  - Lifeline decomposition
- Also known as Interaction Diagrams or Interactions

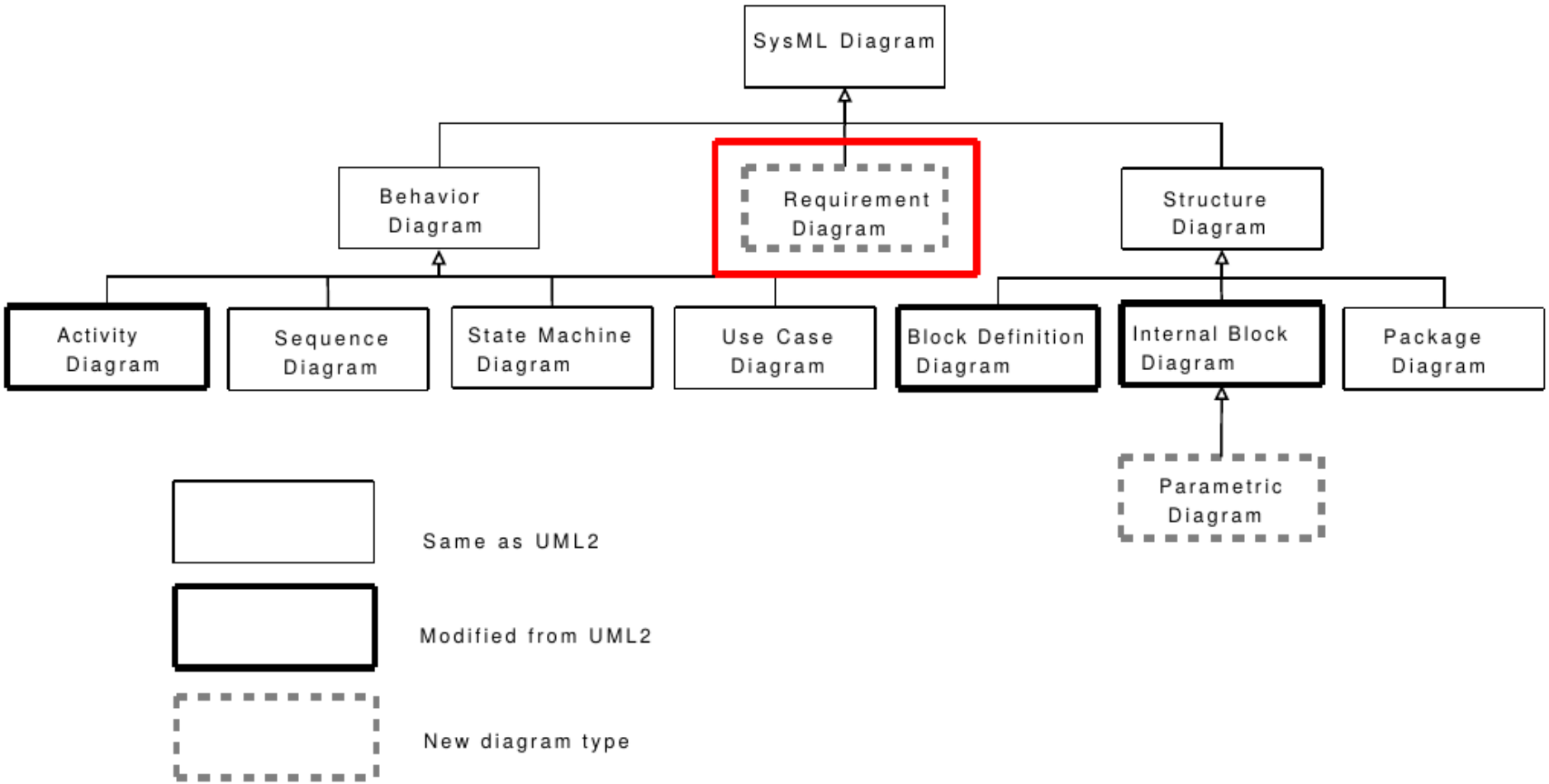
State Machine Diagrams

- State Machines are used to represent the life cycle of a block
- State Machines support the representation of event-based behavior (generally asynchronous behavior)
  - Transition with trigger, guard, action
  - State with entry, exit, and do-activity
  - Can include nested sequential or concurrent states
  - Can send/receive signals to communicate between blocks during state transitions
  - Change events, time events, signal events

Use Case Diagrams

- Provide means for describing basic functionality in terms of usages/goals of the system by actors
  - Use is methodology dependent
  - Often accompanied by use case descriptions
- Common functionality can be factored out via ≪include≫ and ≪extend≫ relationships
- Elaborated via other behavioral representations to describe detailed scenarios
- No changes with respect to UML

Cross-cutting constructs



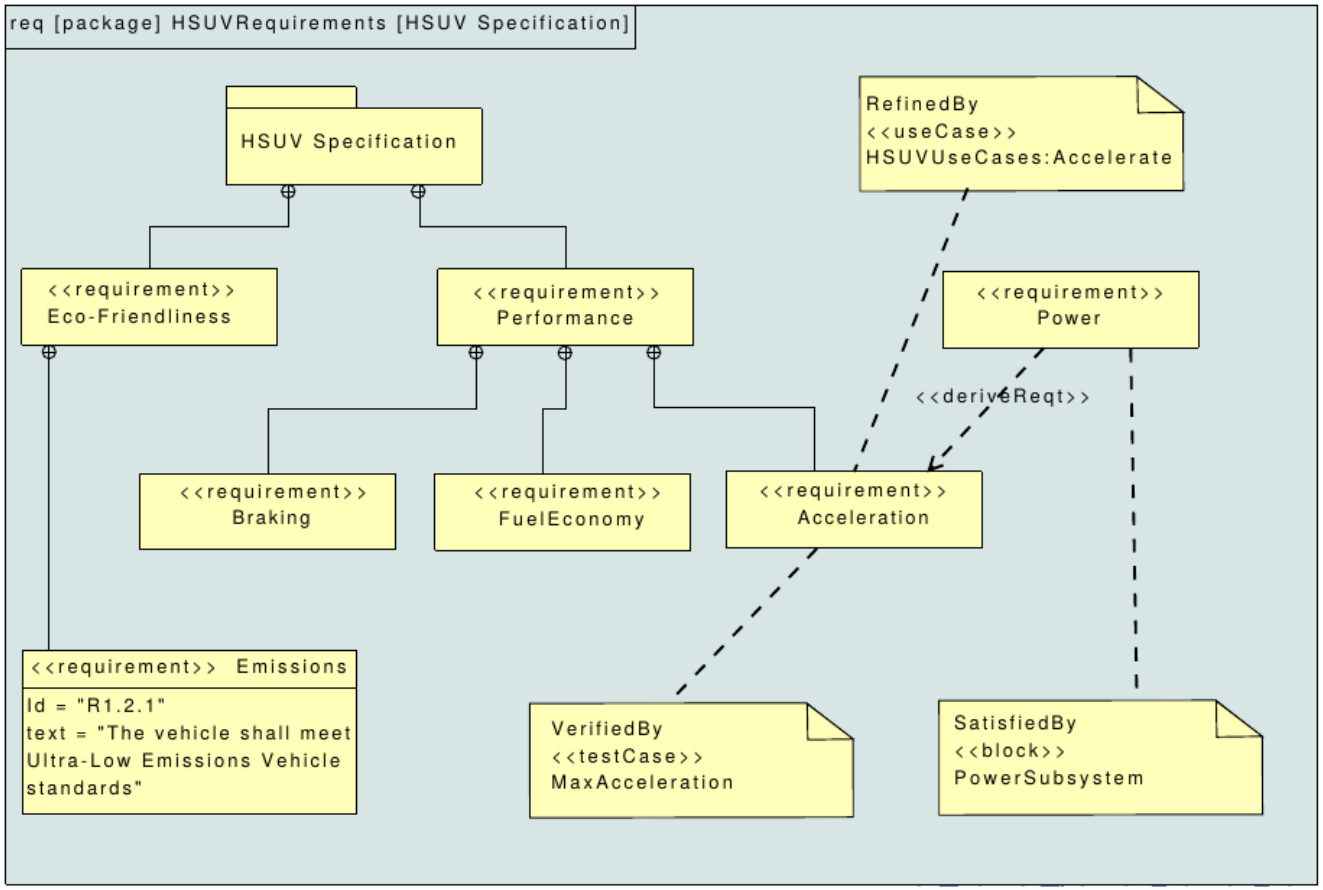
Allocations

- Represent general relationships that map one model element to another
- Different types of allocation
  - Behavioral (i.e., function to component)
  - Structural (i.e., logical to physical)
  - Software to Hardware
  - ...
- Explicit allocation of activities to structure via swimlanes (i.e., activity partitions)
- Both graphical and tabular representations are specified

Requirements

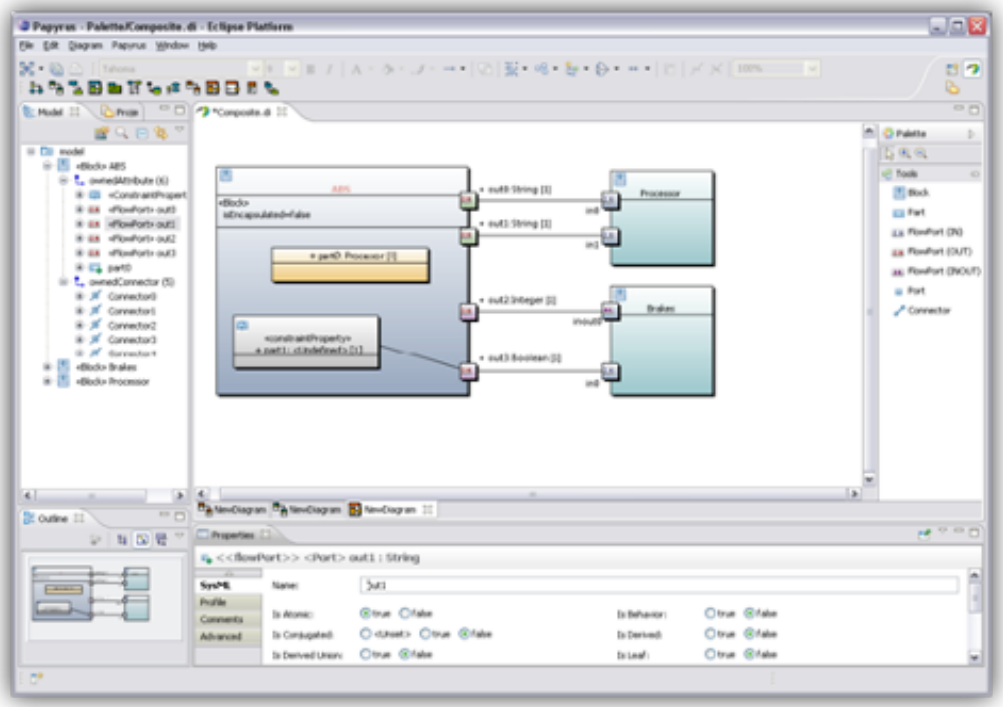
- The ≪requirement≫ stereotype represents a text based requirement
  - Includes id and text properties
  - Can add user defined properties such as verification method
  - Can add user defined requirements categories
    (e.g., functional, interface, performance)
- Requirements hierarchy describes requirements contained in a specification
- Requirements relationships include:
  - `DeriveReqt`
  - `Satisfy`
  - `Verify`
  - `Refine`
  - `Trace`
  - `Copy`

Requirement Diagram



Papyrus

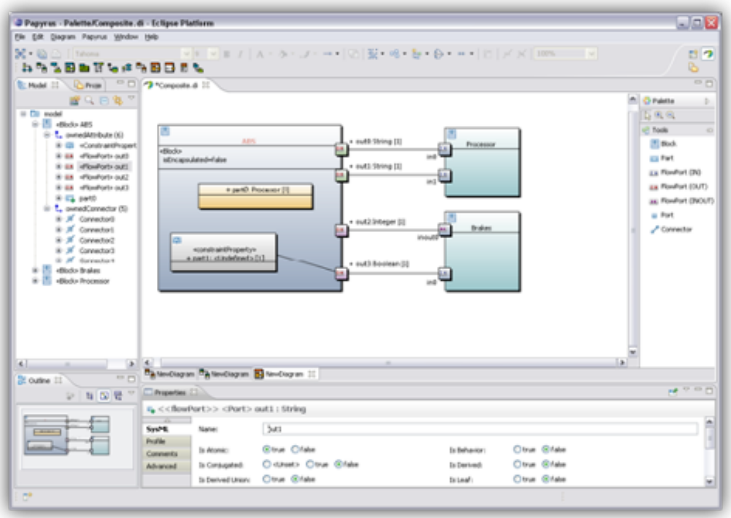
- An open source tool based on Eclipse providing an integrated environment for editing UML and SysML models
  - Developed by the Laboratory of Model Driven Engineering for Embedded Systems of the French Alternative Energies and Atomic Energy Commission
  - Home page: `https://www.eclipse.org/papyrus`
  - Can be used either as a standalone tool or as an Eclipse plugin



Papyrus: how to install the tool

- Select *Help* → *Install New Software*
- In *Work with*, add the following link: `http://download.eclipse.org/modeling/mdt/papyrus/updates/releases/2019-09`
- Select *Add* → *Papyrus for UML* and start the installation

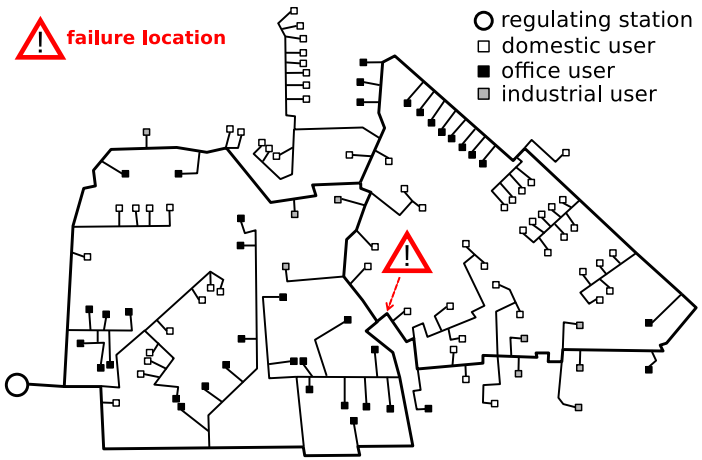
- Select *Help* → *Install New Software*
- In *Work with*, add the following link: `http://download.eclipse.org/modeling/mdt/papyrus/components/sysml14`
- Select *Add* → *SysML* and start the installation

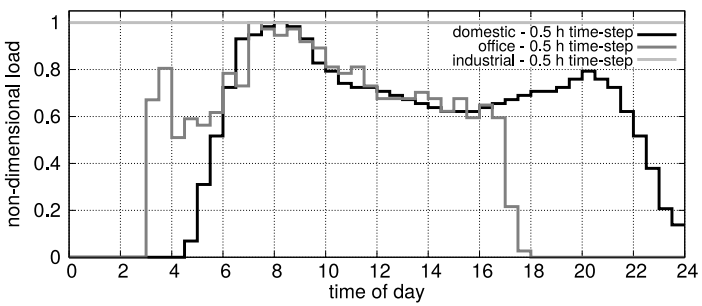


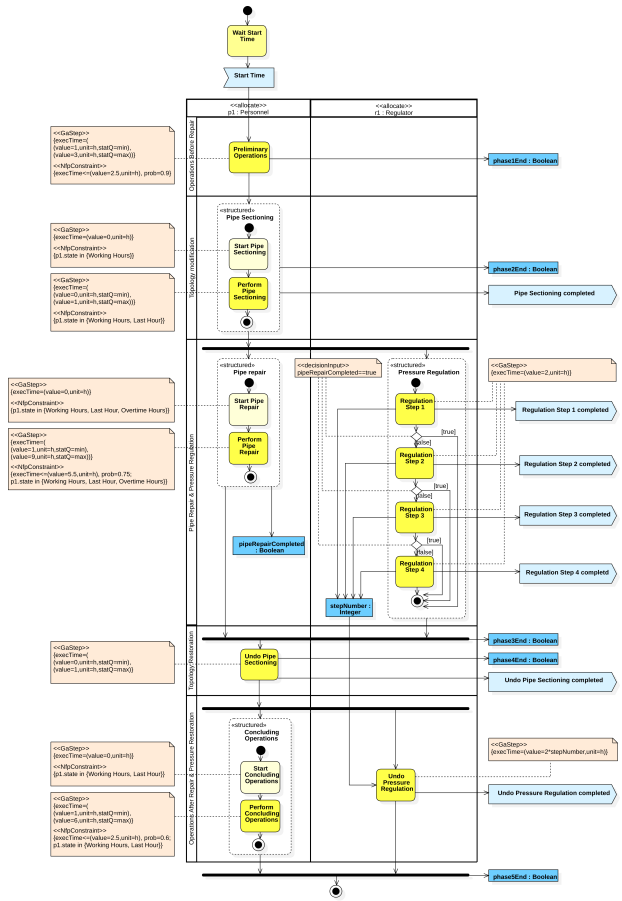
An example in the area of cyber-physical systems

Gas distribution networks

- Couple **physical** fluid-dynamics with **cyber** management procedures
- Goal: evaluate the **low pressure risk** in the transient phase after a repair
  - Fluid-dynamic analysis of gas behavior, stochastic analysis of repair actions



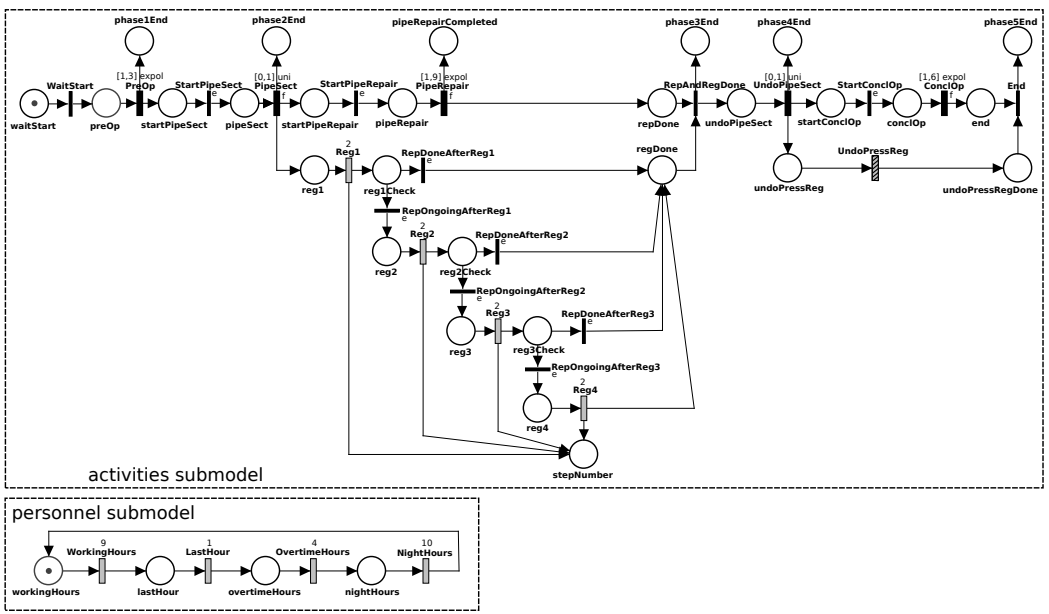




M. Biagi, L. Carnevali, F. Tarani, E. Vicario, "Model-based quantitative evaluation of repair procedures in gas distribution networks," ACM Transactions on Cyber-Physical Systems, 2019.

Solution combining fluid-dynamic and stochastic analyses

- Fluid-dynamic analysis of gas behavior
  - Derives the Low Pressure Risk (LPR) experienced in each fluid-dynamic state
- Forward transient analysis of the repair procedure
  - Derives the transient probability of each fluid-dynamic state
  - Instantaneous transient reward $\sum_{\gamma \in \Gamma} \texttt{If}\,(e(m,\gamma), \mathrm{LPR}_\gamma, 0)$
    (Γ is the set of fluid-dynamic states, LPR_γ is the LPR measure in $\gamma \in \Gamma$, $e(m,\gamma)$ is TRUE if marking m represents state γ, FALSE otherwise)
- Solution yields the expected **Low Pressure Risk (LPR)** over time



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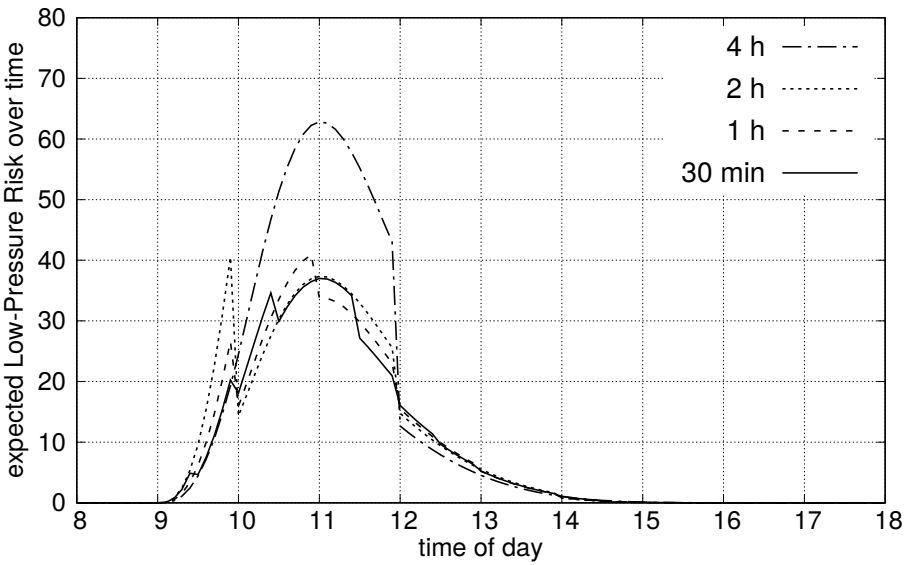
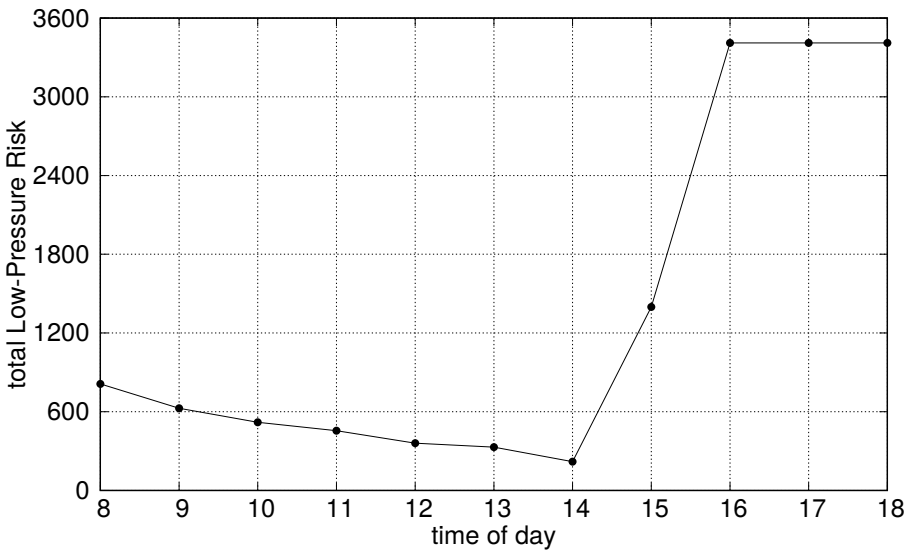
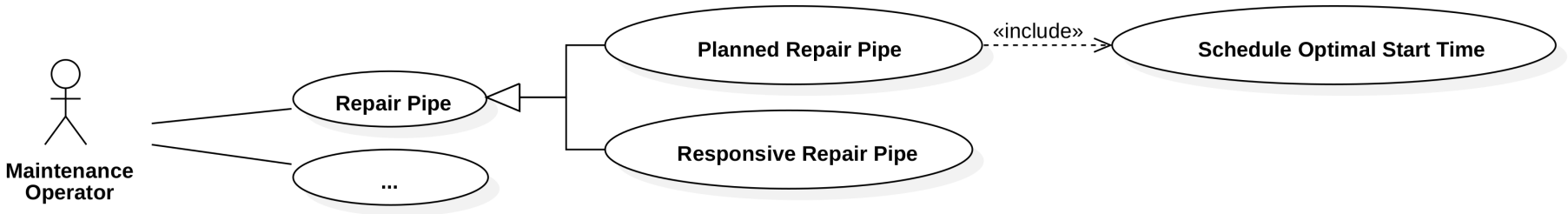




SysML: Use Case Diagram and Requirements

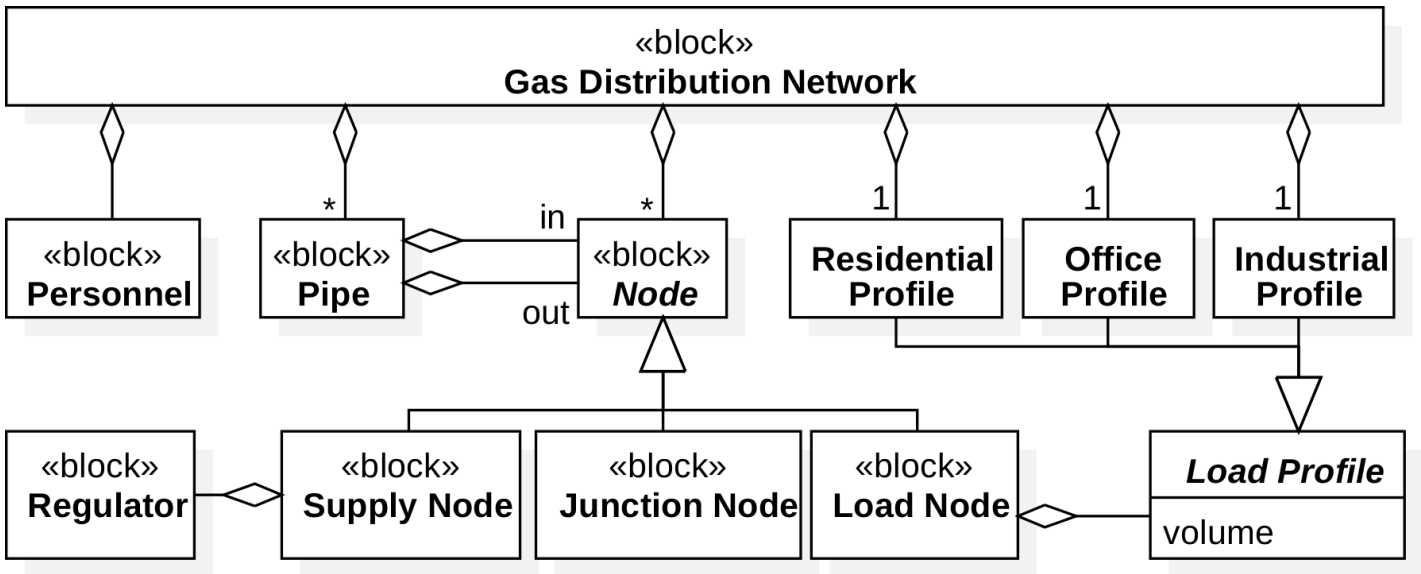
- Use Case Diagram of the pipe repair scenario



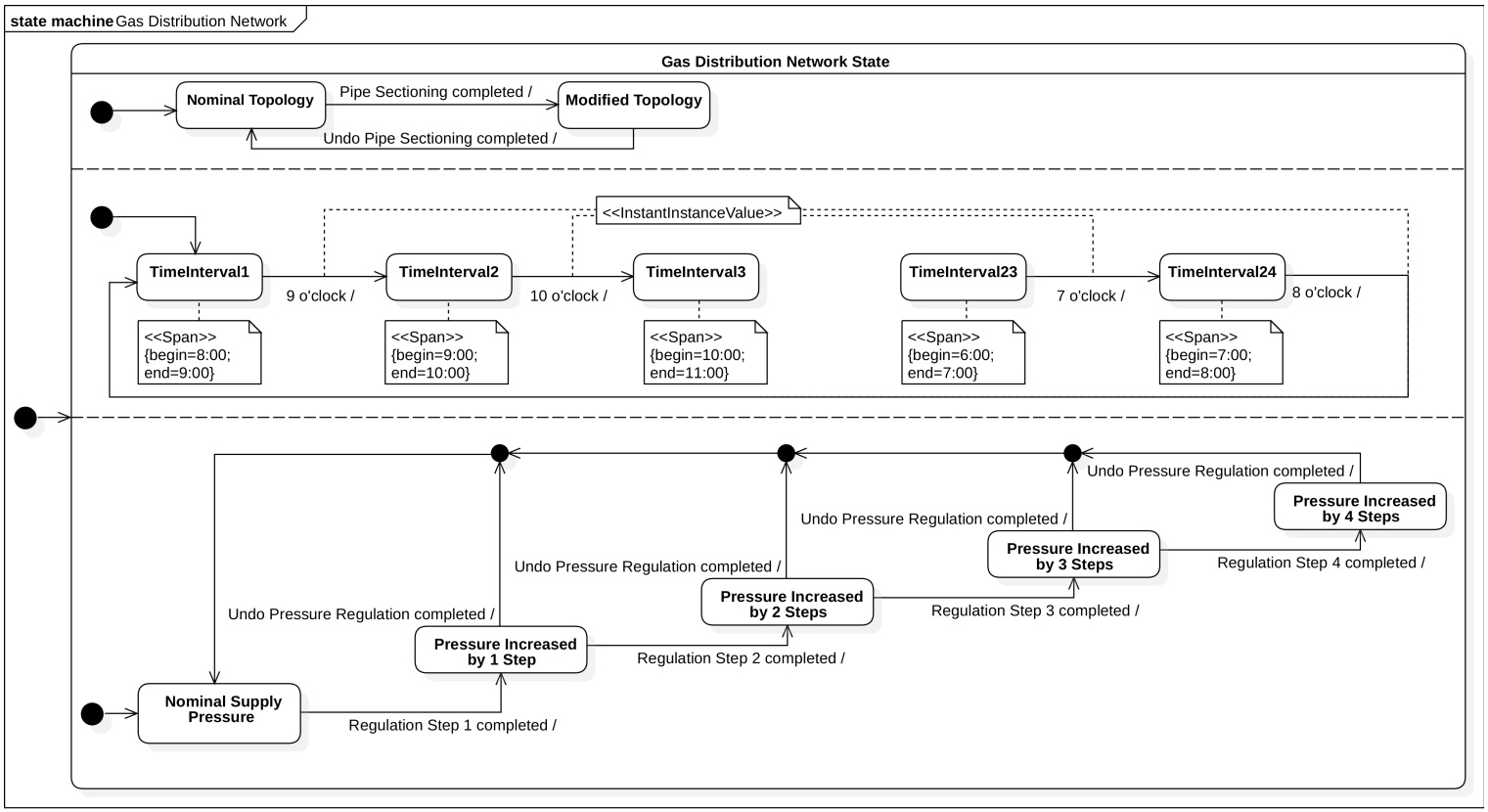
- Requirements Table

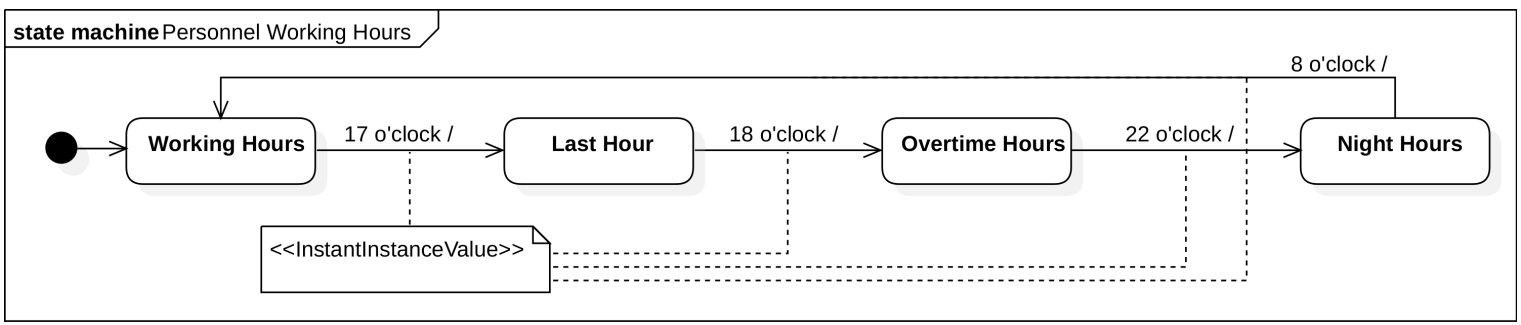
Use Case	Requirements
Planned Repair Pipe	The procedure `Completion Time` must be $<$ 36 h in 75% of the cases, and $<$ 48 h in 99.99% of the cases.
	The `Low-Pressure Risk` at any time must be $<$ 240 $\text{bar}^{1/2}$ on average.
Responsive Repair Pipe	The procedure `Completion Time` must be $<$ 24 h in 75% of the cases, and $<$ 36 h in 99.99% of the cases.
	The `Low-Pressure Risk` at any time must be $<$ 360 $\text{bar}^{1/2}$ on average.

SysML: Block Definition Diagram of the involved resources

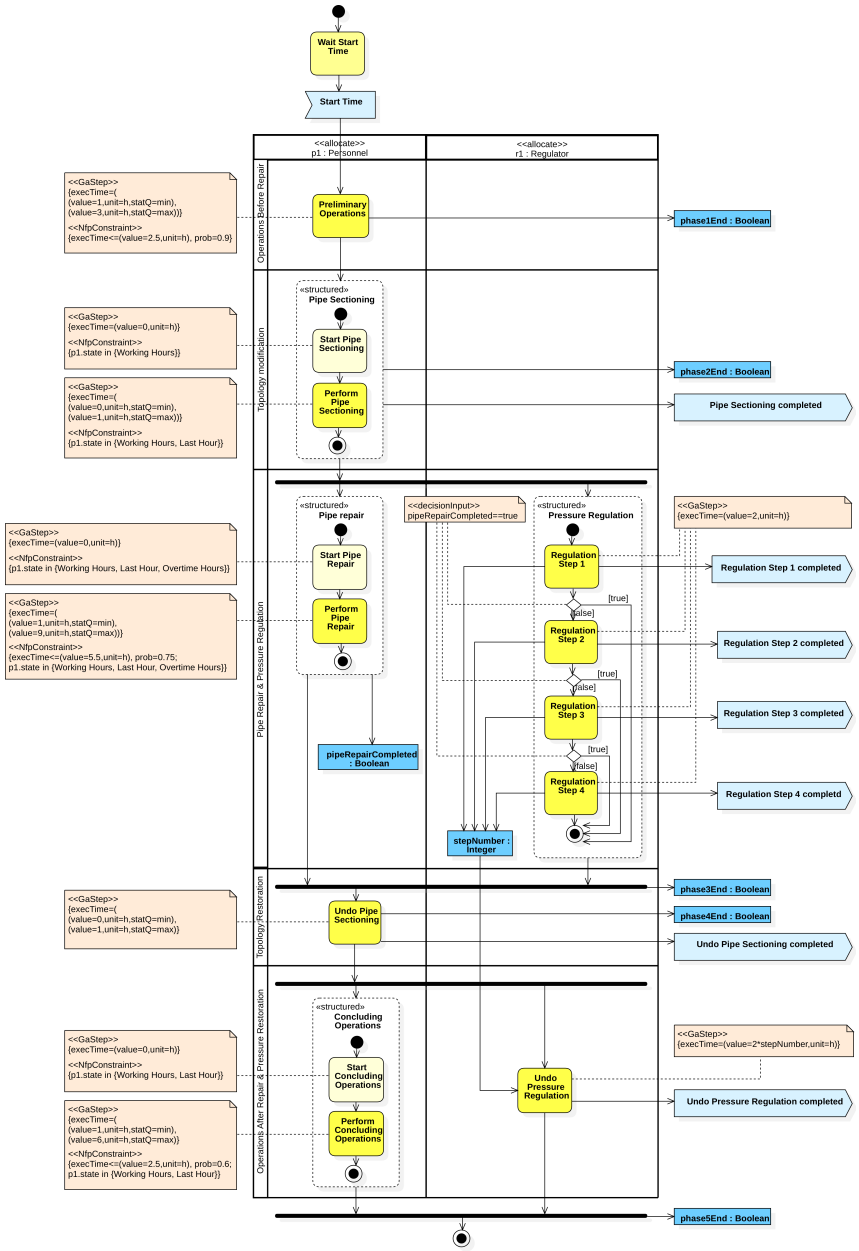


SysML: State Machine Diagrams of the network and personnel





SysML: Activity Diagram of the repair procedure



Credits

Credits

- Most of materials presented in these slides is taken from the OMG SysML tutorial: `http://www.omgsysml.org/INCOSE-OMGSysML-Tutorial-Final-090901.pdf`
- Part of materials presented in these slides is taken from the slides of the course "Embedded Systems - Model-Based Design" given by Prof. Marco Di Natale: `http://retis.sssup.it/~marco/teaching/embeddedsystems`