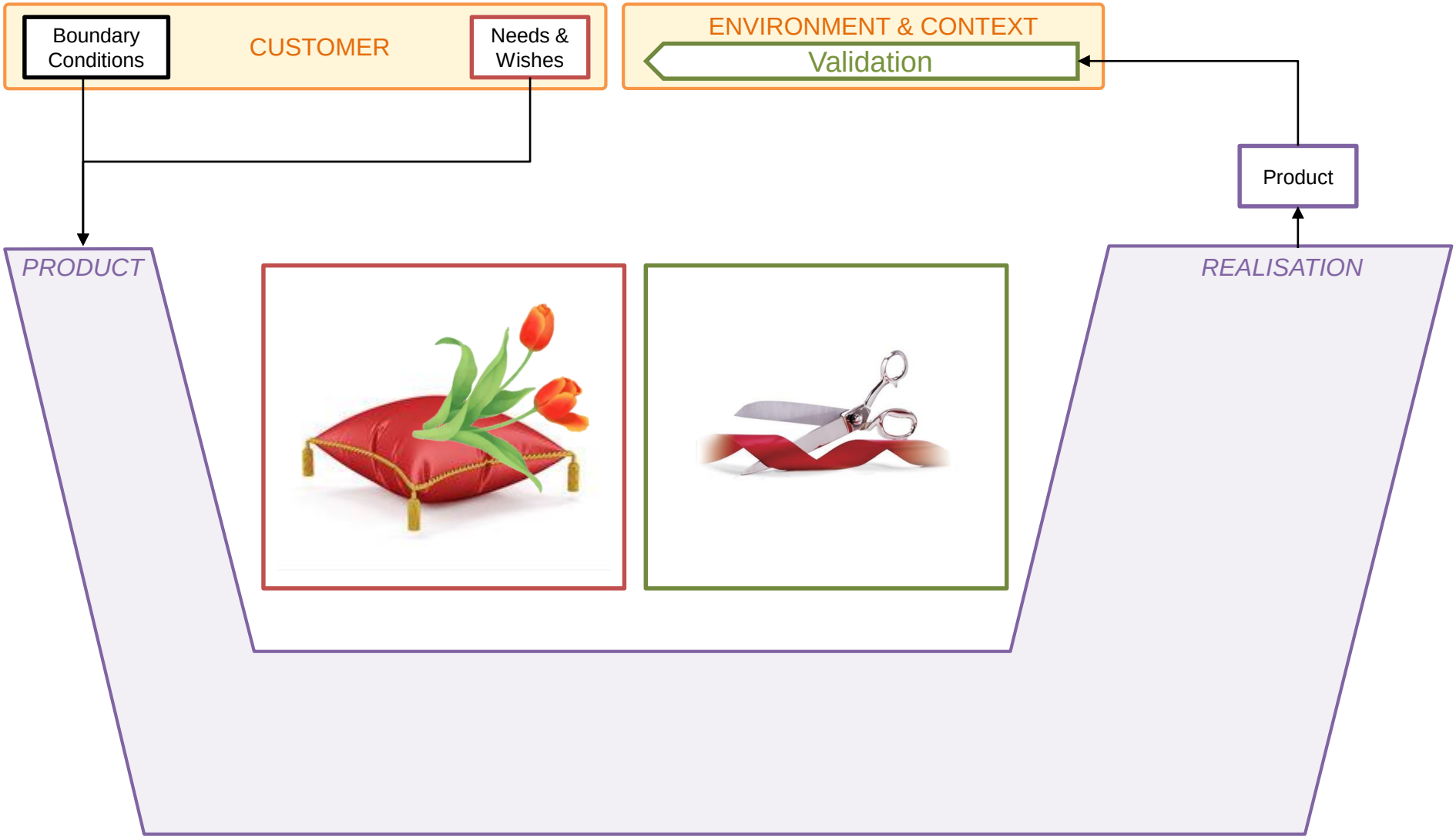
Closed-Loop Systems Engineering

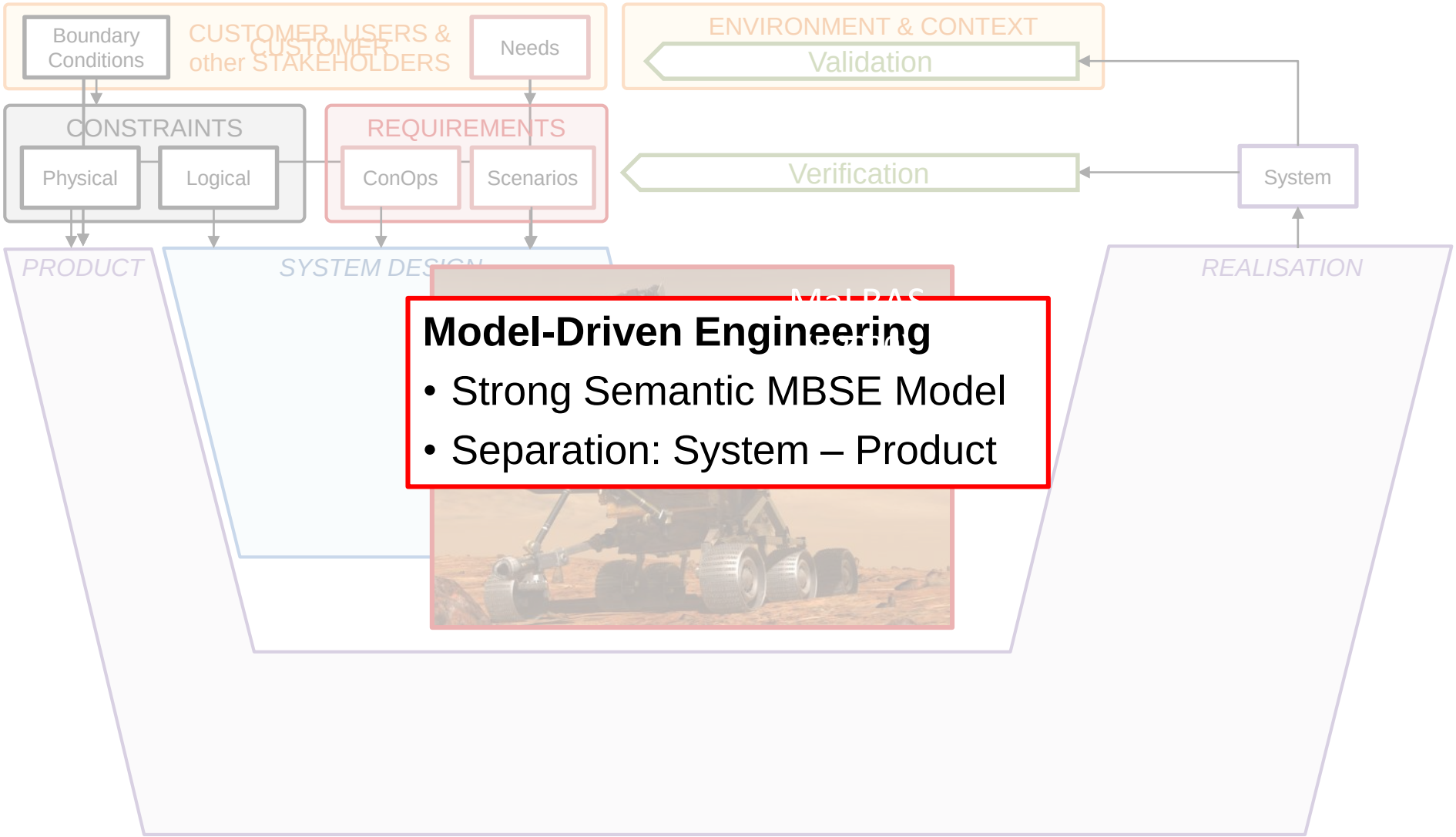
Integrating Digital Twins into Model-Driven Engineering

Prof. Dr.-Ing. Marco Di Maio

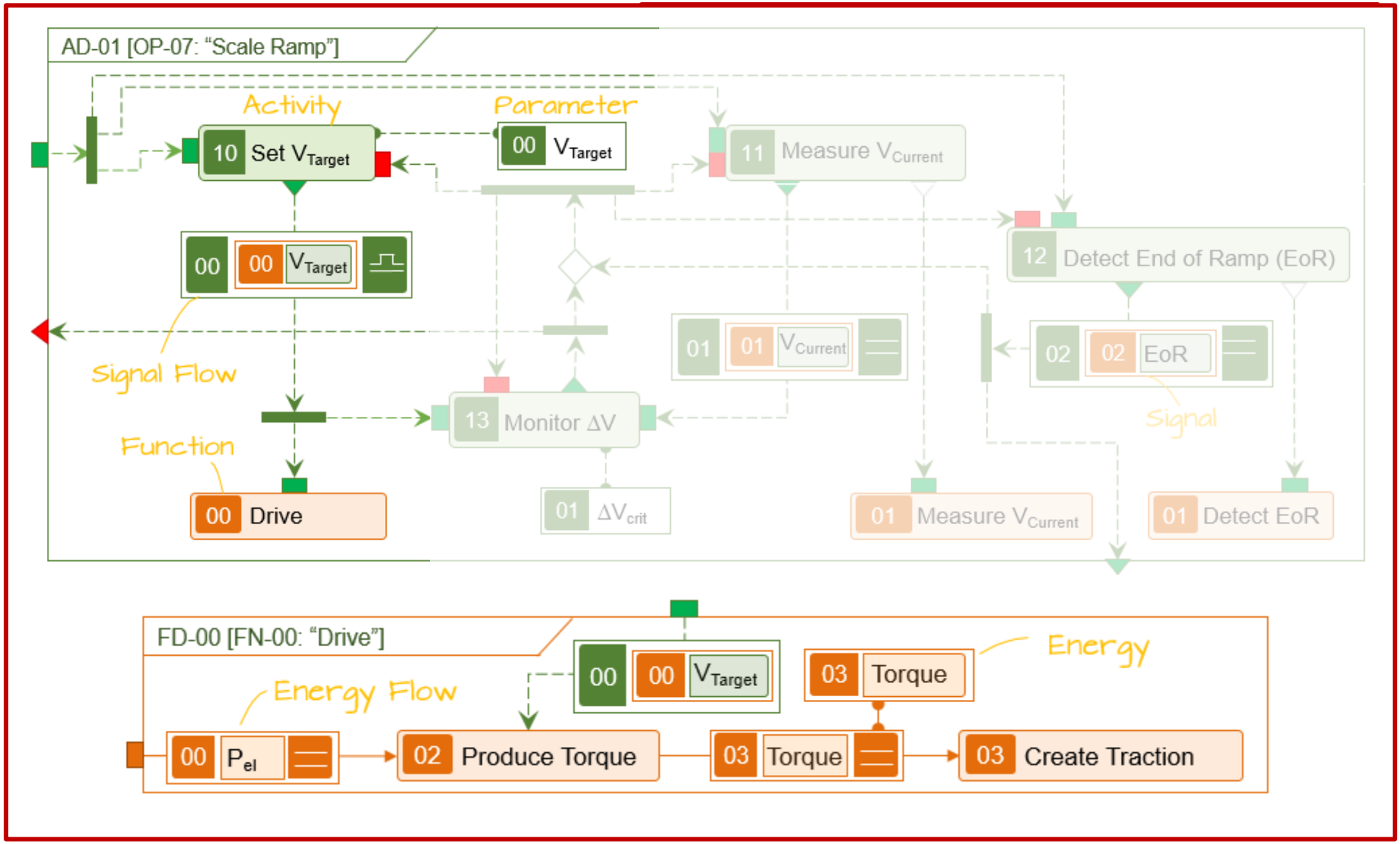
MDE: V-Model


Boundary Conditions
CUSTOMER
Needs & Wishes
ENVIRONMENT & CONTEXT
Validation
Product
PRODUCT
REALISATION

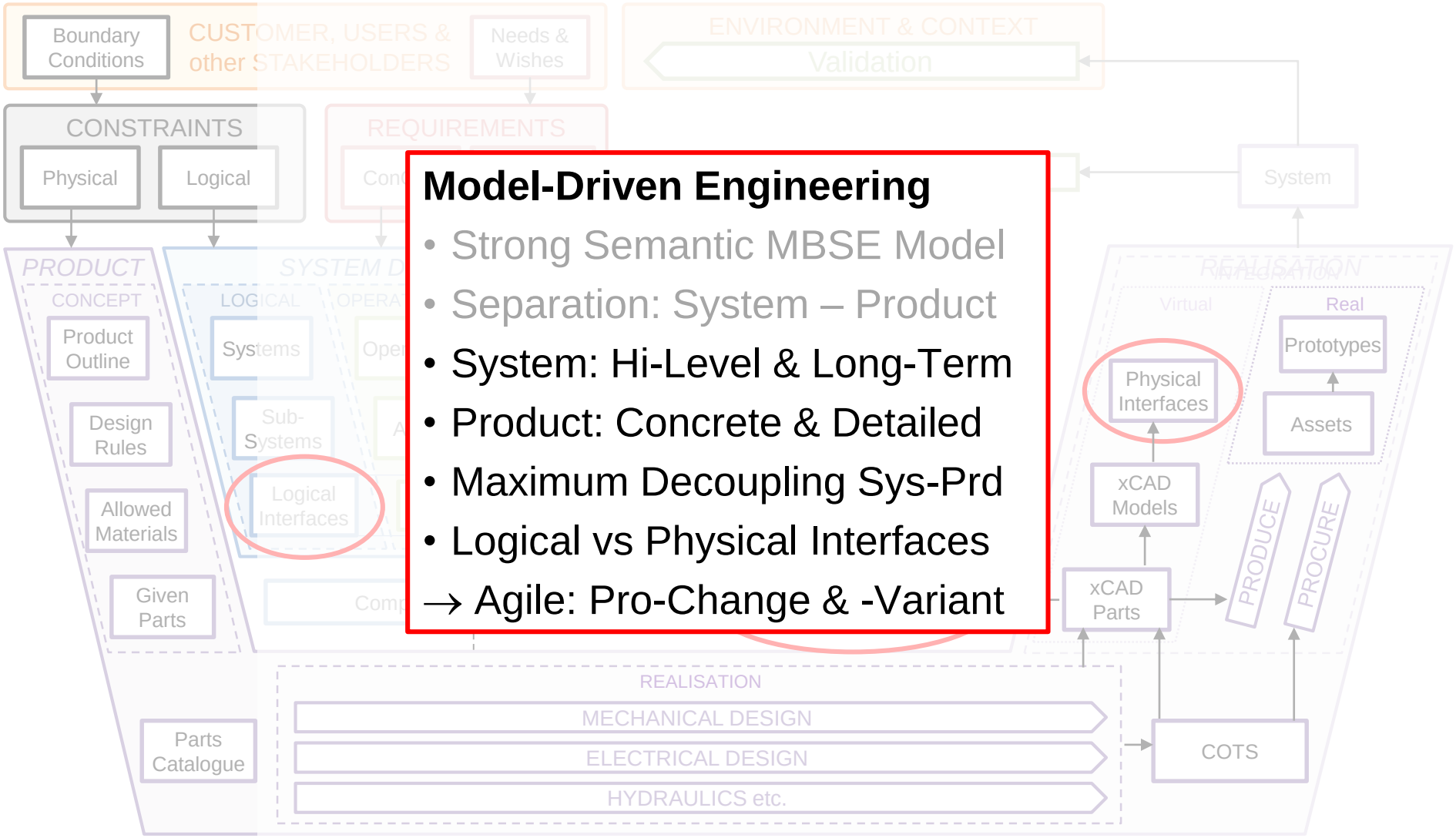
MDE: V-Model


Boundary Conditions
CUSTOMER, USERS & other STAKEHOLDERS
Needs
ENVIRONMENT & CONTEXT
Validation
CONSTRAINTS
Physical
Logical
REQUIREMENTS
ConOps
Scenarios
Verification
System
PRODUCT
SYSTEM DESIGN
REALISATION
Model-Driven Engineering
• Strong Semantic MBSE Model
• Separation: System – Product

MDE: V-Model


AD-01 [OP-07: "Scale Ramp"]
Activity
Parameter
10 Set V_{Target}
00 V_{Target}
11 Measure $V_{Current}$
00 00 V_{Target}
12 Detect End of Ramp (EoR)
01 01 $V_{Current}$
02 02 EoR
Signal Flow
Signal
13 Monitor ΔV
Function
00 Drive
01 ΔV_{crit}
01 Measure $V_{Current}$
01 Detect EoR
FD-00 [FN-00: "Drive"]
Energy
Energy Flow
00 00 V_{Target}
03 Torque
00 P_{el}
02 Produce Torque
03 Torque
03 Create Traction

MDE: V-Model

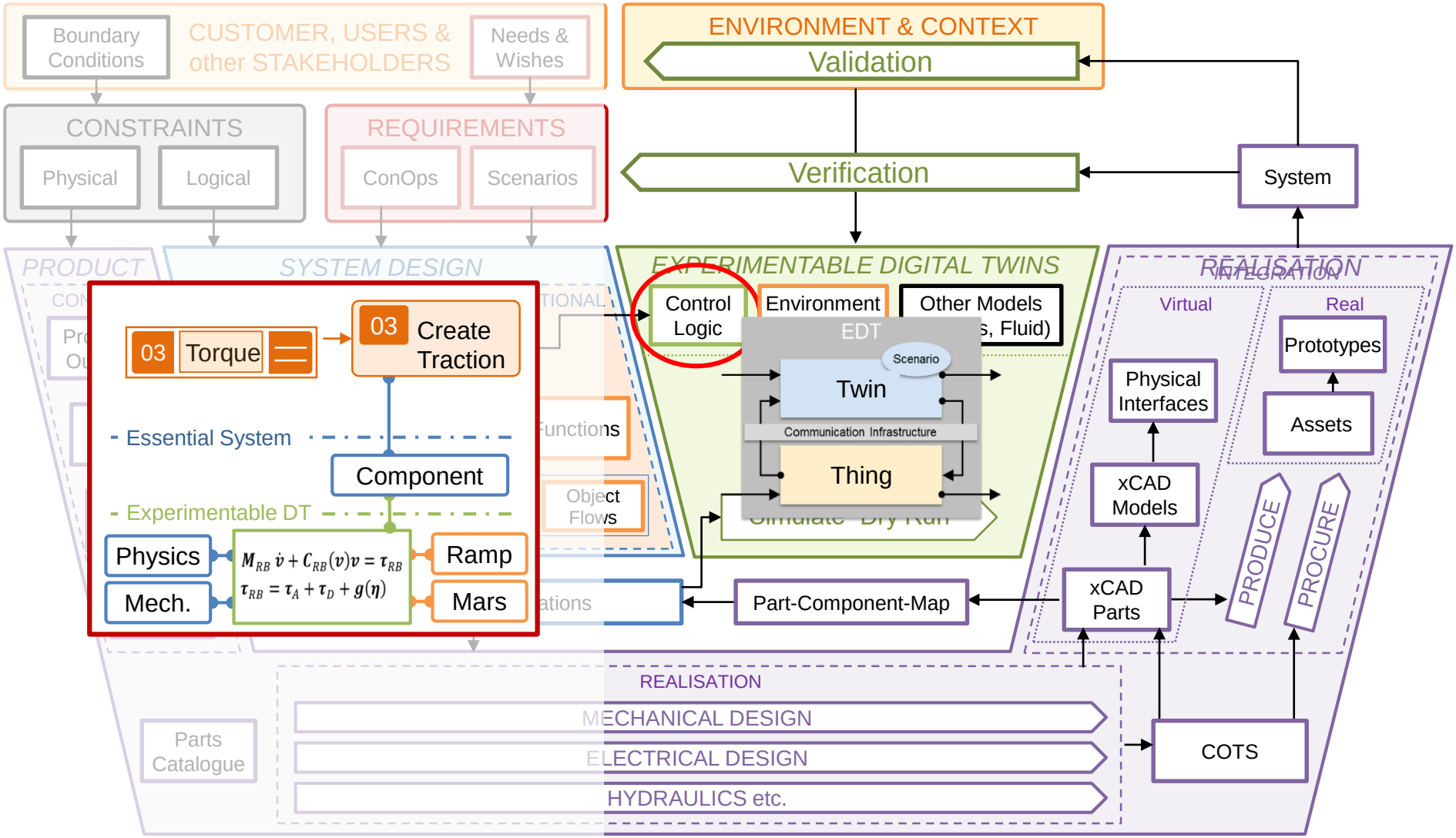


Model-Driven Engineering

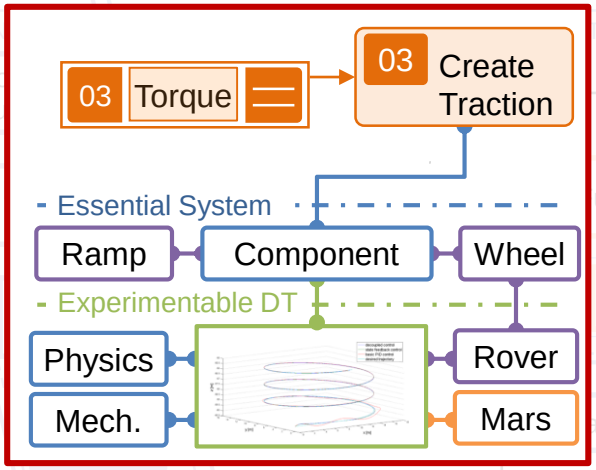
- Strong Semantic MBSE Model
- Separation: System – Product
- System: Hi-Level & Long-Term
- Product: Concrete & Detailed
- Maximum Decoupling Sys-Prd
- Logical vs Physical Interfaces

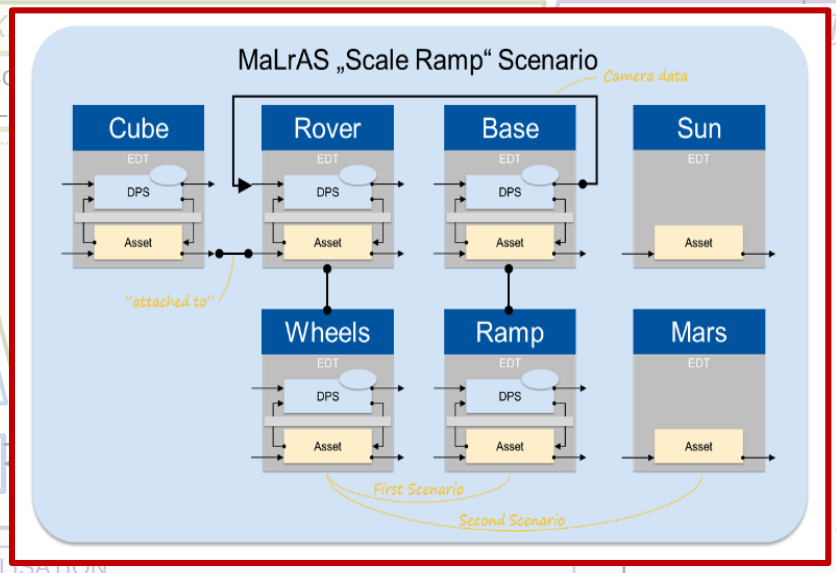
→ Agile: Pro-Change & -Variant

CLOSE: V-Model

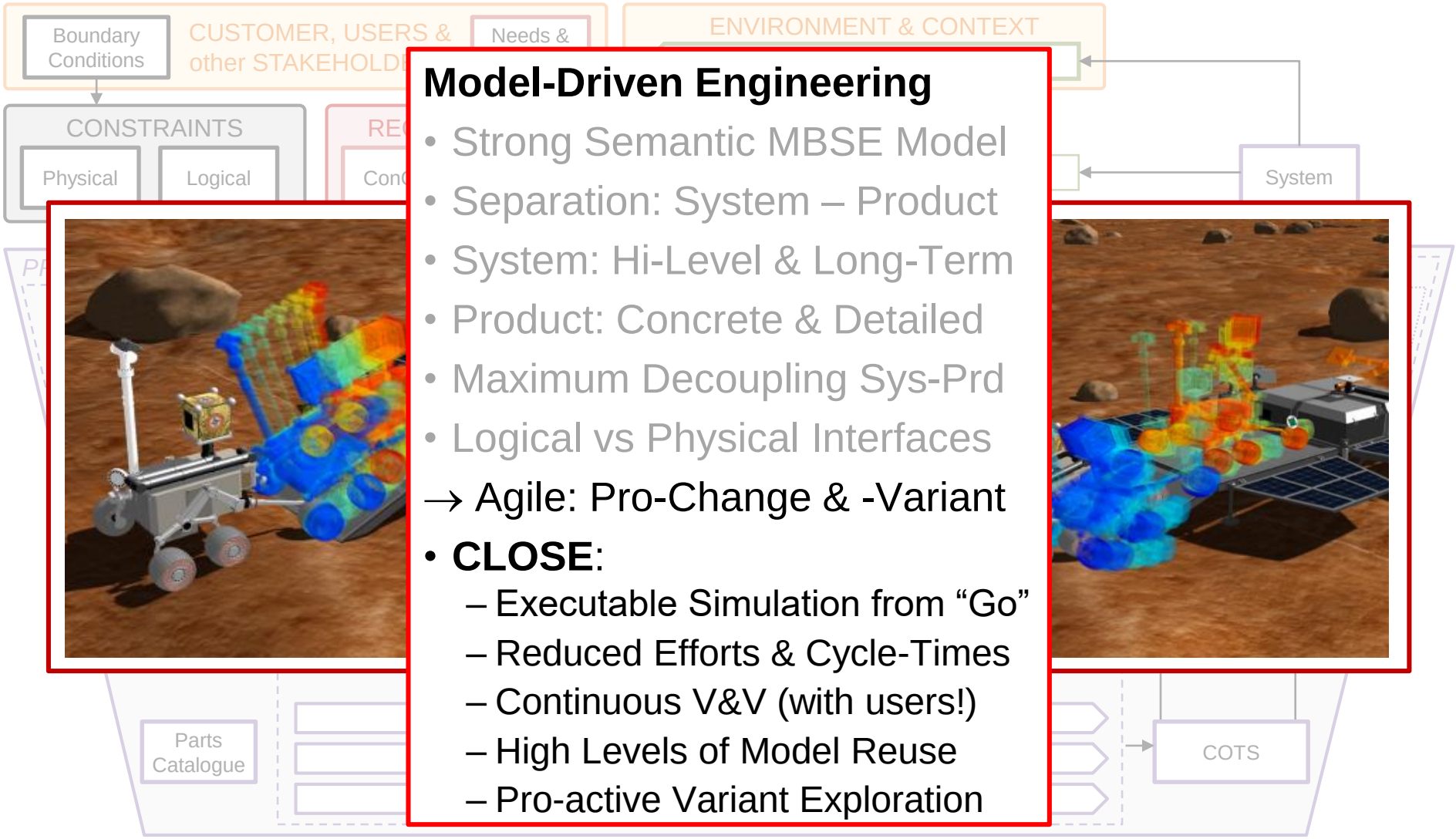


CLOSE: V-Model





CLOSE: V-Model



Model-Driven Engineering

- Strong Semantic MBSE Model
- Separation: System – Product
- System: Hi-Level & Long-Term
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- Maximum Decoupling Sys-Prd
- Logical vs Physical Interfaces

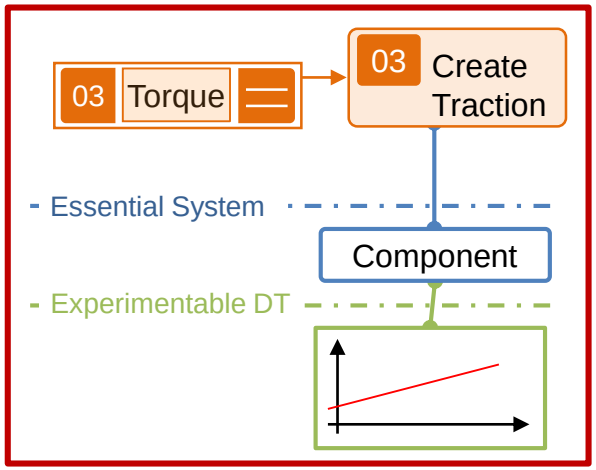
→ Agile: Pro-Change & -Variant

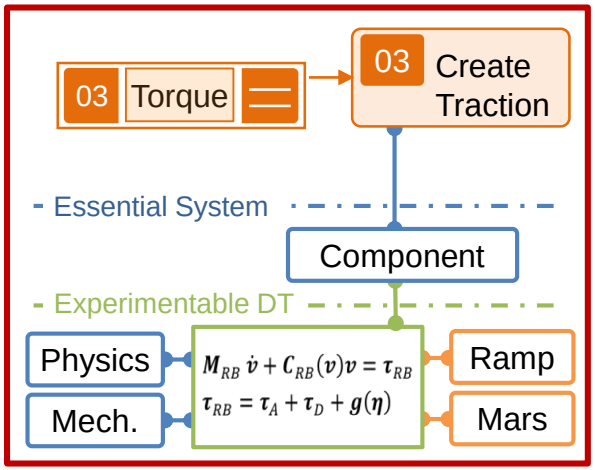
- **CLOSE**:
  - Executable Simulation from “Go”
  - Reduced Efforts & Cycle-Times
  - Continuous V&V (with users!)
  - High Levels of Model Reuse
  - Pro-active Variant Exploration

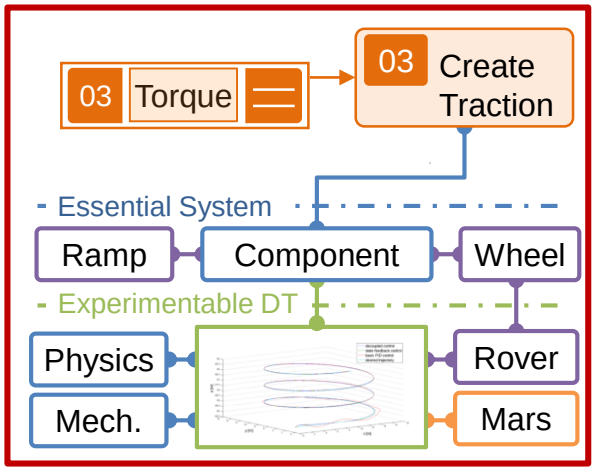
Closed-Loop Systems Engineering:

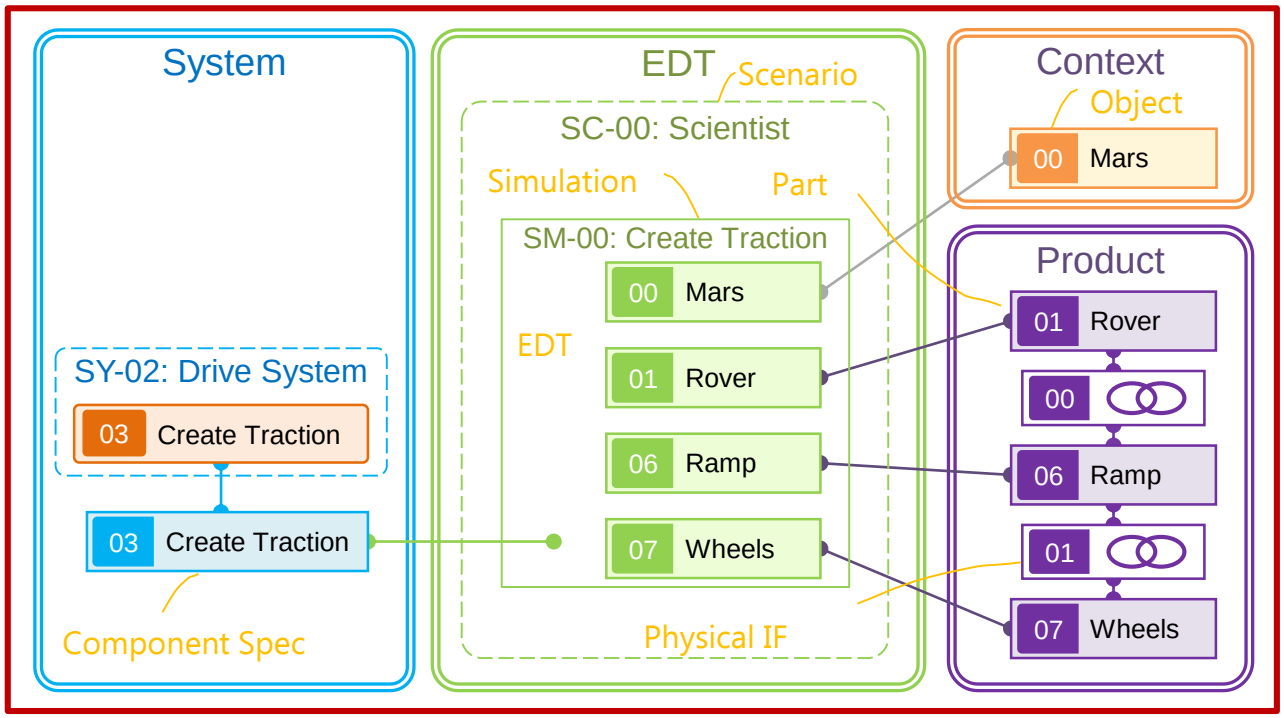
Integrating Digital Twins into Model-Driven Engineering

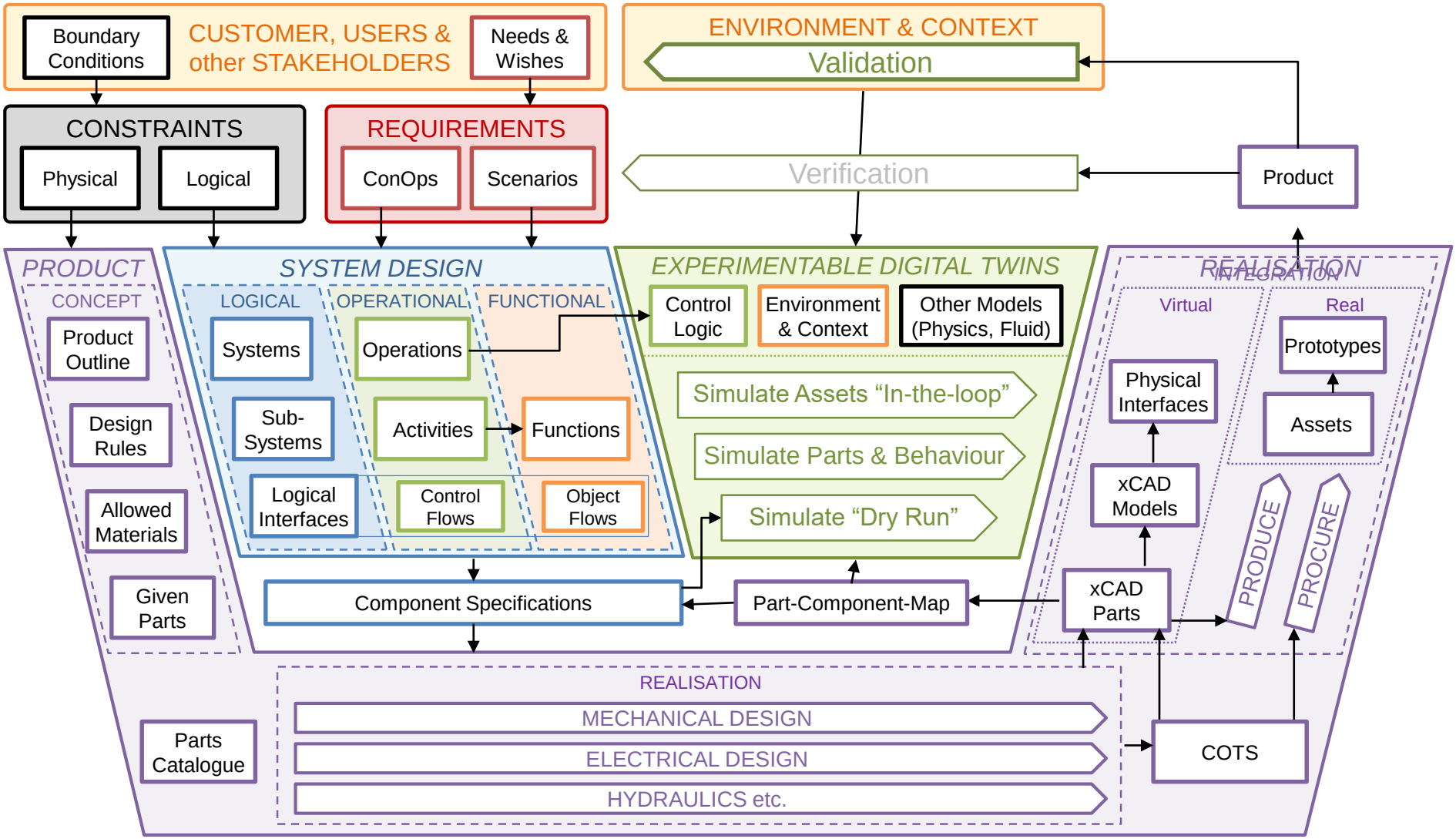
Thank you for listening!

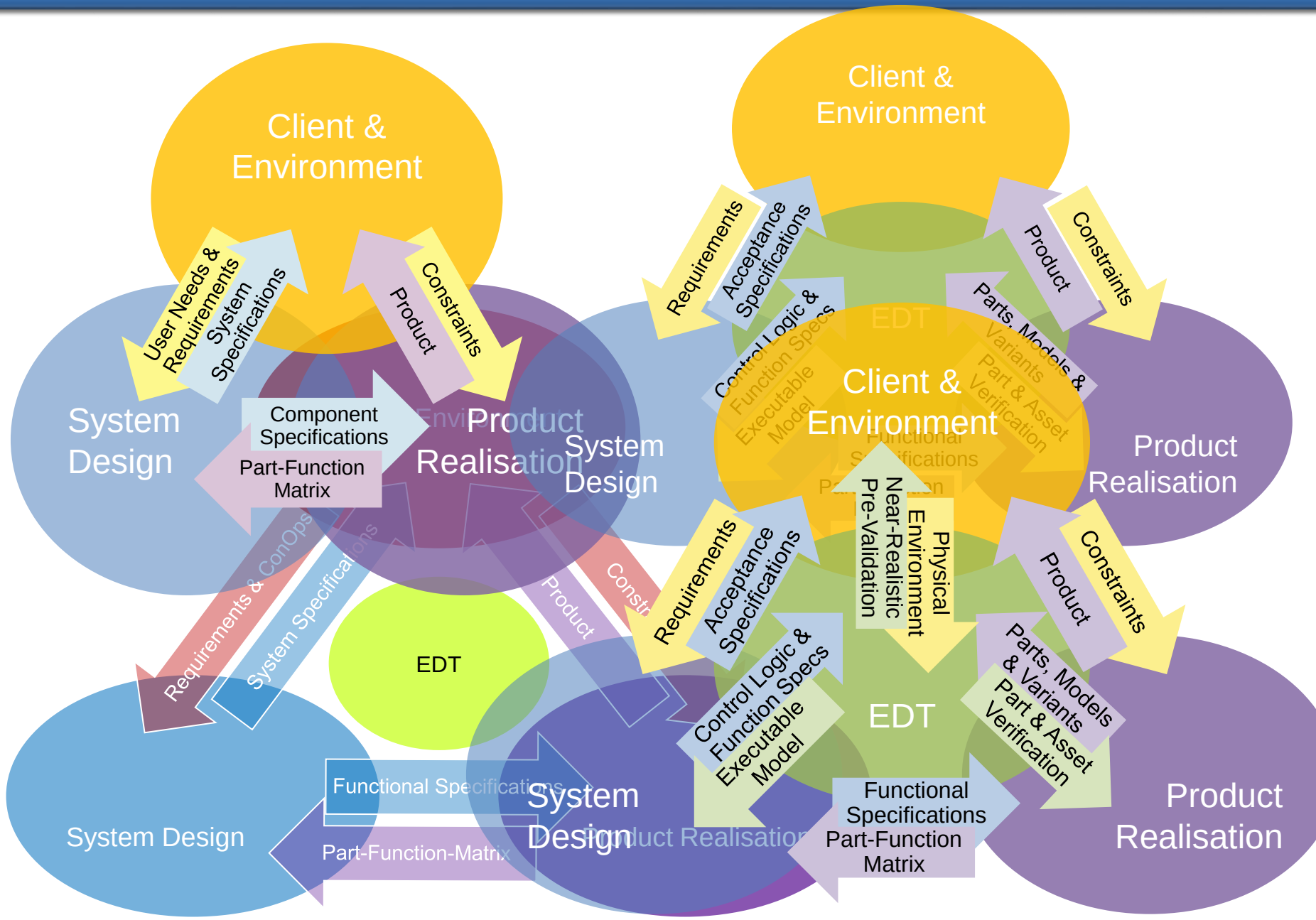

03 Torque
03 Create Traction
Essential System
Component
Experimental DT

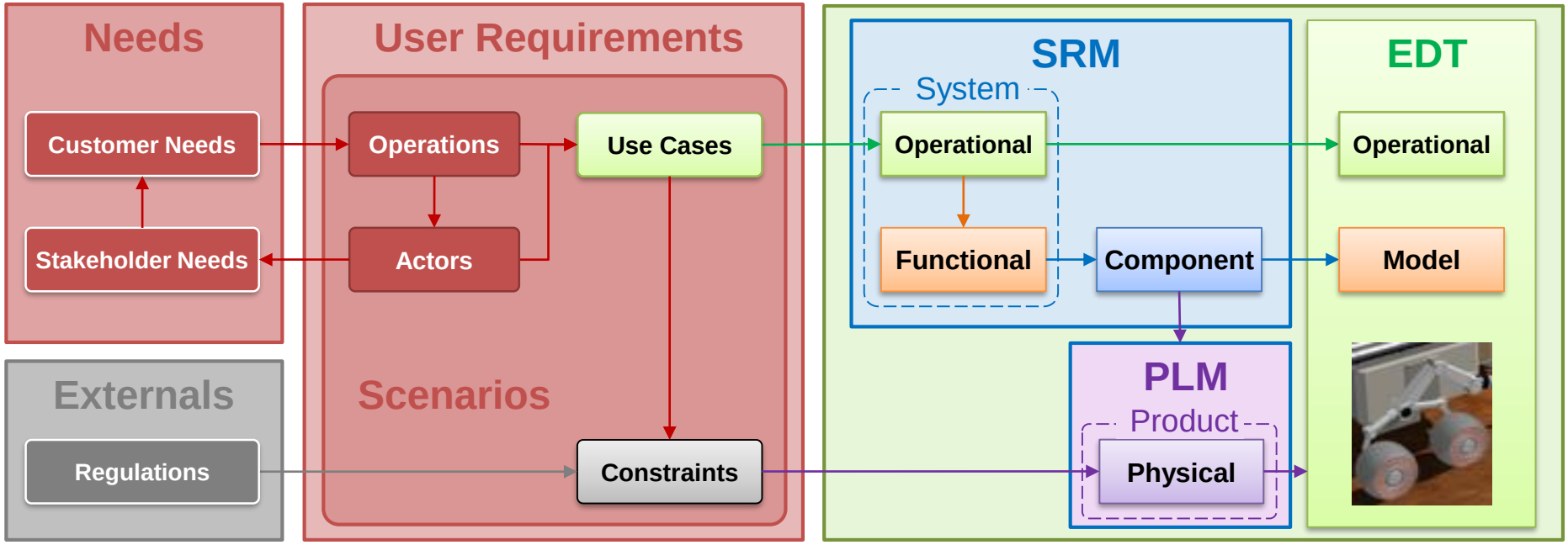

03 Torque
03 Create Traction
Essential System
Component
Experimental DT
Physics
Mech.
$M_{RB}\,\dot{v} + C_{RB}(v)v = \tau_{RB}$
$\tau_{RB} = \tau_A + \tau_D + g(\eta)$
Ramp
Mars

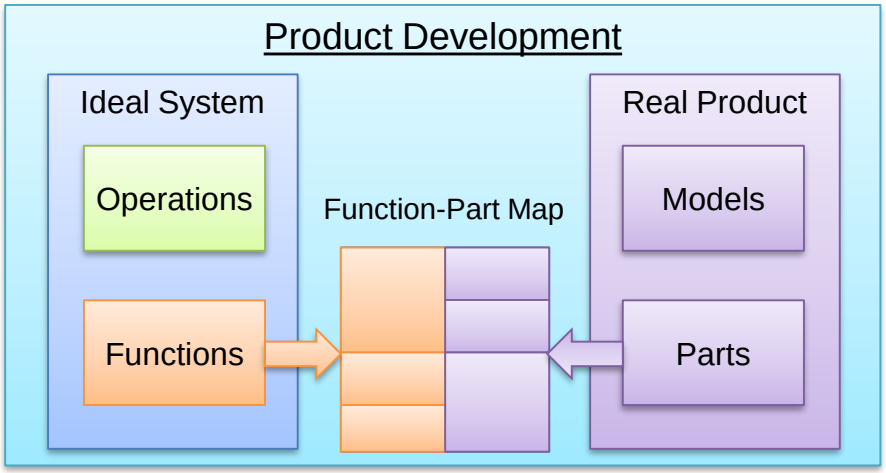

03 Torque
03 Create Traction
Essential System
Ramp
Component
Wheel
Experimental DT
Physics
Mech.
Rover
Mars

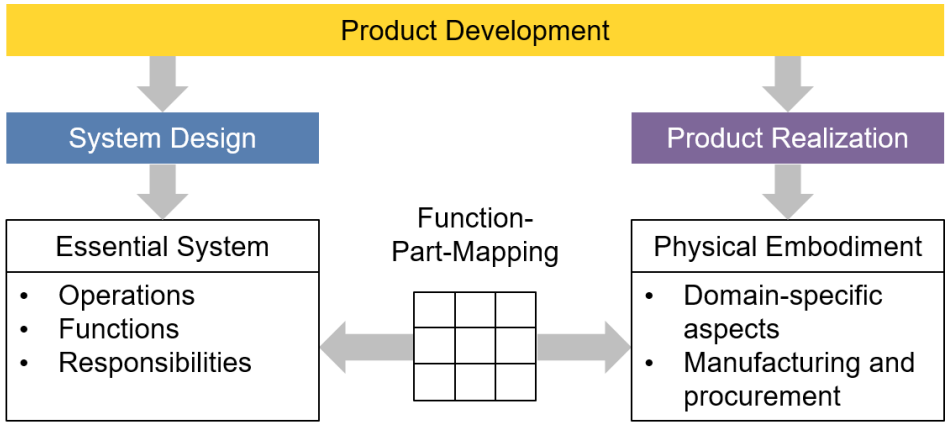

System
SY-02: Drive System
03 Create Traction
03 Create Traction
Component Spec
EDT
Scenario
SC-00: Scientist
Simulation
Part
SM-00: Create Traction
EDT
00 Mars
01 Rover
06 Ramp
07 Wheels
Physical IF
Context
Object
00 Mars
Product
01 Rover
00
06 Ramp
01
07 Wheels


Boundary Conditions
CUSTOMER, USERS & other STAKEHOLDERS
Needs & Wishes
ENVIRONMENT & CONTEXT
Validation
CONSTRAINTS
Physical
Logical
REQUIREMENTS
ConOps
Scenarios
Verification
Product
PRODUCT
CONCEPT
Product Outline
Design Rules
Allowed Materials
Given Parts
SYSTEM DESIGN
LOGICAL
OPERATIONAL
FUNCTIONAL
Systems
Sub-Systems
Logical Interfaces
Operations
Activities
Functions
Control Flows
Object Flows
EXPERIMENTABLE DIGITAL TWINS
Control Logic
Environment & Context
Other Models (Physics, Fluid)
Simulate Assets “In-the-loop”
Simulate Parts & Behaviour
Simulate “Dry Run”
REALISATION
INTEGRATION
Virtual
Real
Prototypes
Physical Interfaces
Assets
xCAD Models
xCAD Parts
PRODUCE
PROCURE
Component Specifications
Part-Component-Map
REALISATION
MECHANICAL DESIGN
ELECTRICAL DESIGN
HYDRAULICS etc.
Parts Catalogue
COTS

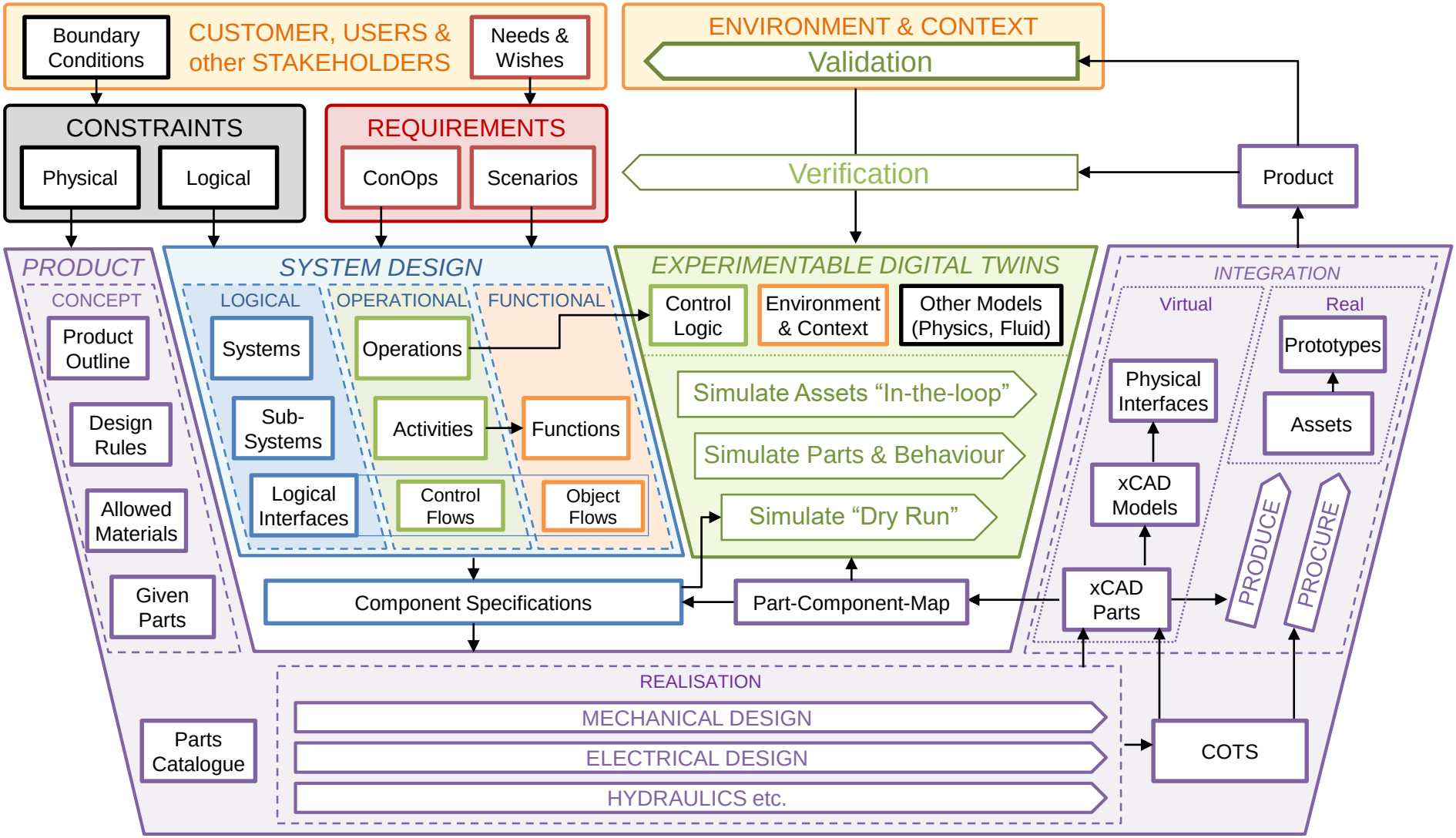

Client & Environment
User Needs & Requirements
System Specifications
Product
Constraints
System Design
Component Specifications
Part-Function Matrix
Product Realisation
Client & Environment
Requirements
Acceptance Specifications
Product
Constraints
Control Logic & Function Specs Executable Model
Parts, Models & Variants Part & Asset Verification
EDT
Client & Environment
Physical Environment Near-Realistic Pre-Validation
System Design
Product Realisation
Requirements & ConOps
System Specifications
Product
Requirements
Acceptance Specifications
Product
Constraints
EDT
Control Logic & Function Specs Executable Model
Parts, Models & Variants Part & Asset Verification
EDT
Functional Specifications
Part-Function-Matrix
System Design
System Design
Functional Specifications
Part-Function Matrix
Product Realisation

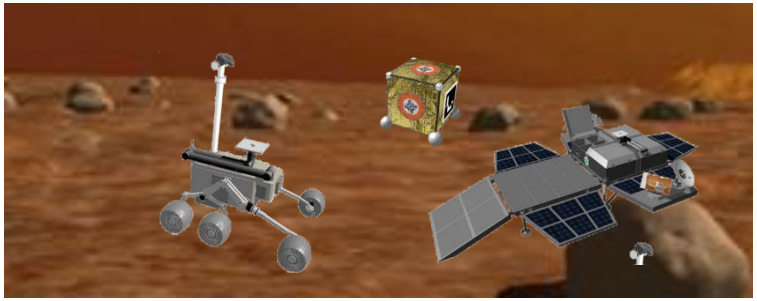

Needs
Customer Needs
Stakeholder Needs
User Requirements
Operations
Use Cases
Actors
Scenarios
Externals
Regulations
Constraints
SRM
System
Operational
Functional
Component
EDT
Operational
Model
PLM
Product
Physical

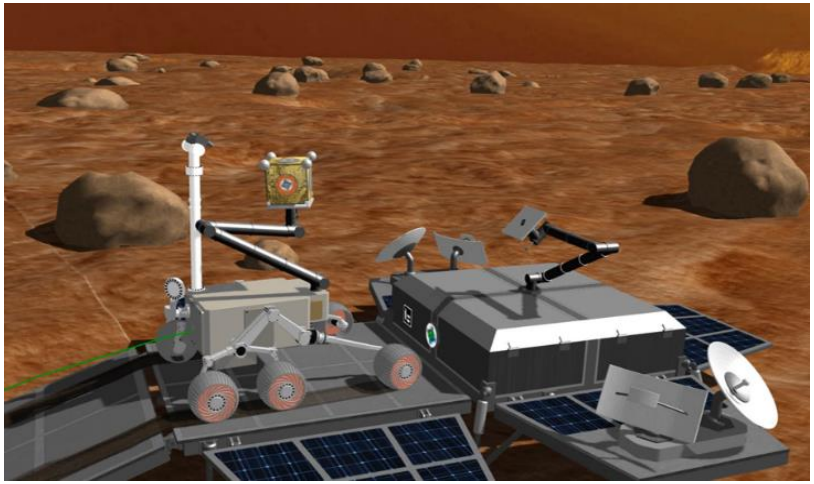

Product Development
Ideal System
Operations
Functions
Function-Part Map
Real Product
Models
Parts

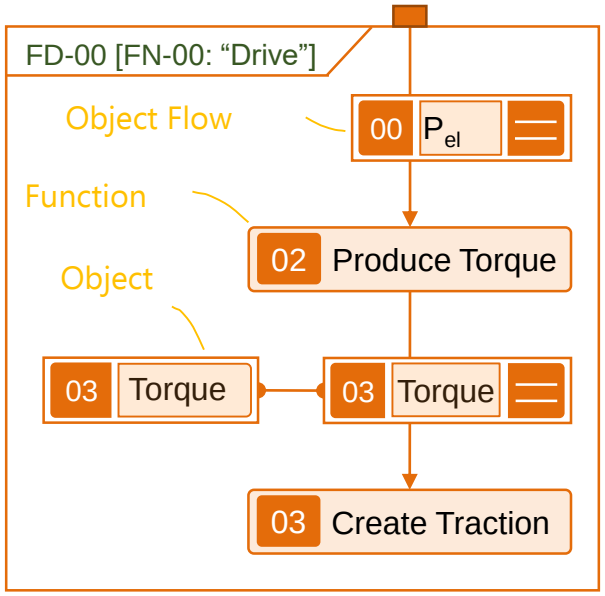

Product Development
System Design
Product Realization
Essential System
• Operations
• Functions
• Responsibilities
Function-
Part-Mapping
Physical Embodiment
• Domain-specific aspects
• Manufacturing and procurement

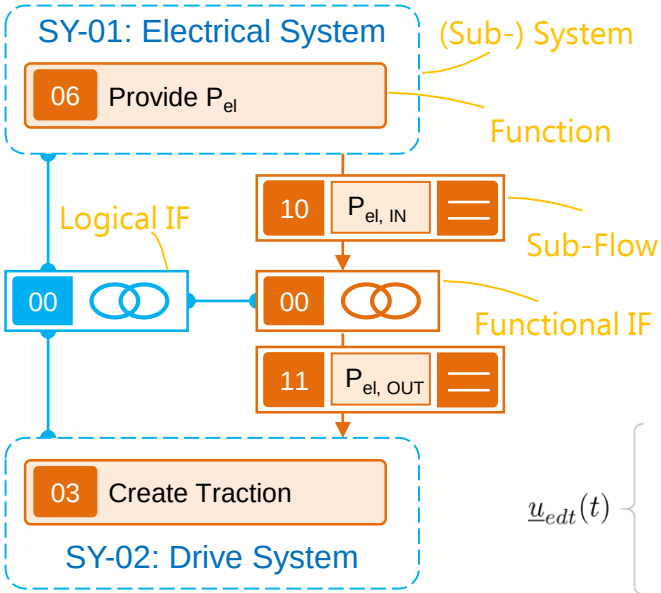
CLOSE: V-Model

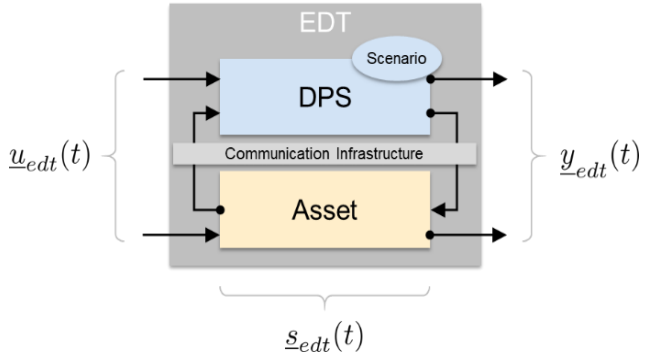




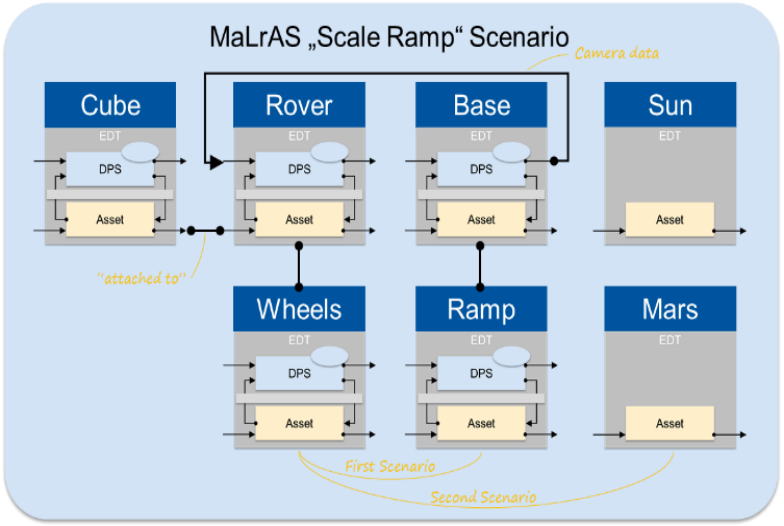


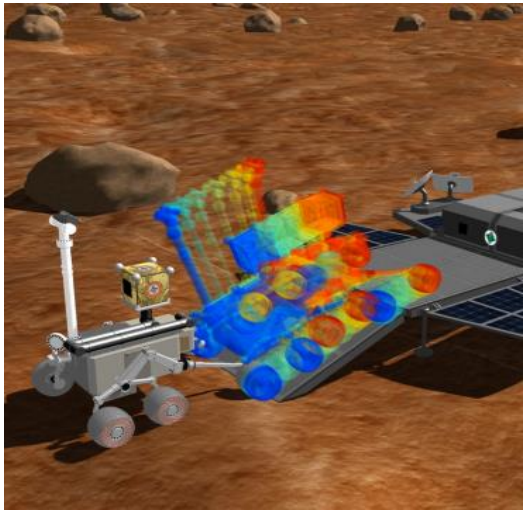

FD-00 [FN-00: “Drive”]
Object Flow
00 Pel
Function
02 Produce Torque
Object
03 Torque
03 Torque
03 Create Traction

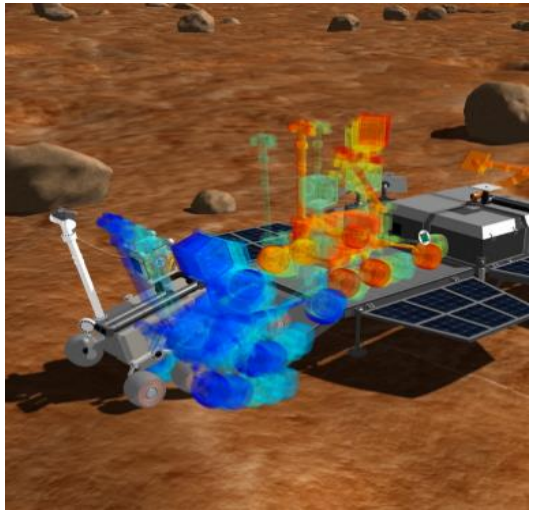

SY-01: Electrical System
(Sub-) System
06 Provide Pel
Function
Logical IF
10 Pel, IN
Sub-Flow
00
00
Functional IF
11 Pel, OUT
03 Create Traction
SY-02: Drive System

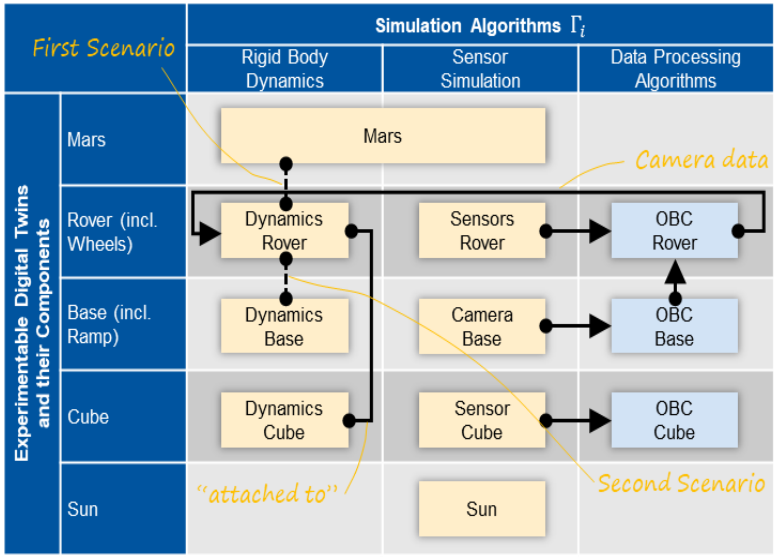

EDT
Scenario
DPS
Communication Infrastructure
Asset
$u_{edt}(t)$
$y_{edt}(t)$
$s_{edt}(t)$

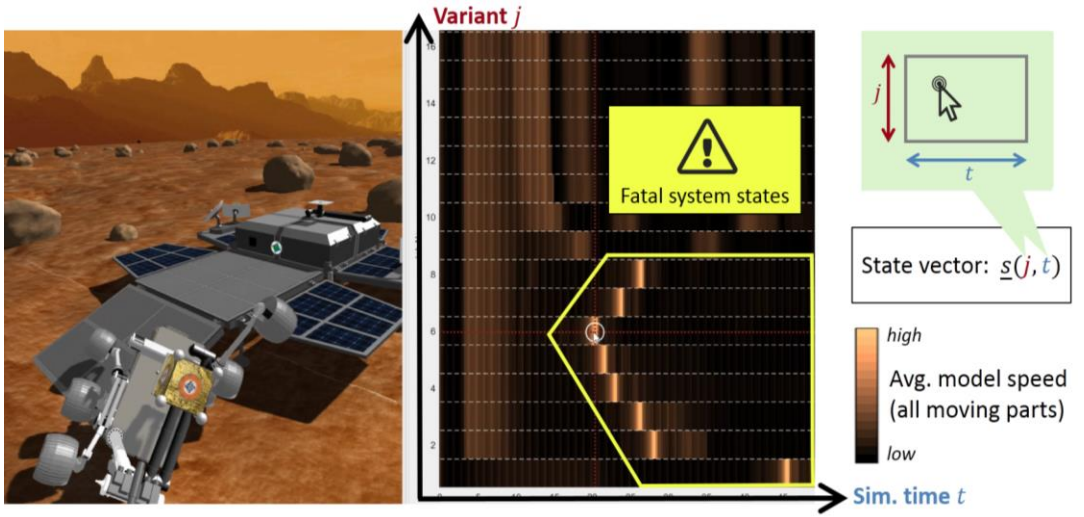
CLOSE: EDT Scenarios



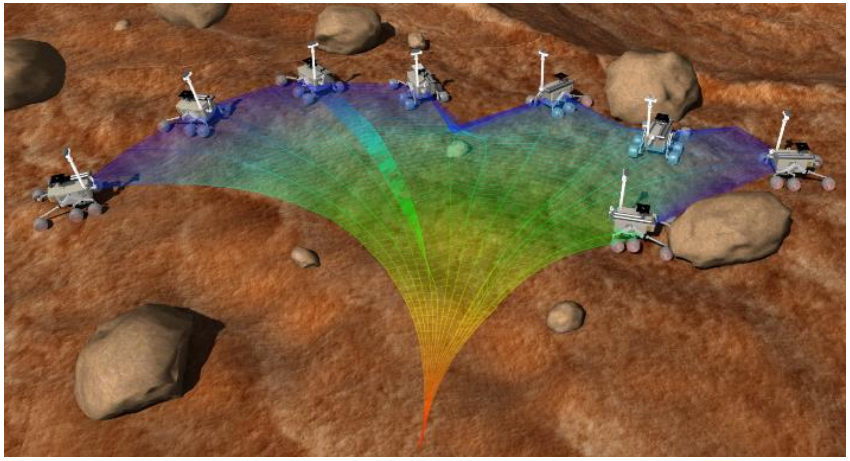


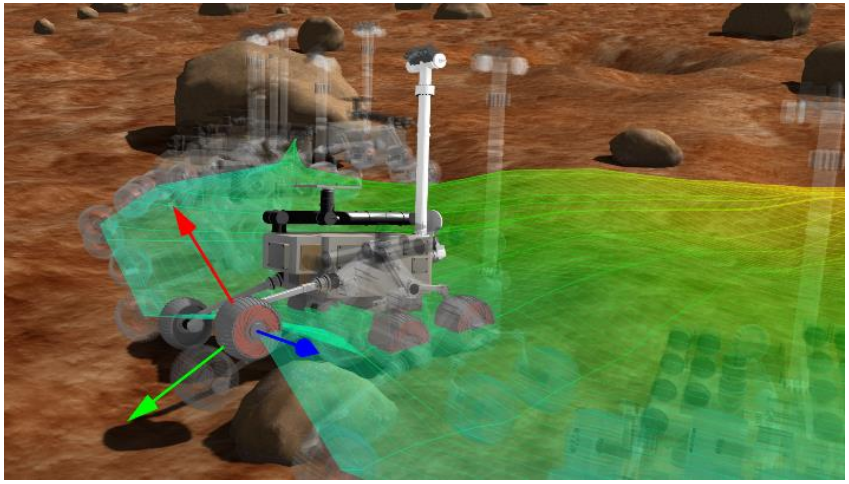


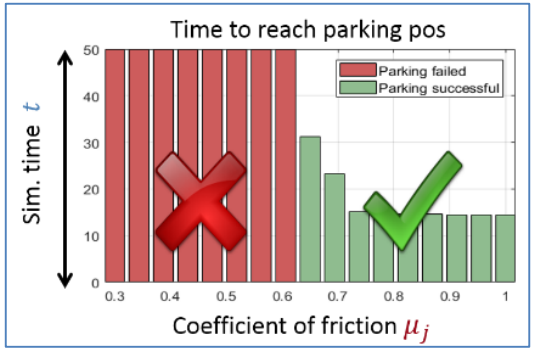


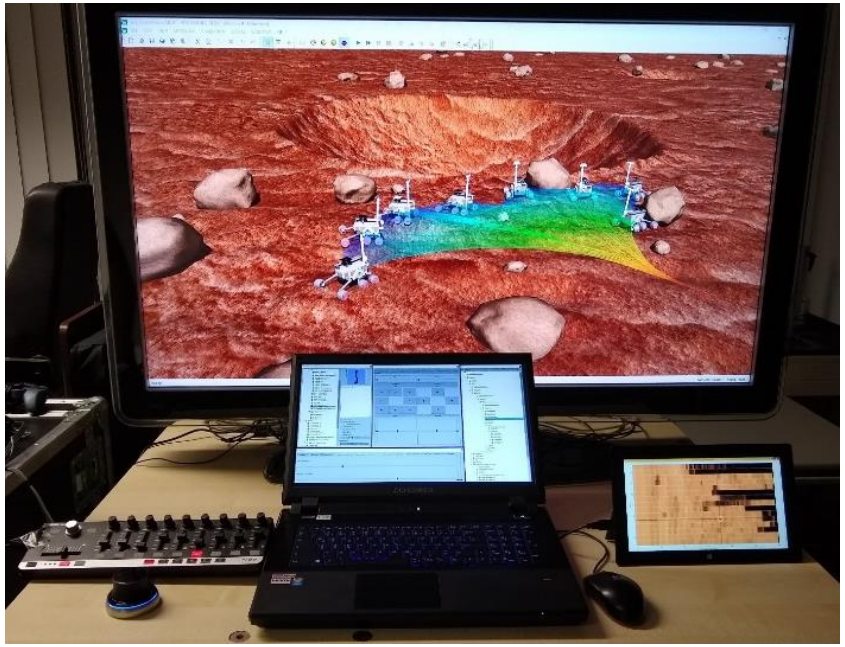


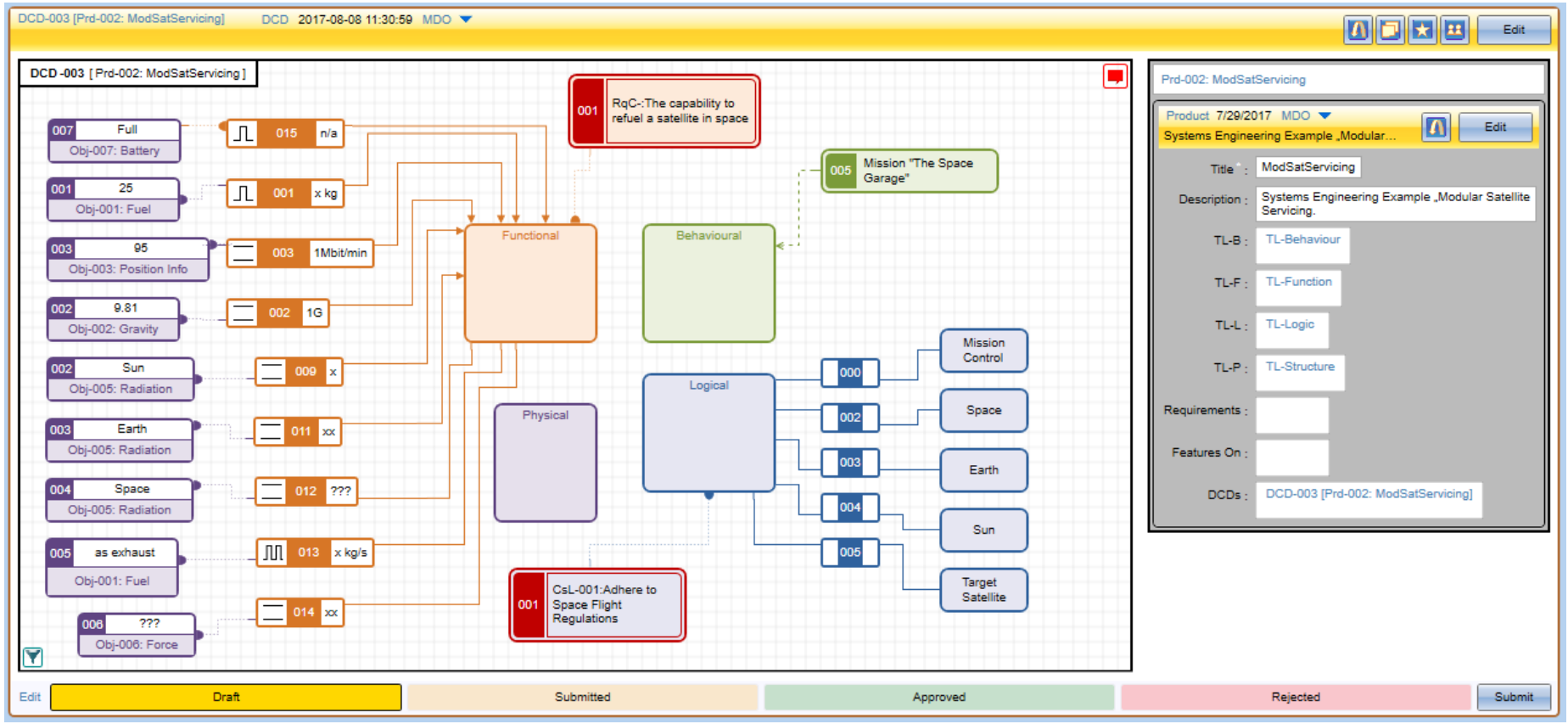
CLOSE: EDT Scenarios










DCD-003 [Prd-002: ModSatServicing]
DCD 2017-08-08 11:30:59 MDO
Edit
DCD -003 [Prd-002: ModSatServicing]
001 RqC-:The capability to refuel a satellite in space
005 Mission "The Space Garage"
007 Full
Obj-007: Battery
015 n/a
001 25
Obj-001: Fuel
001 x kg
003 95
Obj-003: Position Info
003 1Mbit/min
002 9.81
Obj-002: Gravity
002 1G
002 Sun
Obj-005: Radiation
009 x
003 Earth
Obj-005: Radiation
011 xx
004 Space
Obj-005: Radiation
012 ???
005 as exhaust
Obj-001: Fuel
013 x kg/s
006 ???
Obj-006: Force
014 xx
Functional
Behavioural
Physical
Logical
000
002
003
004
005
Mission Control
Space
Earth
Sun
Target Satellite
001 CsL-001:Adhere to Space Flight Regulations
Prd-002: ModSatServicing
Product 7/29/2017 MDO
Systems Engineering Example „Modular...
Edit
Title * : ModSatServicing
Description : Systems Engineering Example „Modular Satellite Servicing.
TL-B : TL-Behaviour
TL-F : TL-Function
TL-L : TL-Logic
TL-P : TL-Structure
Requirements :
Features On :
DCDs : DCD-003 [Prd-002: ModSatServicing]
Edit
Draft
Submitted
Approved
Rejected
Submit