Instrumentation & Control of Nuclear Power Plants

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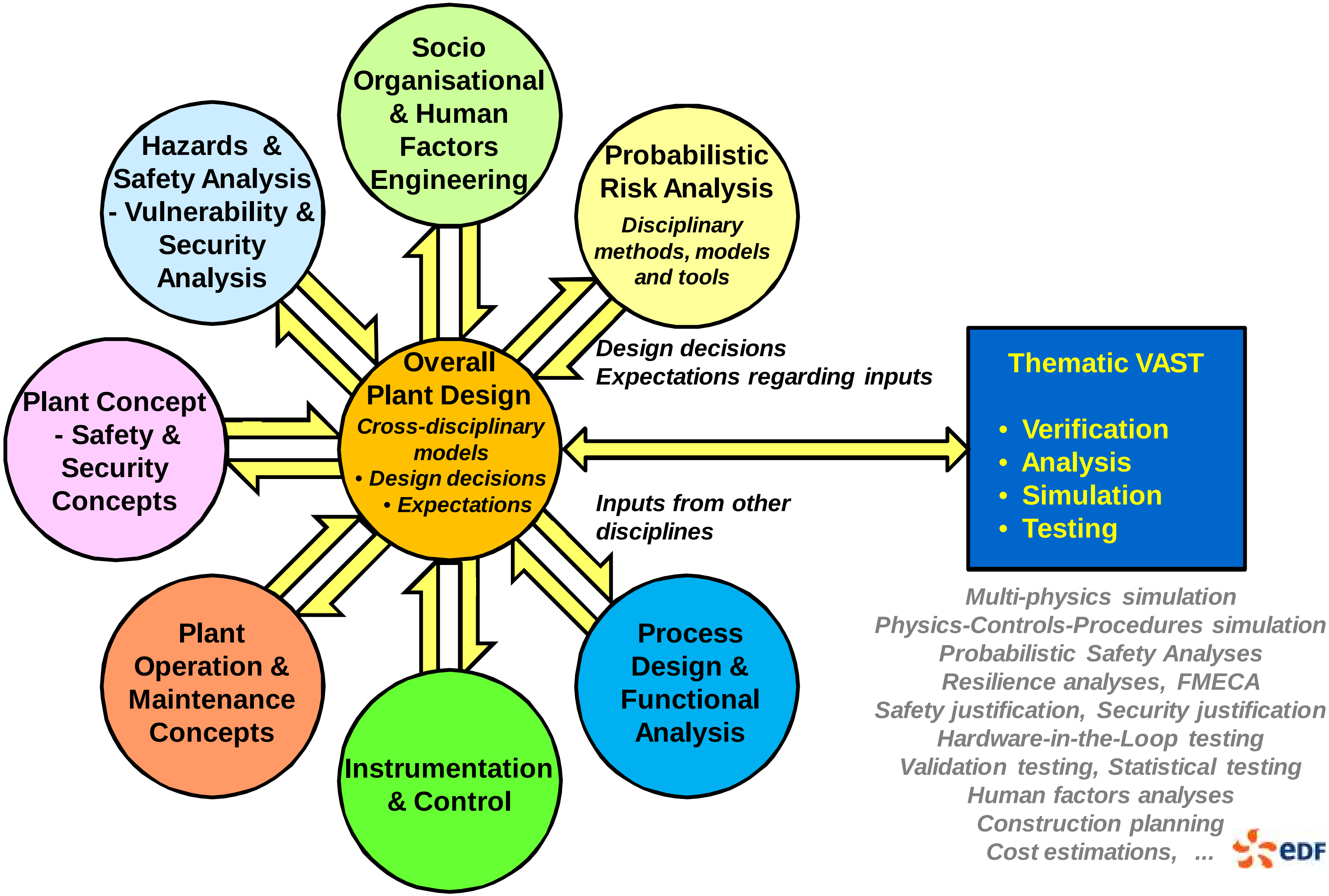
CHANGER L'ÉNERGIE ENSEMBLE

Nuclear Power Plants as Complex Systems

- From initial concept to operation: 10+ years
  - Construction per se: 6 or 7 years
- Expected lifetime: 60+ years
- Strong safety and security regulatory requirements
  - But significant differences between national regulatory bodies, and even within the same regulatory body
- 250+ plant systems, involving a wide range of scientific and engineering disciplines
  - Electrical engineering, civil engineering, thermohydraulics, chemistry, nuclear physics, aerodynamics, ...
- Cross systems concerns
  - Operation and maintenance (including periodic testing), socio-organisational and human factors, risk & hazards analysis, vulnerability and security analysis, failure analysis, instrumentation and control (I&C), ...

Systems Engineering



The I&C Challenges

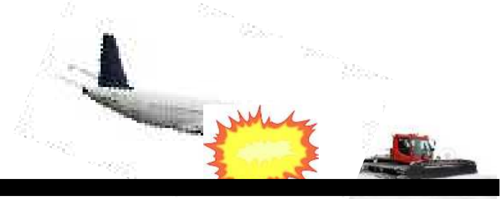
- 10 000+ signals
  - Several thousands I&C functions
- 10+ different I&C systems
  - Totaling several hundred cabinets
- Interact with nearly all plant systems
- Need to address all plant situations
  - Normal plant states: commissioning, starting up, intermediate power levels, normal power, shutting down, ...
  - Periodic testing and calibration, maintenance during operation, outages, ...
  - Abnormal states: equipment failure, incidents, accidents, severe accidents
- Subject to requirements and constraints from many other disciplines
- Changes more frequent than in other disciplines
  - Product and technological evolution
  - I&C as a solution for improved plant performance, resiliency, safety, ...
  - Digital I&C is the focus of regulatory suspicion
- I&C studies represent a significant part of the design cost of a new power plant

Examples of I&C Engineering Topics

- Overall I&C architectural design
  - Organisation of the 10+ I&C systems into a safe, secure, functional, resilient whole
    - Levels of defence-in-depth / security zones, safety classification / security degrees, diversity, data communications, human-system interfaces, ...
  - Minimising, as far as reasonably feasible, the need for country specific features
- Individual I&C systems architectural design
  - Several thoudand functions, 100+ cabinets
  - Optimisation: minimise the number of necessary cabinets
    - Satisfy performance requirements, taking into account the processing required, inputs/outputs, and the characteristics of the platform chosen
  - Segmentation to reduce potential for complete system failure
- Logical design verification
  - Including system architecture, software, FPGA logic, executable binary code
  - Testing, formal verification, proven compilers and generation tools, ...
- Design of Human-System interfaces
- Probabilistic safety modelling and analysis
- Verification of I&C functional and timing requirements

Why is That Necessary?

- Experience from multiple industrial sectors shows that functional requirements are sometimes inadequate
  - Even for highly dependable systems
  - Errors will be revealed late in the development process, or worse, during operation
- Such weaknesses result from multiple causes
  - E.g., functional complexity or inadequate understanding or analysis of I&C system environment and operational context
- Evolutionary designs limit the risk
  - But radically new designs need to address the issue more explicitly
- One objective of the FP7 HARMONICS, ITEA2 MODRIO and CONNEXION projects is to enhance confidence in I&C functional and timing requirements



By regulation, to prevent spurious deployment while airborne, hydraulic circuits of thrust reversers are disabled

Wheels on the ground → Thrust reversers in operation

Pilots see a snow plough on the tarmac → They disengage the thrust reversers and take-off

Wheels no longer on the ground → Hydraulic circuits disabled. Reverser on one side is fully folded, but not on the other side

Aerodynamic pressure reopens the thrust reverser → Airplane is thrown off balance, pilots do not have time to react

Small airport, No local control tower, Snowing, Poor visibility

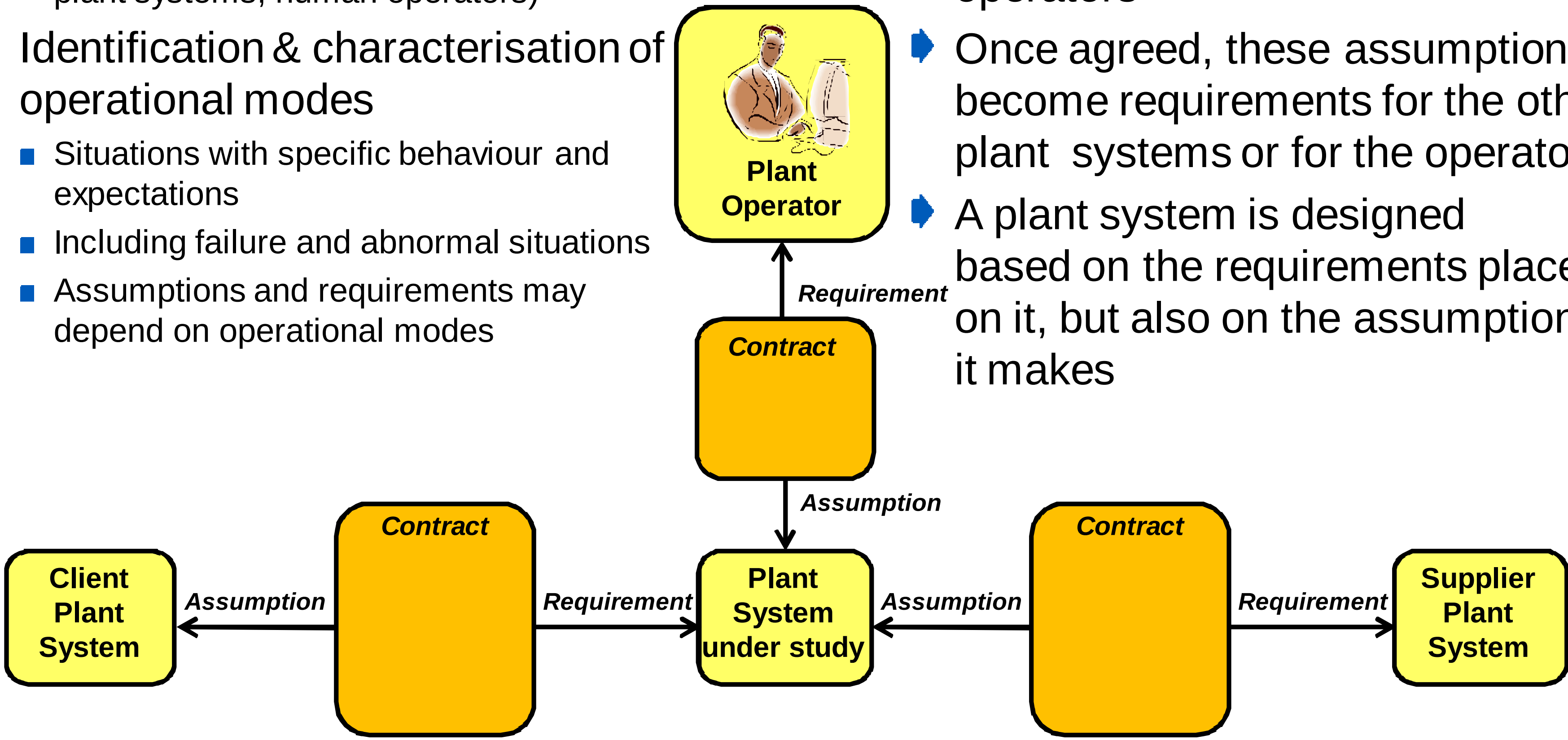
Overall Approach

- Consider the functional and timing requirements for I&C in the framework of those of the parent plant system, and of the assumptions that system makes on its own environment
  - Including human actions, generally following specified operational procedures
- Formal requirements and behavioural modelling
- (Massive) use of co-simulation to verify that requirements are satisfied
  - Physical processes, Human actions (and operational procedures), Automatic control
- Also for
  - STPA (System Theoratical Process Analysis)
  - FMECA (Failure Modes, Effects and Consequences Analysis)
  - System validation (hardware-in-the-loop)
  - ...

Step 1 - Non-Formal Plant System Analysis

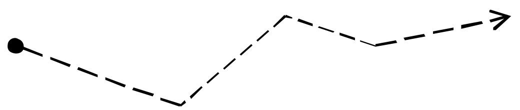
- Identification & characterisation of a plant system environment
  - All entities that interact with it (e.g., other plant systems, human operators)
- Identification & characterisation of operational modes
  - Situations with specific behaviour and expectations
  - Including failure and abnormal situations
  - Assumptions and requirements may depend on operational modes

- A plant system needs, and assumes, certain behaviour from other plant systems or from operators
- Once agreed, these assumptions become requirements for the other plant systems or for the operators
- A plant system is designed based on the requirements placed on it, but also on the assumptions it makes

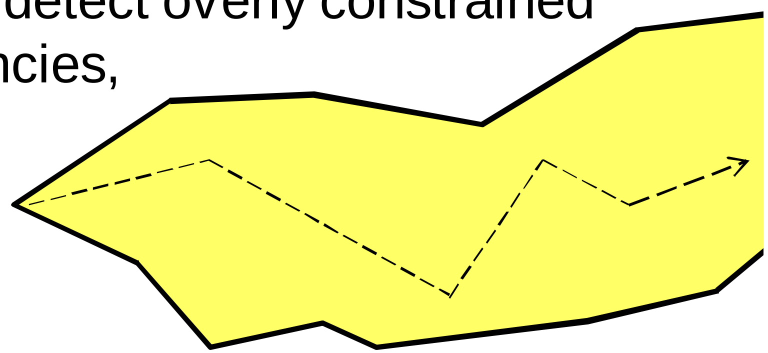


Step 2 - Plant System Requirements Modelling

- Formal modelling of the plant system and its environment
  - Object(s) representing the plant system
  - Objects interacting with the plant system and representing its environment
  - Operational modes
  - Assumptions on the plant system environment
  - Requirements regarding the plant system
- At this stage, this is preferably not an imperative, deterministic model
  - To avoid over-specification and the precluding of possible solutions
- Formal modelling often helps improve the informal requirements specification
- Tool assisted verification may be used to detect overly constrained models (no possible solution), inconsistencies, incompleteness, ...



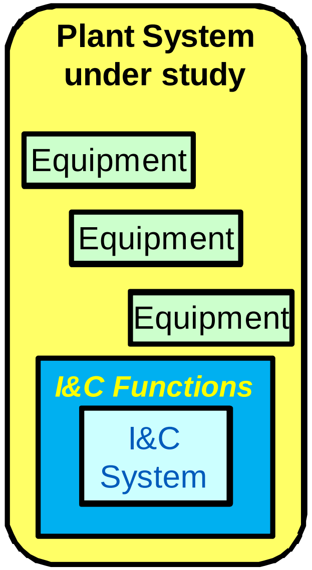
Deterministic behavioural model



Non-deterministic requirements model

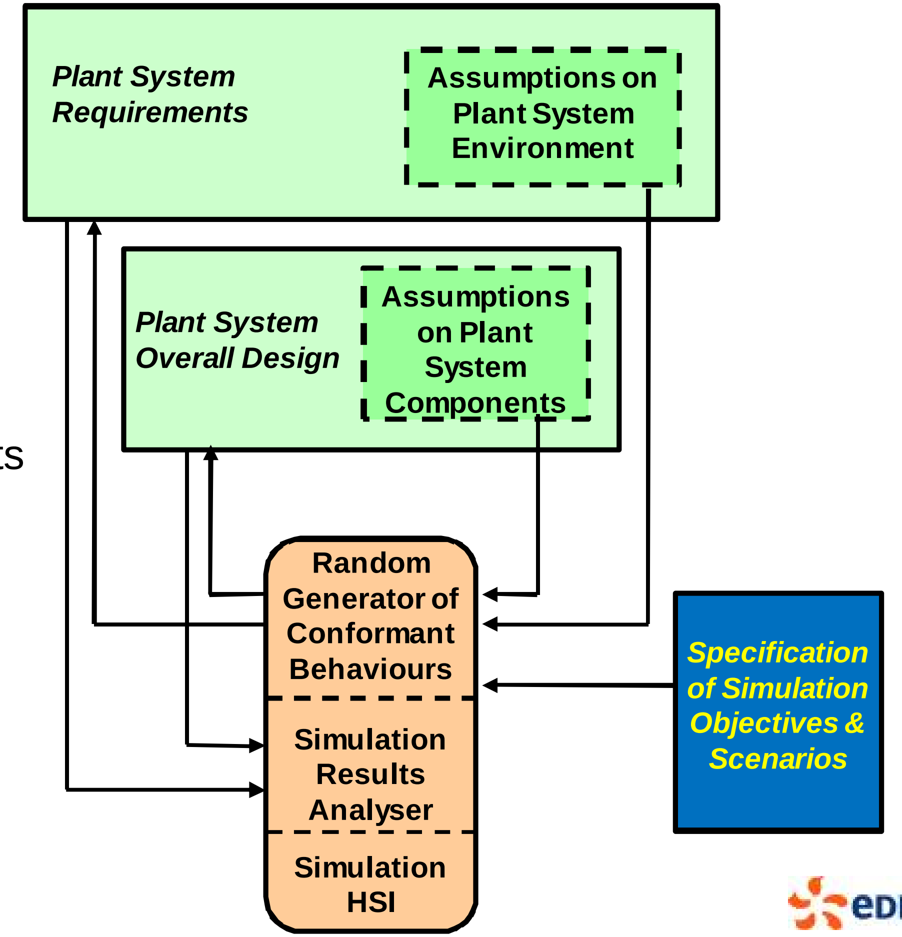
Step 3 - Plant System Overall Design Modelling

- Identification and characterisation of the plant system main components
  - Including Instrumentation & Control
- Identification and characterisation of the plant system main internal modes
- Assumptions made on each component
  - Requirements, from the component standpoint
  - Allocation of plant system requirements
- First in a non-formal manner, and then in a formal model
  - Here again, preferably not an imperative, deterministic model
- Multiple design alternatives may be modelled and analysed



Step 4 - Plant System Overall Design Verification

- Co-simulation of the requirements model and the overall design model
- Stimulation using a random generator of conformant scenarios
  - Such as StimuLus (from ArgoSim)
  - Conformant to assumptions made regarding the plant system environment and plant system components
- Verification that the overall design satisfies the plant system requirements
  - The I&C functional and timing requirements specification are part of the plant system overall design
  - Application of coverage criteria



Step 5 - Detailed Design and Verification

- As design becomes more detailed, the precise behaviour of individual components can be represented by deterministic, behavioural models
  - E.g., in MODELICA for the physical process
  - In functional diagrams for I&C functions
- Detailed design decisions just need to comply with the overall design

Modelling

- Process models
  - Models based on ad hoc techniques
  - Models based on general, multi-physics modelling languages, e.g., MODELICA
  - Multiple models can cooperate using the FMI (Functional Mock-up Interface)
- MODELICA is being extended by the ITEA2 project MODRIO
  - FOrmal Requirements Modelling Language (FORM-L), to formally specify requirements and assumptions at process level
  - Stochastic modelling, to model random events such as components failures
  - Multi-mode modelling, to facilitate the representation of components failure modes

FORM-L

- The language allows the expression of
  - Requirements to be satisfied
    - Functional & timing requirements
    - Fault-tolerance and probabilistic requirements
  - Assumptions made on the environment of the system
  - Overall design decisions
    - Such as allocation of requirements to system components
- Designed to be undertandable by application domain experts
  - Who are not necessarily modelling experts
  - Graphic version of the language allowing different graphic *styles* and natural languages (*dialects*)

FORM-L Main Concepts

- FORM-L addresses four main questions: WHAT, WHEN, WHERE and HOW WELL
- WHAT
  - Boolean conditions
  - Duration of Boolean conditions
  - Constraints on the number of occurrences of an event
- WHEN (temporal logic)
  - During time periods (with duration)
  - At particular instants (without duration)
  - During "sliding time windows"
- WHERE
  - Sets of objects concerned
  - Set memberships often not know at requirements specification
- HOW WELL
  - Fault tolerance
  - (Conditional) failure probabilities

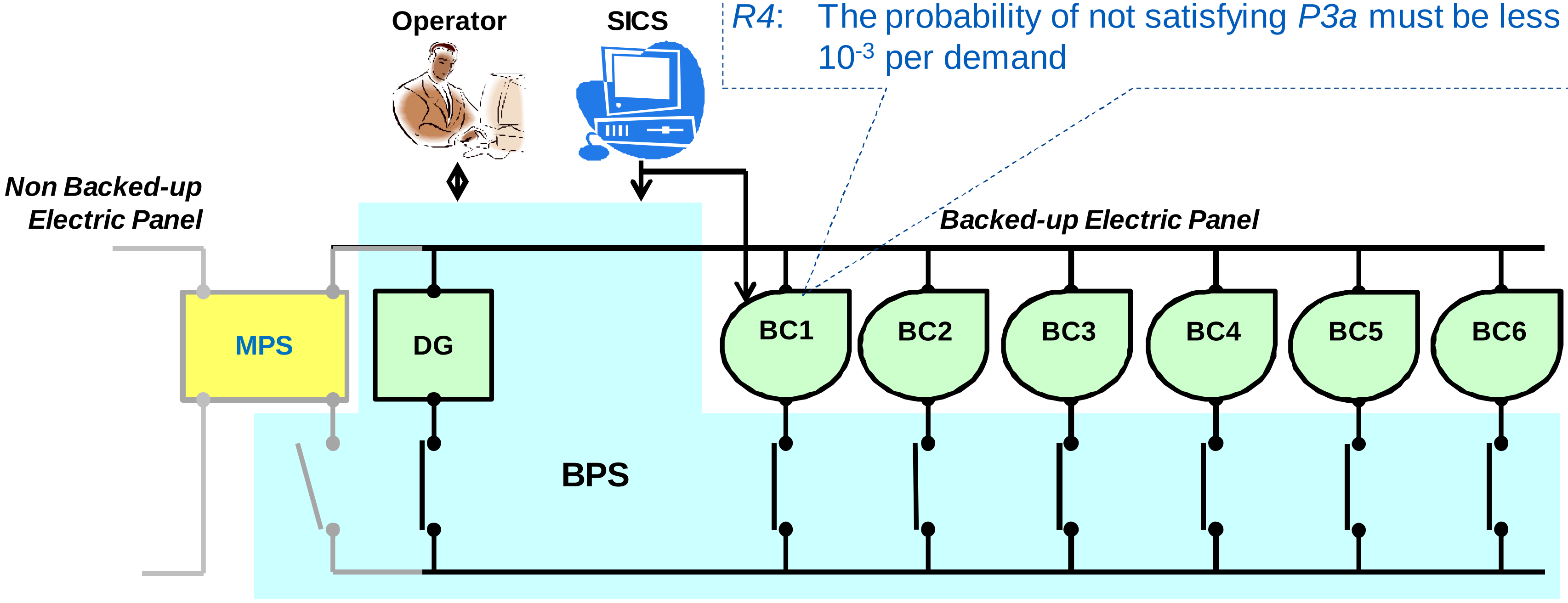
BPS, a Detailed Case Study - Requirements

- The *BPS* (Backup electric Power Supply) provides electric power to Backed-up Components (*BC*s) in case of loss of Main Power Supply (*MPS*)

P3a: When in operation, and when the *BPS* is not under maintenance, *BC1* should not be without power for more than 30 seconds per any 30 minutes time period

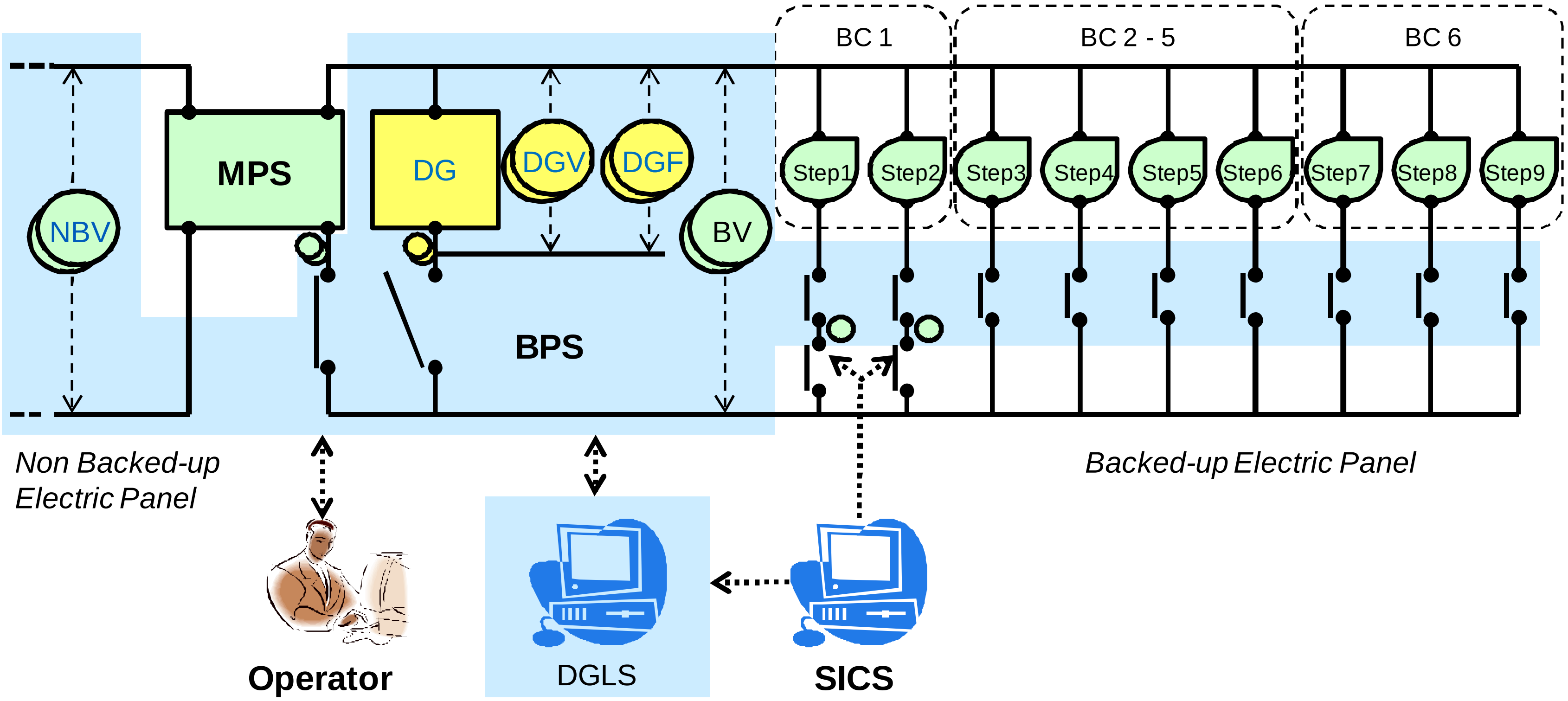
R3a: When there are no *BPS* components failures, or at most a single sensor failure, *P3a* is required

R4: The probability of not satisfying *P3a* must be less than 10^{-3} per demand



BPS Overall Design

- The *DGLS* (Diesel Generator Load Sequencer) is the control system of the *BPS*
  - It operates in a discrete time domain
- The *BPS* overall design specifies requirements for the *DGLS*



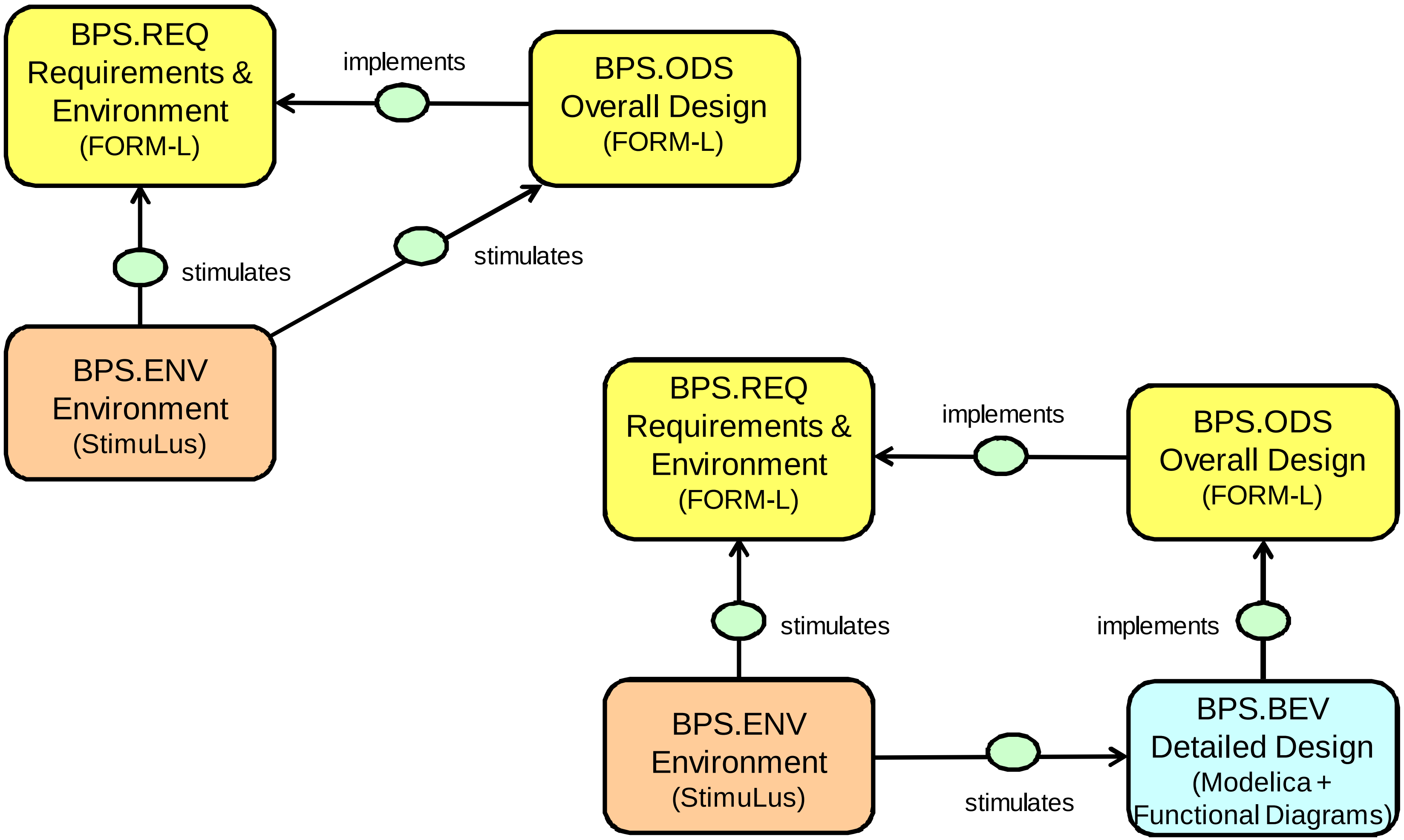
I&C Requirements Specification in FORM-L

- DGLS-R9: When reloading is allowed, the required, unpowered Step with the highest priority shall be reloaded within 100 ms
  - When there are remaining required, unpowered Steps
  - An unrequired Step may become required at any moment

```
Boolean reloadingAllowed;
class Step
  Boolean required;
  Integer priority;
  Breaker brk;
  end Step;
class Breaker
  event openOrder;
  event closeOrder;
  fsa state = {open, closing, closed, opening}  ... end state;
  ...
  end Breaker;
Step step[9]
  ....          // initialiation
  end step;
```

```
Step stepsToBeReloaded = {s ∊ step | s.required and not s.brk.state=closed};
Integer maxPriority = max{stepsToBeReloaded.priority};
Step candidate = any{s ∊ stepsToBeReloaded | s.priority = maxPriority};
requirement R9 =
  when (reloadingAllowed and card(stepsToBeReloaded)>0) becomes true
  within ms100
  check candidate.brk.closeOrder;
```

BPS Formal Models



Conclusion

- More explicit statement of WHY I&C requirements are as they are
  - Particularly useful when systems are revisited (for upgrades for example) many years after initial development
- Helps identify possible impacts of plant systems modifications on I&C
- The same models may be used for various purposes
  - Improve confidence in requirements
  - Early design functional verification
  - Probabilistic and failure analyses
  - FMECA
  - Hardware-in-the-Loop testing
  - ...