Comparative Evaluation of Modeling and Simulation Techniques for Interdependent Critical Infrastructures

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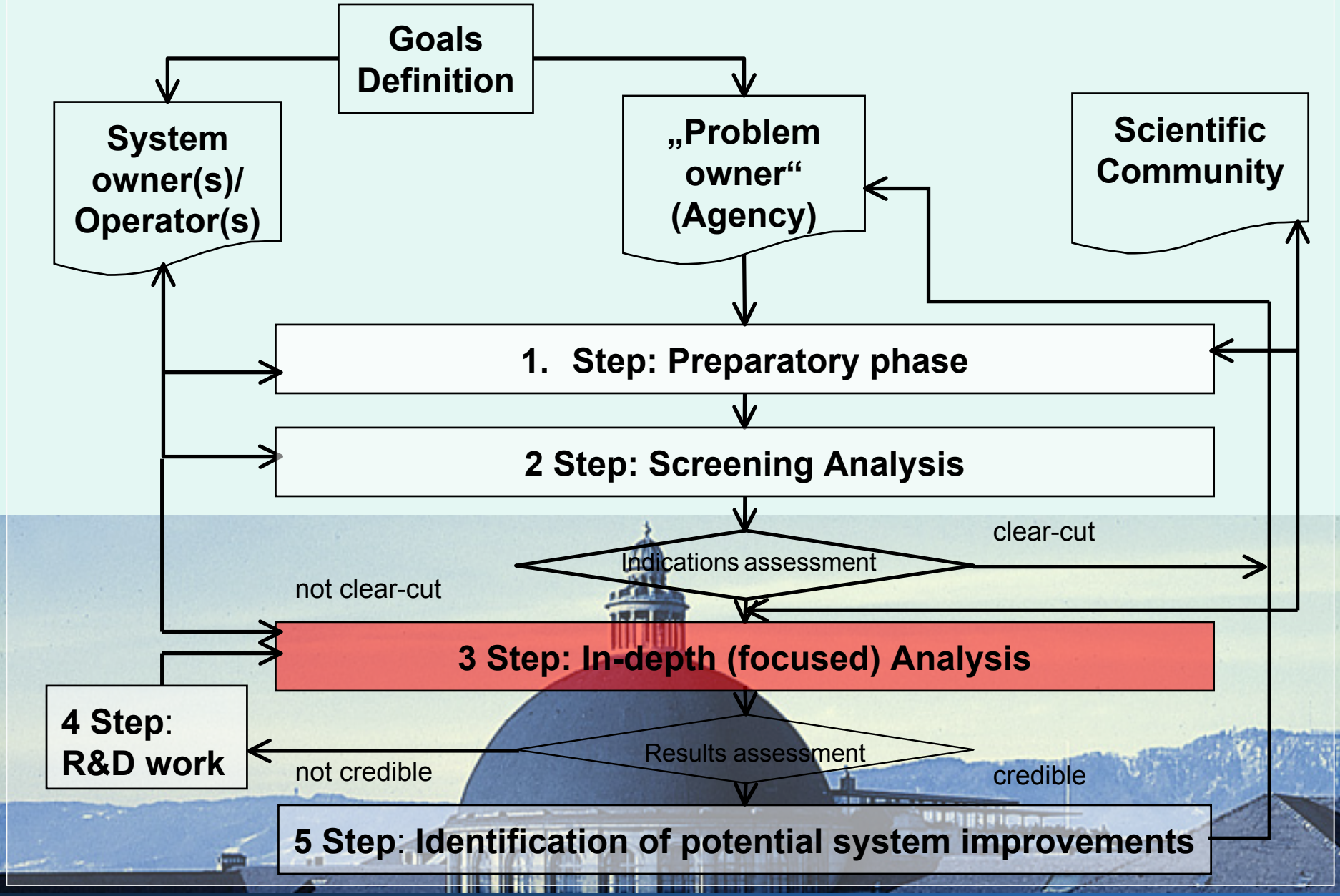

Goals Definition
System owner(s)/ Operator(s)
„Problem owner“ (Agency)
Scientific Community
1. Step: Preparatory phase
2 Step: Screening Analysis
Indications assessment
clear-cut
not clear-cut
3 Step: In-depth (focused) Analysis
4 Step: R&D work
Results assessment
not credible
credible
5 Step: Identification of potential system improvements

Goal

To evaluate and elaborate techniques adequate for vulnerability analysis, not to find “the best method”!

Source

Open source material research

Problems

- Lack of progress in this research field
- Inconsistency of definitions and taxonomy
- Confidential issue

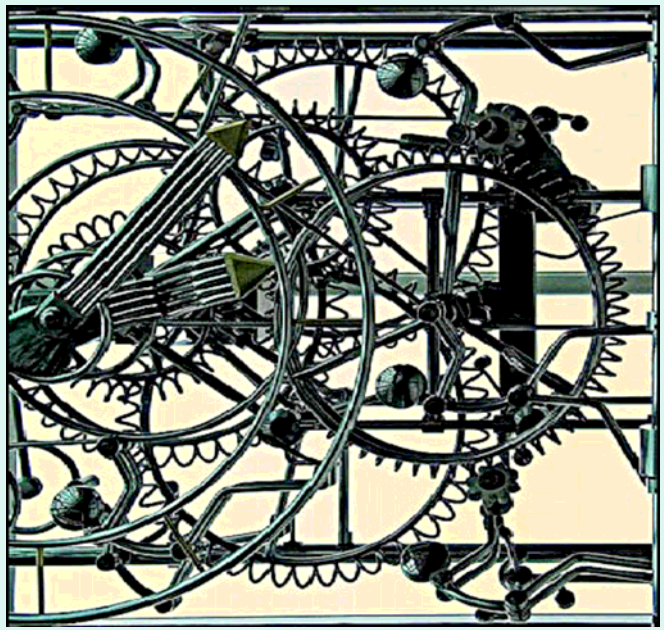
Major challenge : From reliability engineering of complicated systems ...

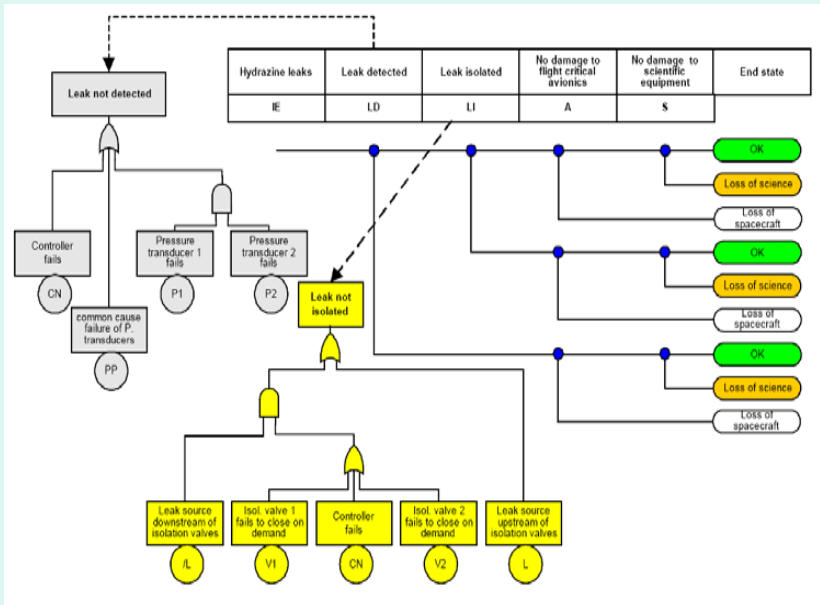
Problems:

- Numerous variables, highly integrated
- Structure stable over time, low dynamics
- Analytical thinking and diligence sufficient

Methods:

- Decomposition of systems, causal chains; PSA framework
- Further development required, e.g. human factors





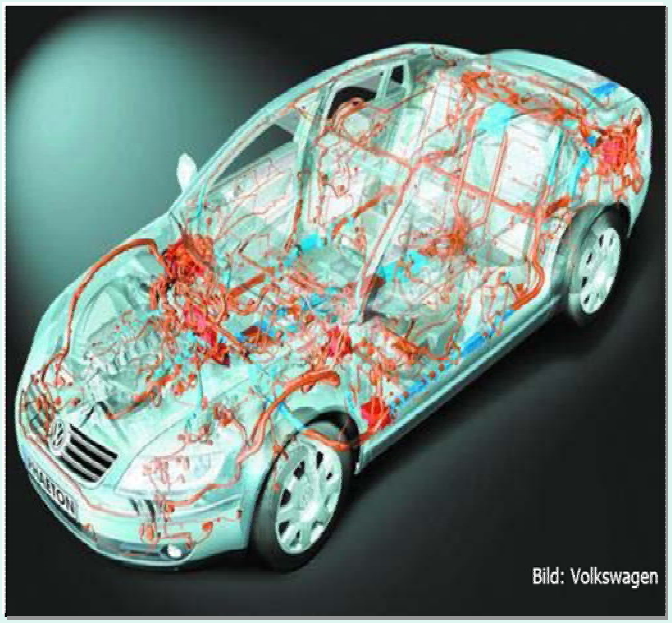
... to reliability engineering of complex systems

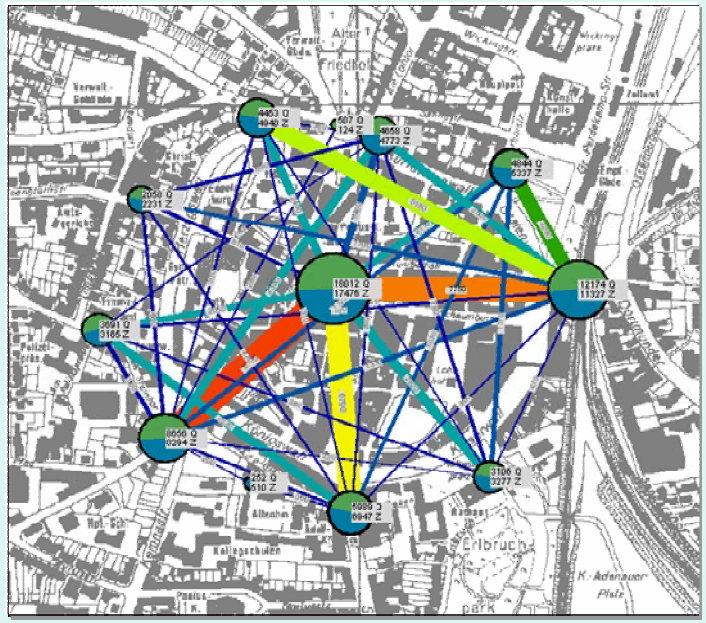
Complex systems:

- Inadequate information about elements, states and interactions
- Nonlinearities, adaptive emergent behavior
- Feedback loops
- Tend to create surprise

Problems:

- System behavior unequal sum of single elements' behavior
- Strong interdependencies
- Need to model and simulate „system-of-systems"





Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
  - Interdependencies Analysis
  - System Analysis
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
  - Bottom-up
  - Top-down
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
  - Cyber
  - Geographic
  - Physical
  - Logical
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
  - Accident
  - Attack
  - Failure
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
  - Cascading events
  - Escalating events
  - Common cause events
  - Confined events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
  - High
  - Low
- Monitoring area
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
  - Vulnerability assessment
  - Failure analysis
  - Mitigation/prevention and self healing strategies
  - Information generation
- Modeling and simulation paradigms
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
  - Discrete events
  - Continuous events
- Maturity

Criteria for comparative evaluation:

- Modeling focus
- Methodical design strategies
- Type of interdependencies
- Types of events for simulation
- Course of triggered events
- Data needs
- Monitoring area
- Modeling and simulation paradigms
- Maturity
  - High
  - Middle
  - Poor

Modeling and Simulation Techniques

- Agent-based modeling
- System Dynamics
- Hybrid System Modeling
- Input-Output Model
- Hierarchical holographic modeling
- Critical Path Method
- High Level Architecture
- Petri Nets

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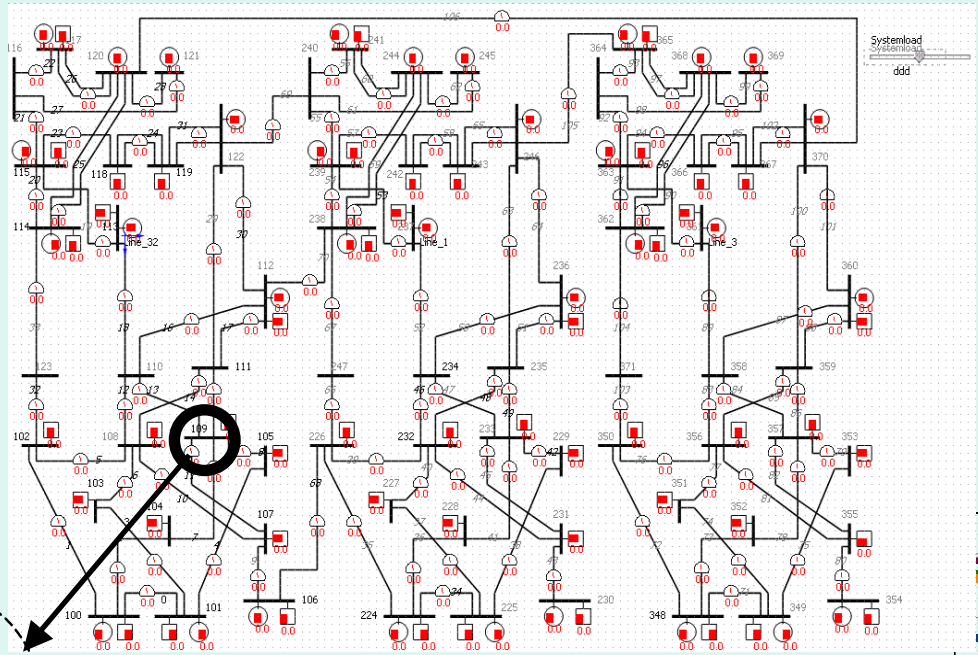
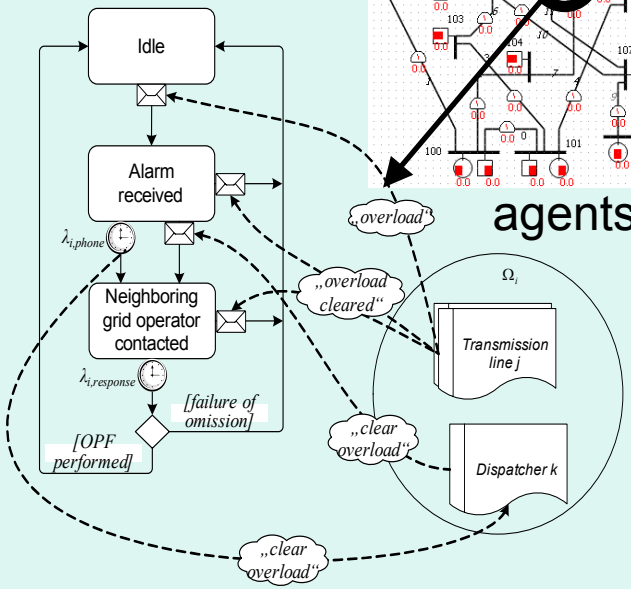
Modeling and Simulation Technique: ABM

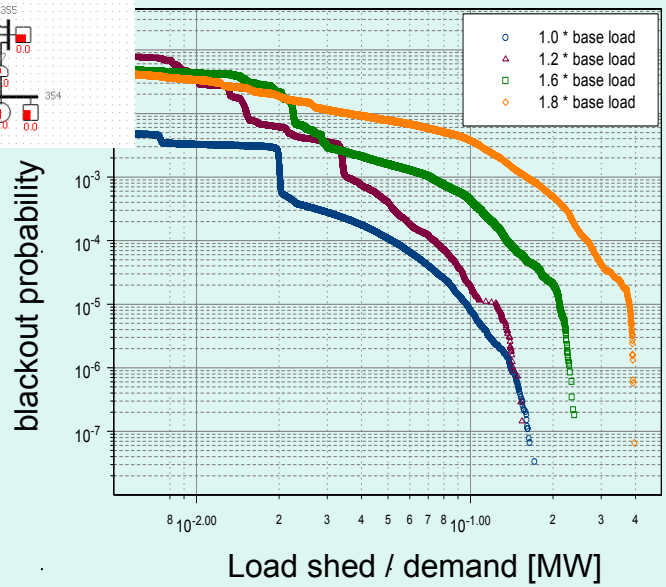
(Electric Power Supply Infrastructure exemplenary)



agents



Simulation Results



Evaluation Example (I): **Agent-based modeling**

ABM was successful applied in:

- Economics (supply chain optimization, consumer behavior, etc.)
- Informatics (distributed computing, traffic congestion, etc.)
- Critical infrastructures interdependencies
- etc.

Problems:

- Each simulation is very time consuming
- Larger number of parameters
- Data availablity problem

Evaluation Example (I): **Agent-based modeling**

Maturity	High			
Paradigm	Discrete			
Monitoring Area		Failure Analysis		Information
Data Needs	High	Low		
Course of Triggered Events	Cascading	Escalating	Common cause	Confined
Types of Events	Accidents	Attacks	Failures	
Types of Interdependencies	Physical	Cyber	Geographic	Logical
Design Strategies	Bottom up			
Modeling Focus		System Analysis		

Modeling and Simulation Techniques

- Agent-based modeling
- System Dynamics
- Hybrid System Modeling
- Input-Output Model
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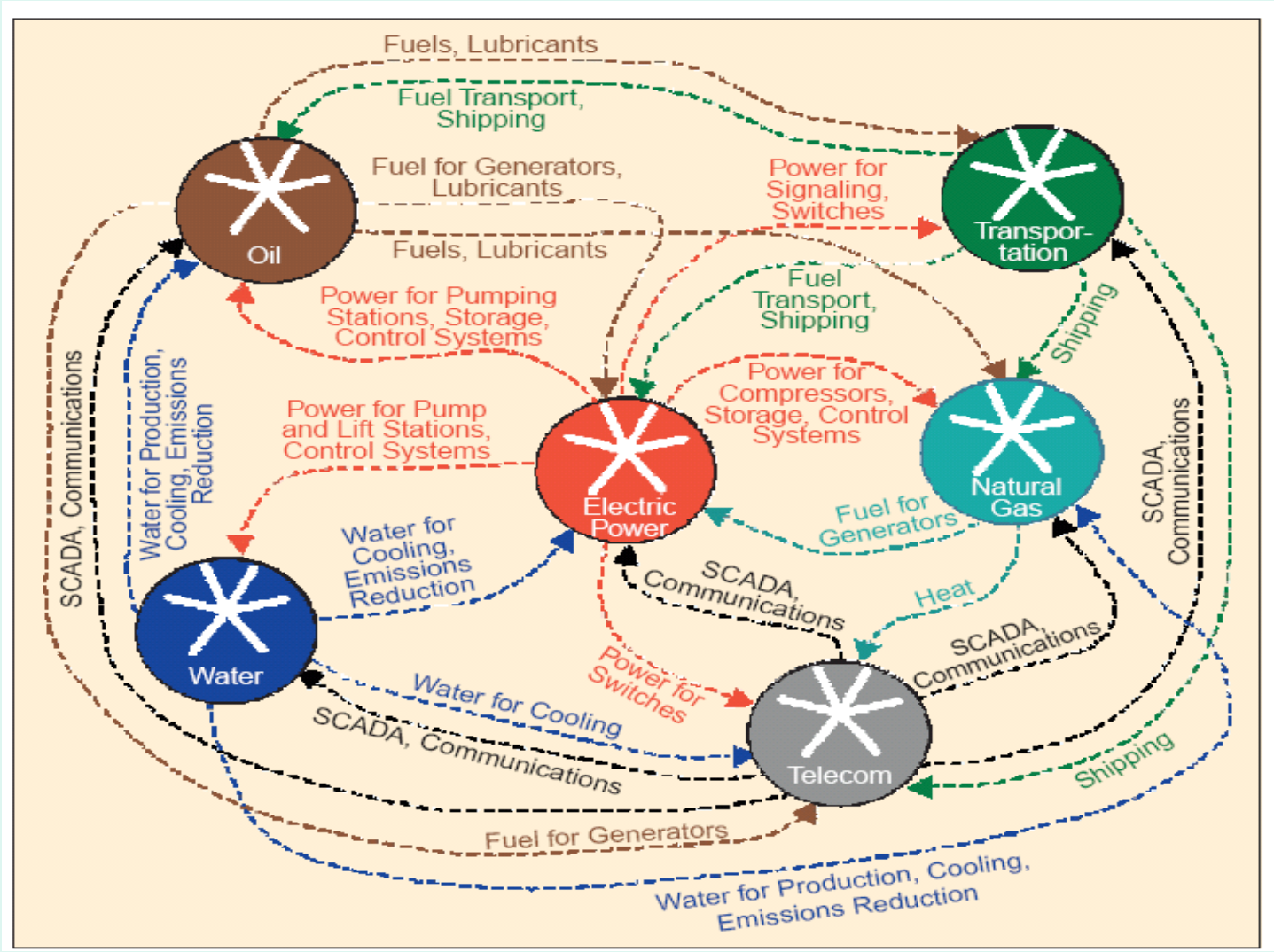
- Critical Path Method
- High Level Architecture
- Petri Nets

Examples of infrastructure interdependencies [Rinaldi et al. 2001]



Petri Net Model of infrastructure interdependencies [Gursesli & Desrochers, 2003]

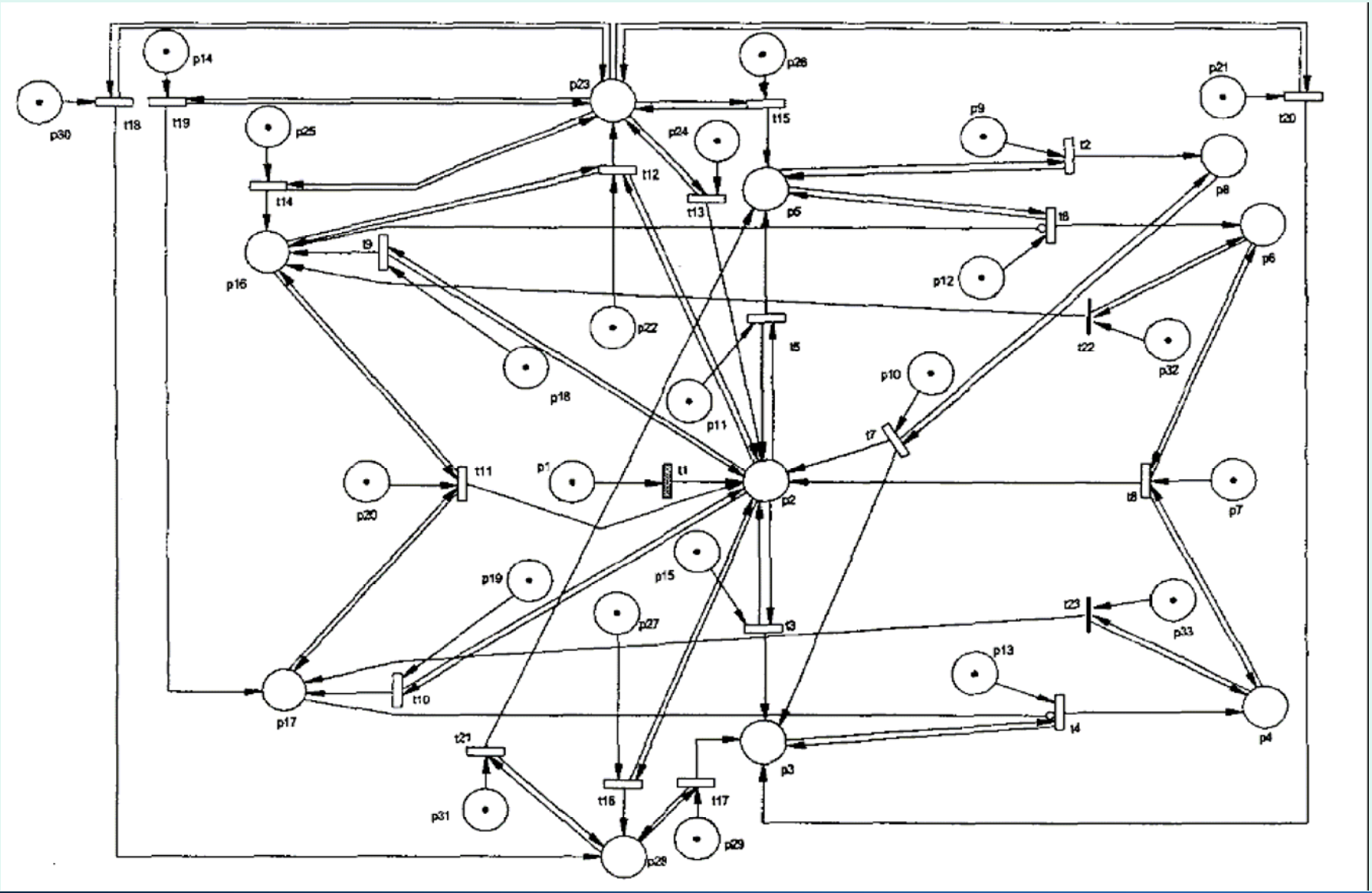


Table 4.8.1 Legend for Petri Net Model [GuDe 2003]

TRANSITIONS	**PLACES**
1 "Electric Power is Disrupted" 2 "Lubricants in Reserves are Consumed" 3 "Power Disruption Affects Natural Gas Production" 4 "Natural Gas in Reserves is consumed ***5*** "Power Disruption affects OivLuhricants Production" 6 "Oil in Reserves is Consumed" 7 "Lubricants are Disrupted" 8 "Both Oil and Natural Gas are Disrupted" 9 "Power Disruption Affects Oil Transportation" 10 "Power Disruption Affects Natural Gas Transportation" 1 1 "Transportation Affects Electric Power Generation" 12 "Power Disruption Affects Telecommunication" …….. 23 "Consumed Natural Gas Affects Transportation"	1 "Electric Power ON" 2 "Electric Power **OFF"** 3 "Natural Gas Production Stops" ***4*** "Consumed Natural **Gas"** **5** "OiVLubricant Productions Stop" **6** "Consumed **Oil"** 7 8 "Consumed Lubricants" 9 "Lubricant Production Stops Mirror" IO "Consumed Lubricants Mirror" 11 "Electric Power OFF Mirror (for Oil Production)" **12** "Oil Production Stops Mirror" 13 "Natural Gas Production Stops Mirror" 14 "Telecommunication OFF Mmor (for Natural Gas …… 33 "Consumed Natural Gas Mirror (for Transportation)"

Evaluation Example (II): Petri Nets

PNs were applied to:

- Common mode and cascading effects in complex systems
- Analysis the impact of communication on power grid

also suitable to

formalise and simulate dynamic aspects e. g.

- Workflow systems
- Distributed and concurrent computing systems

Problems:

- Graphical representation may become too complex to be useful
- Additional Information needs many parameters or programming
- Numerical solution is not always feasible
- Simulation may be very time consuming

Evaluation Example (II): Petri Nets

Maturity		Middle		
Paradigm	Discrete			
Monitoring Area		Failure Analysis		Information
Data Needs	High	Low		
Course of Triggered Events	Cascading		Common cause	Confined
Types of Events			Failures	
Types of Interdependencies	Physical			
Design Strategies		Top down		
Modeling Focus	Interdependency Analysis	System Analysis		

Comparative evaluation of methods: Evaluation code

	ABM	SD	HSM	IOM	HHM	CPM	HLA	PNs
Maturity	●○○○	●○○○	○○●○	○●○○	○●○○	○○●○	○○●○	○●○○
Paradigm	●○○○	●●○○	●●○○	○●○○	○●○○	●○○○	●○○○	●○○○
Monitoring Area	○●○●	○○○●	●●○●	○●○○	●○○○	○●○●	○●●○	○●○●
Data Needs	●●○○	○●○○	○●○○	○●○○	●○○○	●○○○	○●○○	●●○○
Course of Triggered Events	●●●●	●○○●	●○○●	●○○○	○●○●	●○○●	●●●●	●●○●
Types of Events	●●●○	○○●○	●●●○	○○●○	●●○○	○○●○	●●●○	○○●○
Types of Interdependencies	●●●●	●●○○	●●●●	●○○○	●●○●	●●●●	●●●●	●○○○
Design Strategies	●○○○	○●○○	○●○○	○●○○	○●○○	○●○○	●●○○	○●○○
Modeling Focus	○●○○	●●○○	○●○○	●○○○	●○○○	●●○○	●●○○	●●○○

Comparative evaluation of methods: Evaluation code

	ABM	SD	HSM	IOM	HHM	CPM	HLA	PNs
Maturity	●○○○	●○○○	○○●○	○●○○	○●○○	○○●○	○○●○	○●○○
Paradigm	●○○○	●●○○	●●○○	○●○○	○●○○	●○○○	●○○○	●○○○
Monitoring Area	○●○●	○○○●	●●○●	○●○○	●○○○	○●○●	○●●○	○●○●
Data Needs	●●○○	○●○○	○●○○	○●○○	●○○○	●○○○	○●○○	●●○○
Course of Triggered Events	●●●●	●○○●	●○○●	●○○○	○●○●	●○○●	●●●●	●●○●
Types of Events	●●●○	○○●○	●●●○	○○●○	●●○○	○○●○	●●●○	○○●○
Types of Interdependencies	●●●●	●●○○	●●●●	●○○○	●●○●	●●●●	●●●●	●○○○
Design Strategies	●○○○	○●○○	○●○○	○●○○	○●○○	○●○○	●●○○	○●○○
Modeling Focus	○●○○	●●○○	○●○○	●○○○	●○○○	●●○○	●●○○	●●○○

Comparative evaluation of methods: Evaluation code

	ABM	SD	HSM	IOM	HHM	CPM	HLA	PNs
Maturity	●○○○	●○○○	○○●○	○●○○	○●○○	○○●○	○○●○	○●○○
Paradigm	●○○○	●●○○	●●○○	○●○○	○●○○	●○○○	●○○○	●○○○
Monitoring Area	○●○●	○○○●	●●○●	○●○○	●○○○	○●○●	○●●○	○●○●
Data Needs	●●○○	○●○○	○●○○	○●○○	●○○○	●○○○	○●○○	●●○○
Course of Triggered Events	●●●●	●○○●	●○○●	●○○○	○●○●	●○○●	●●●●	●●○●
Types of Events	●●●○	○○●○	●●●○	○○●○	●●○○	○○●○	●●●○	○○●○
Types of Interdependencies	●●●●	●●○○	●●●●	●○○○	●●○●	●●●●	●●●●	●○○○
Design Strategies	●○○○	○●○○	○●○○	○●○○	○●○○	○●○○	●●○○	○●○○
Modeling Focus	○●○○	●●○○	○●○○	●○○○	●○○○	●●○○	●●○○	●●○○

Underlying methods by tools for M&S of CI

No.	Underlying Methodologies	Abbreviations	No. of Methods
1	Agent-Based Method	ABM	13
2	Geografic Information Systen	GIS	6
3	System Dynamics	SD	4
4	Statistical Data Analysis	SDA	3
5	Monte Carlo	MC	2
6	Input-Output Methods	IOM	2
7	Graph Theory	GT	1
8	Control Theory	CT	1
9	Miscellaneous	MI	1

Conclusions

- Nine evaluation criteria defined
- Eight M&S methods selected, analysed, described and evaluated
- Reasons for their use hypothesized
- Overview about strengths and weaknesses of methods given
- Basis for the decision on single or combined methods offered

Complex Systems