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POLITECNICO DI MILANO

Extension of DMCI to heterogeneous Critical Infrastructure systems

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Agenda

- DMCI background: main features and modularisation
- Modelling heterogeneous CI: Transportation + Electricity
- Testing DMCI capability with a simple cascading failure
- Findings and future developments

Approaches to Modelling Interdependent Critical Infrastructure systems

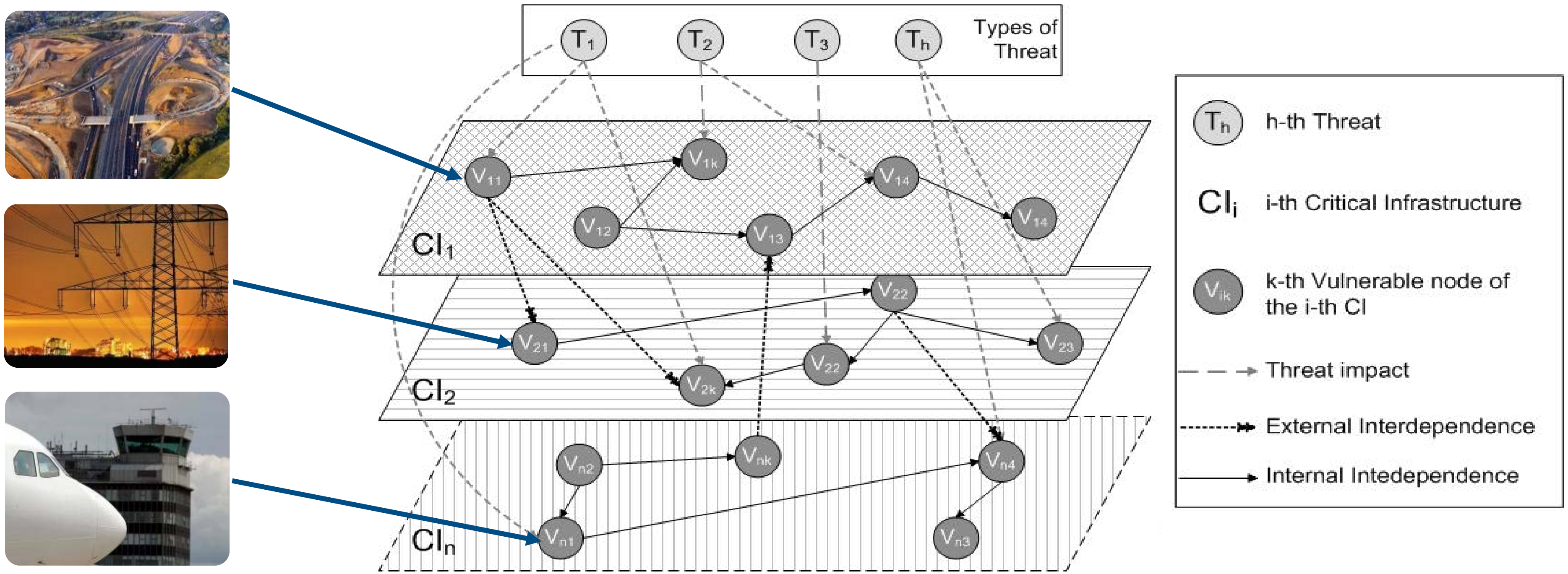
Ouyang's state-of-the art review (2014)

Approach type	Sub-approach	Quantity of input data	Accessibility of input data	Types of interdependencies	Computation cost	Maturity	Resilience
Empirical		M, L	M	P, C, G, L	S	M	1.3,2.3, 2.4, 3.3
Agent-based		L	S	P, C, G, L	L	L	1.1, 1.2, 1.4, 1.6, 2.1, 2.5, 3.1, 3.3
SD based		M, L	M	P, C, L	M	L	1.6, 2.5, 3.3
Economic theory based	Input output	M	L	P, C	S	L	1.3, 2.3, 2.4, 3.2
	Computable general equilibrium	L	M	P, C, G, L	M	M	1.3, 1.6, 2.3, 2.4, 2.5, 3.2,
Network based	Topology-based method	S, M	M	P, C, G, L	S, M	L	1.3, 2.2, 2.3, 3.2, 3.3
	Flow-based method	L	S	P, C, G,L	L	L	1.3, 1.5, 1.6, 2.2, 2.3, 2.4, 2.5, 2.6, 3.2, 3.3, 3.4
Others	HHM	L	S	P, C, L	S	S	1.6, 2.5, 3.3
	HLA based	L	L	P, C, G, L	L	S	1.1–1.6, 2.1–2.6, 3.1–3.4
	PN	M, L	M	P	M, L	M	1.3, 1.6, 2.3, 2.4, 2.5, 3.3, 3.4
	DCST	M, L	S	P, C, G, L	M	S	1.3, 1.6, 2.3, 2.4, 2.5, 2.6, 3.3, 3.4
	BN	M, L	S	P, C, G, L	M	S	1.3, 1.5, 1.6, 2.3–2.6, 3.3, 3.4

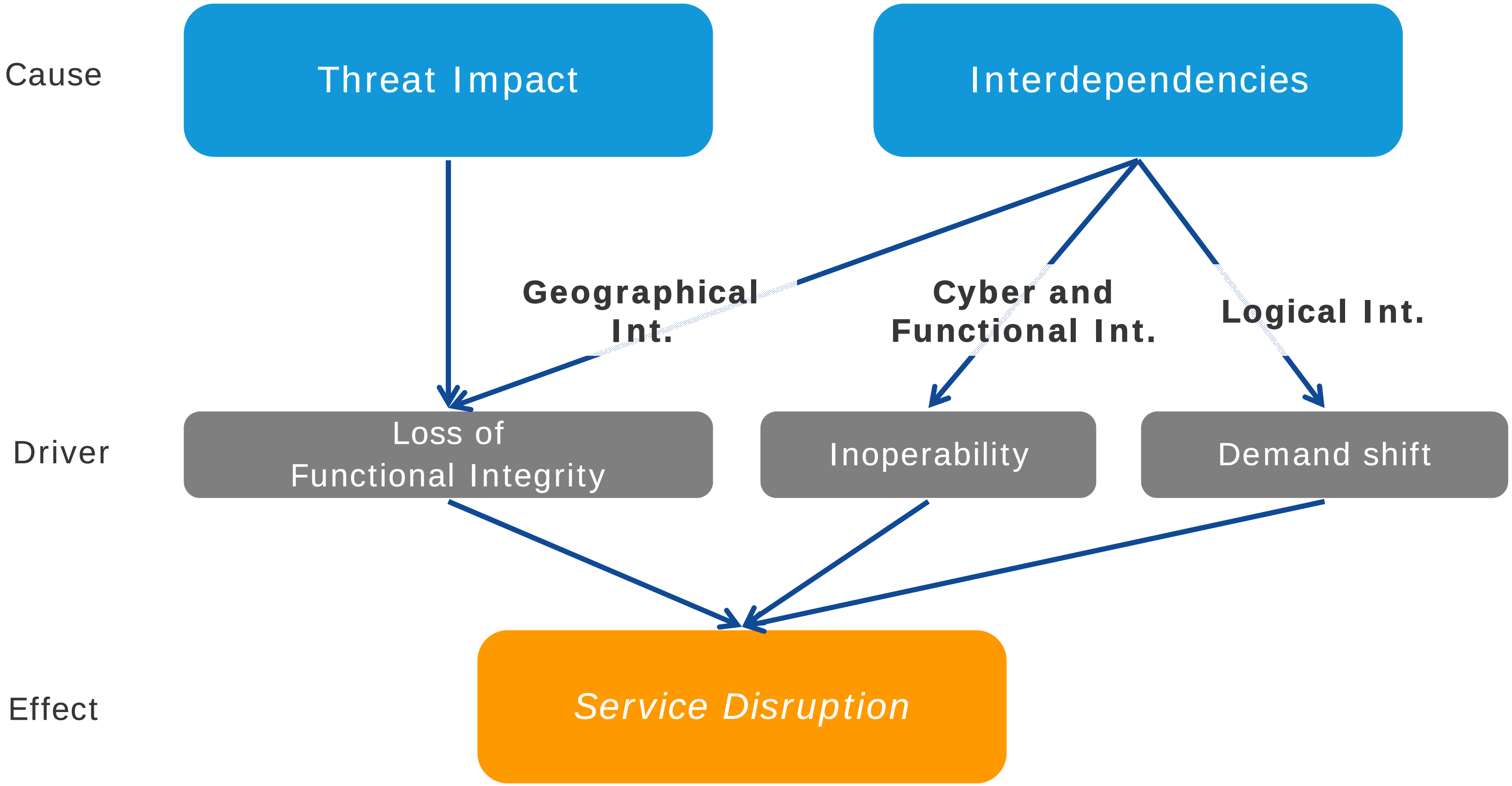
- **DMCI (Dynamic Functional Modelling of vulnerability and interoperability of CIs)** firstly delivered in 2012 (Trucco et al., 2012) is a Network-based / flow-based approach
- According to Ouyang's review (Ouyang, 2014), flow-based approaches are those with the highest potential to model all the resilience capabilities of CI systems

DMCI modelling approach
Vulnerable Node definition

- Is a system: the smallest portion of an infrastructure that can be collectively regarded as a system, able to supply a value added service through its own means and available resources.
- Is vulnerable: exposed to disruptive events (Threats) that may affect its functional integrity.



DMCI modelling approach
Assessment of Service Disruption

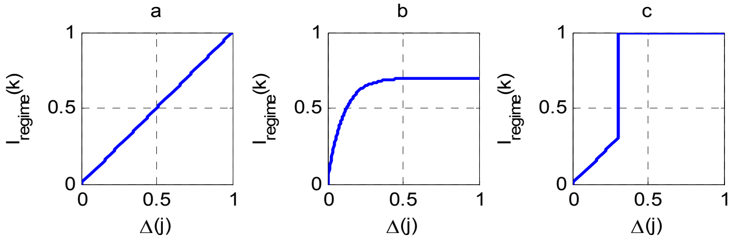


DMCI modelling approach
Functional and Logical Int. modelling

- **Functional interdependencies** cause a reduction of the maximum service ($S_{max}(k,t)$) that the generic "child" node is able to deliver.
  - The marginal variation of **inoperability** in the child node due to a disservice Δ in the father node is:

$$dI(k,t) = df_{I\Delta(k,j)}[\Delta(j,t)] \cdot f_{It(k,j)}(dt)$$

Inoperability rate

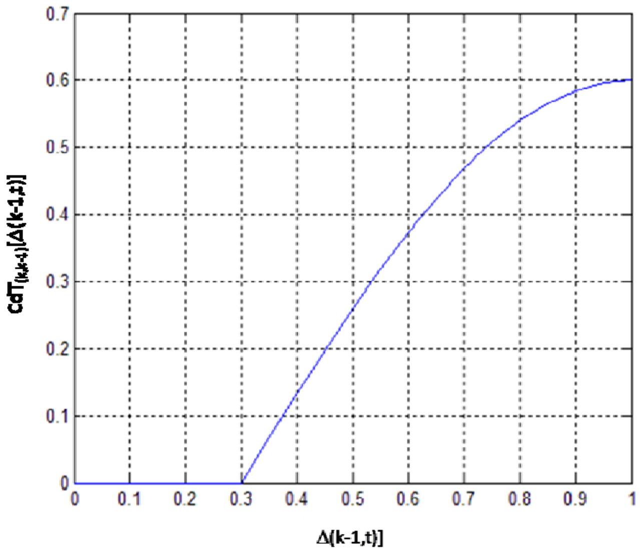


Operator of dynamic modulation of inoperability

- **Logical interdependencies** (demand shift): the child node bears an increasing demand $D_l(k,t)$ depending on the service loss of the father and the time in which the demand changes.

$$D_{l(k,t)} = \sum_{i=1}^{n_{LK}} DS_{(k_i,k)}[\Delta(k_i,t)] \cdot D_{(k_i,t)} \cdot f_{L(k_i,k)}(t)$$

$$D(k,t) = D_{ext}(k,l) + D_l(k,t)$$



DMCI modelling approach
Determining each node's state

Maximum Capacity

Nominal Demand

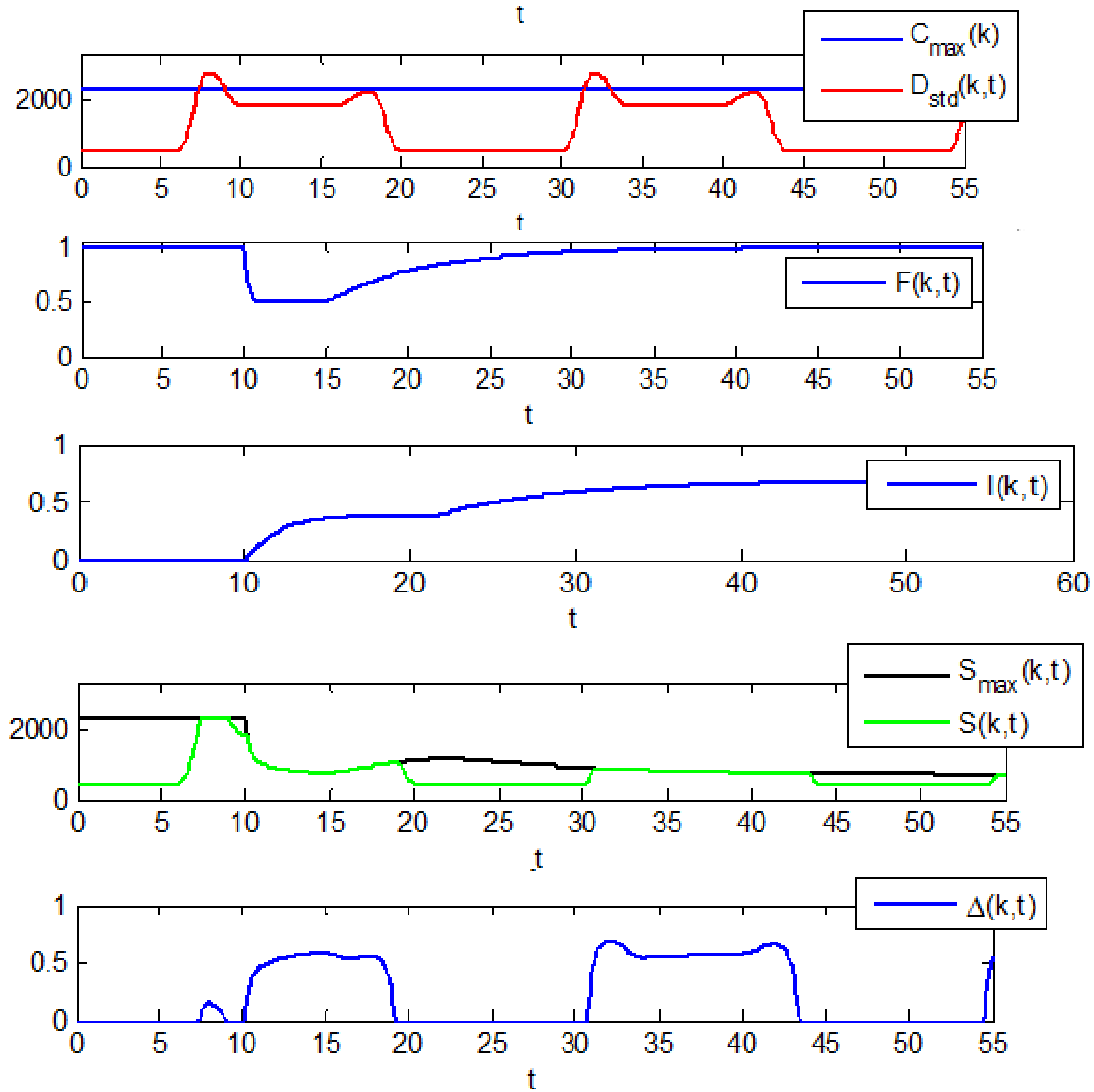
Functional Integrity

Inoperability

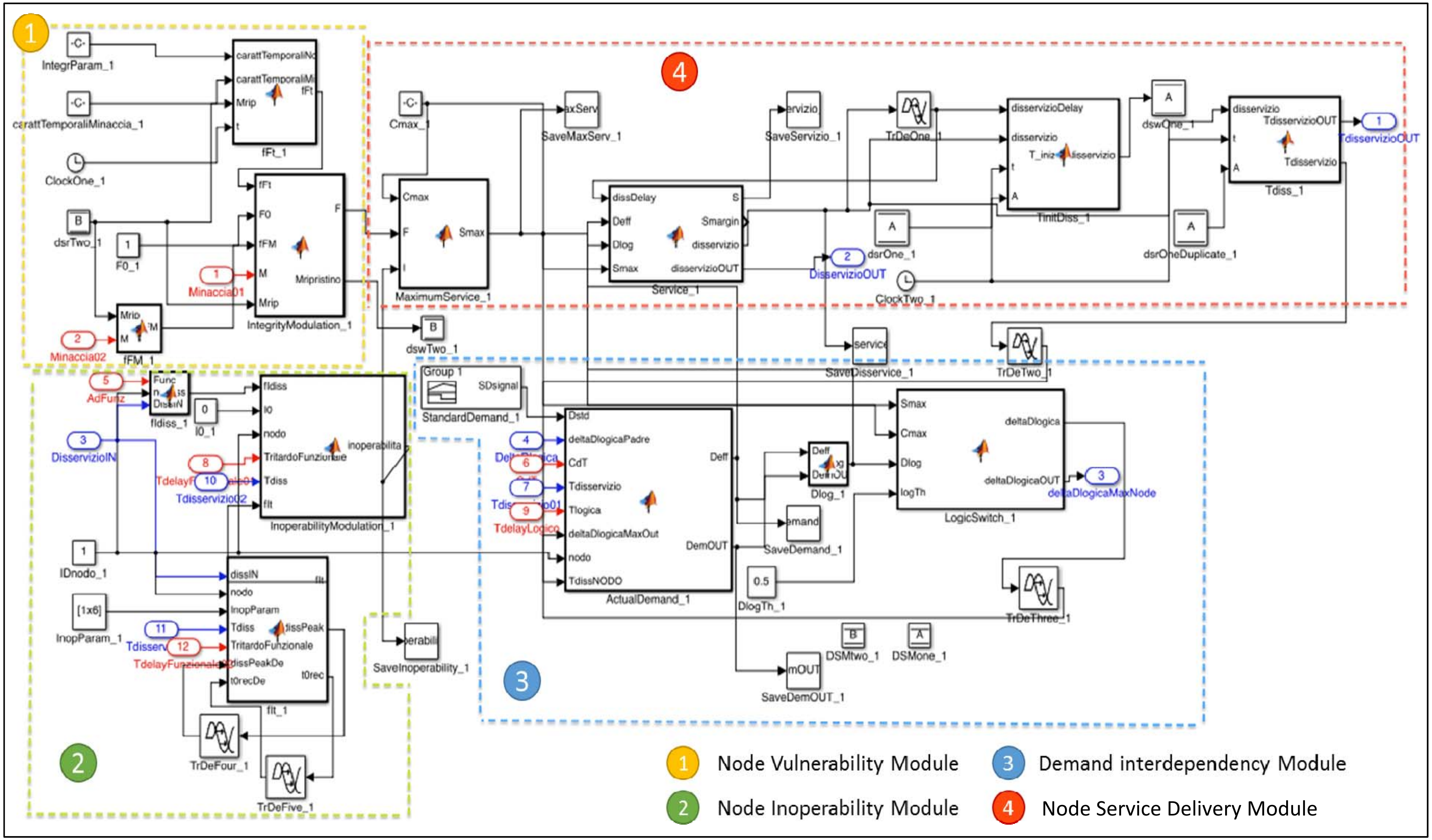
Maximum Service

Delivered Service

Service loss



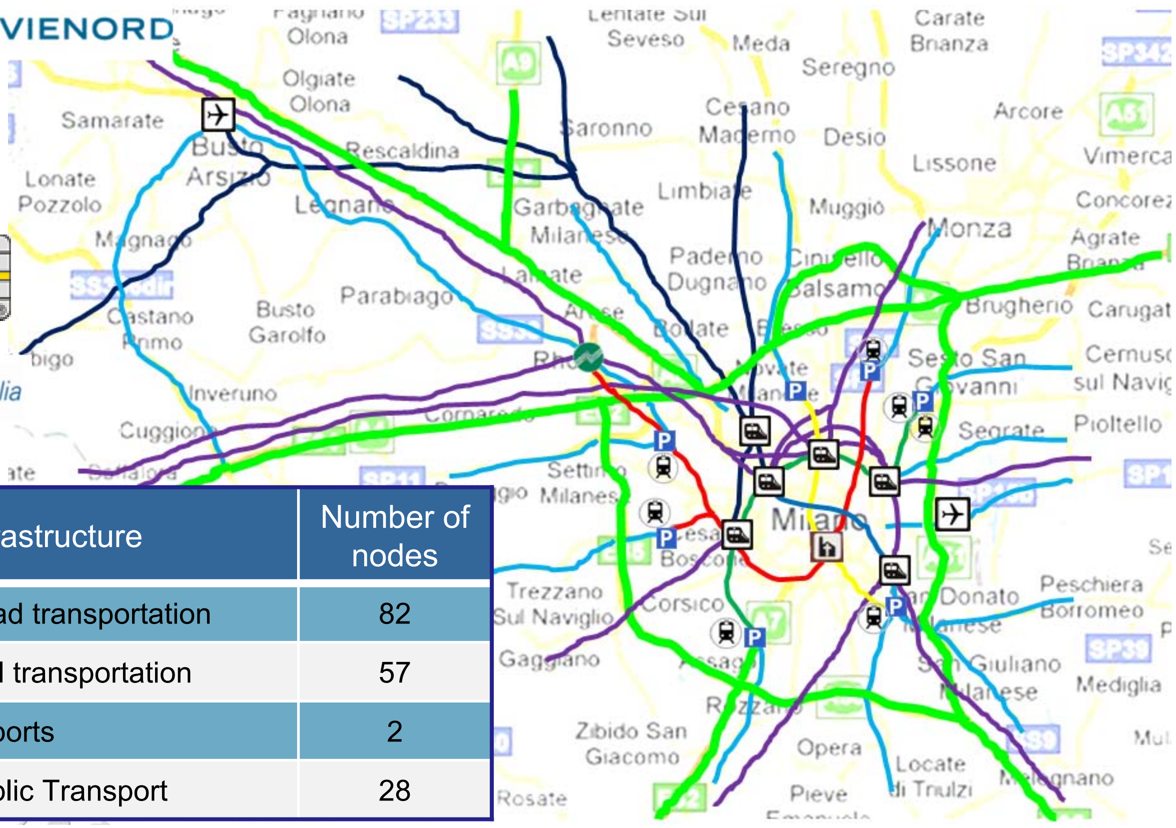
DMCI Modularization
Simulink® implementation



Pilot study in the metropolitan area of Milan, Italy
Transportation Networks

- Comprises 169 vulnerable nodes and CI from 4 different categories
- Characterisation of vulnerable nodes by means of:
  - PReSIC program and other data gathered from operators
  - Regional data from the Civil Protection system
  - Public data and theoretical models

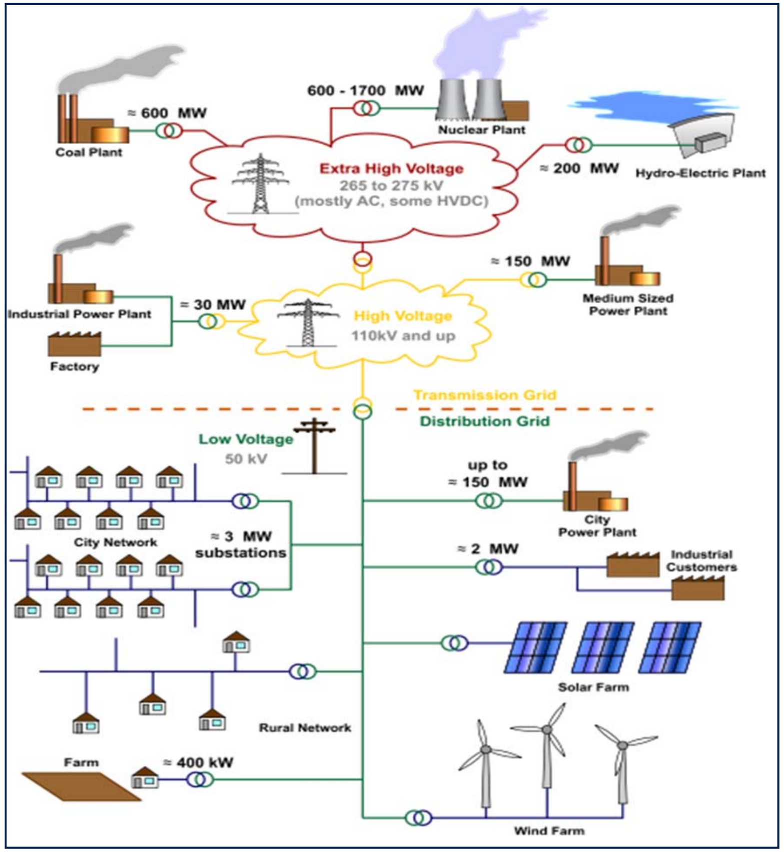
TRENORD
FERROVIENORD
RFI RETE FERROVIARIA ITALIANA GRUPPO FERROVIE DELLO STATO ITALIANE
ATM AZIENDA TRASPORTI MILANESI S.p.A.
SEA AEROPORTI DI MILANO LINATE E MALPENSA
milanoserravalle milanotangenziali
SNAM
Terna
autostrade per l'italia
Enel L'ENERGIA CHE TI ASCOLTA.
ANAS
a2a
Orio al Serio international airport S.A.C.B.O. S.p.A.
SATAP S.p.A.



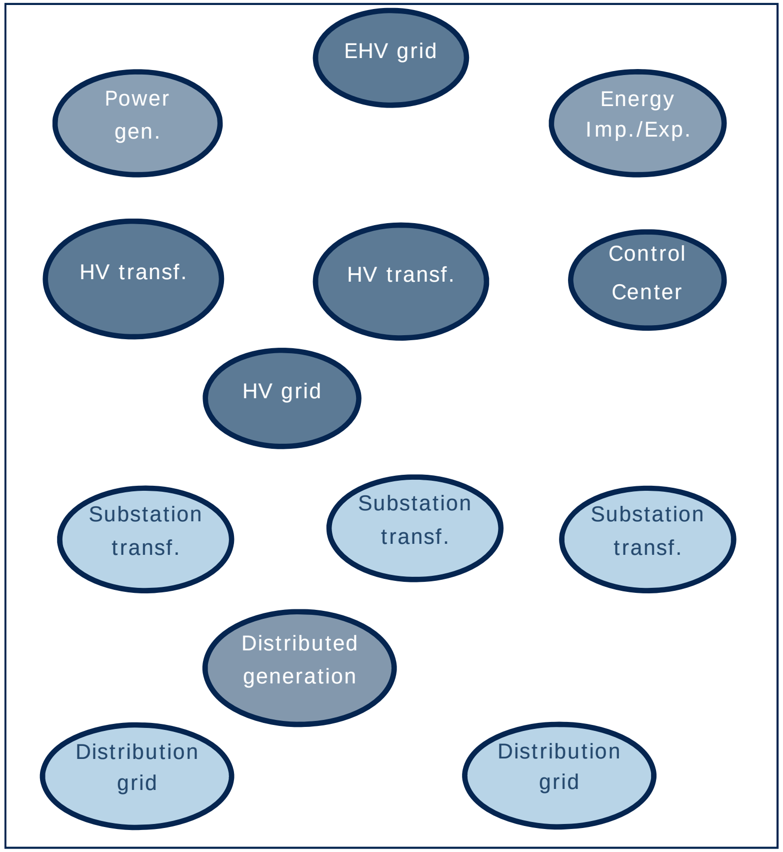
Infrastructure	Number of nodes
Road transportation	82
Rail transportation	57
Airports	2
Public Transport	28

Extended DMCI for heterogeneous CI
Functional modelling of the Electrical Grid

General layout of the Electric Grid



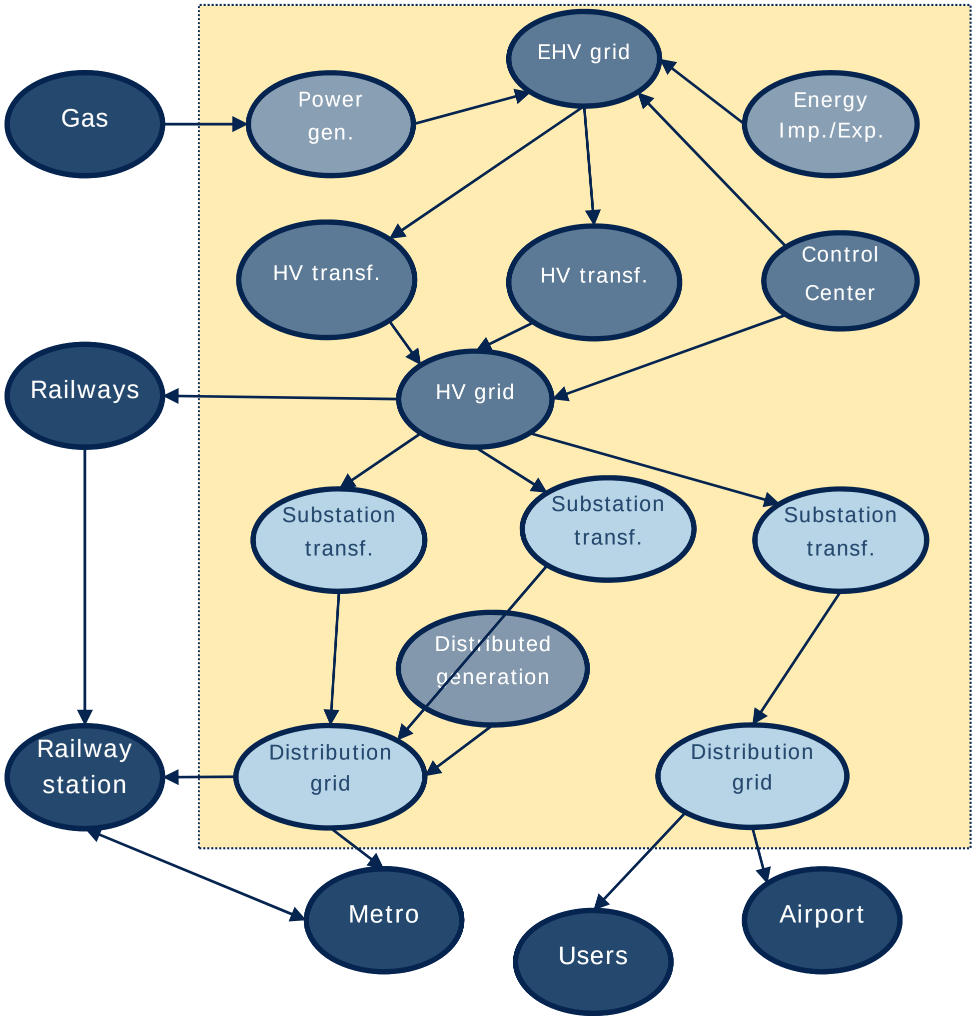
Vulnerable Nodes under the DMCI formalism



Extended DMCI for heterogeneous CI
Functional modelling of the Electrical Grid

- Functional Interdependencies
  - Power gen
  - Transmission
  - Distribution
- Cyber Interdependencies
  - Supervision and monitoring from the Control Center

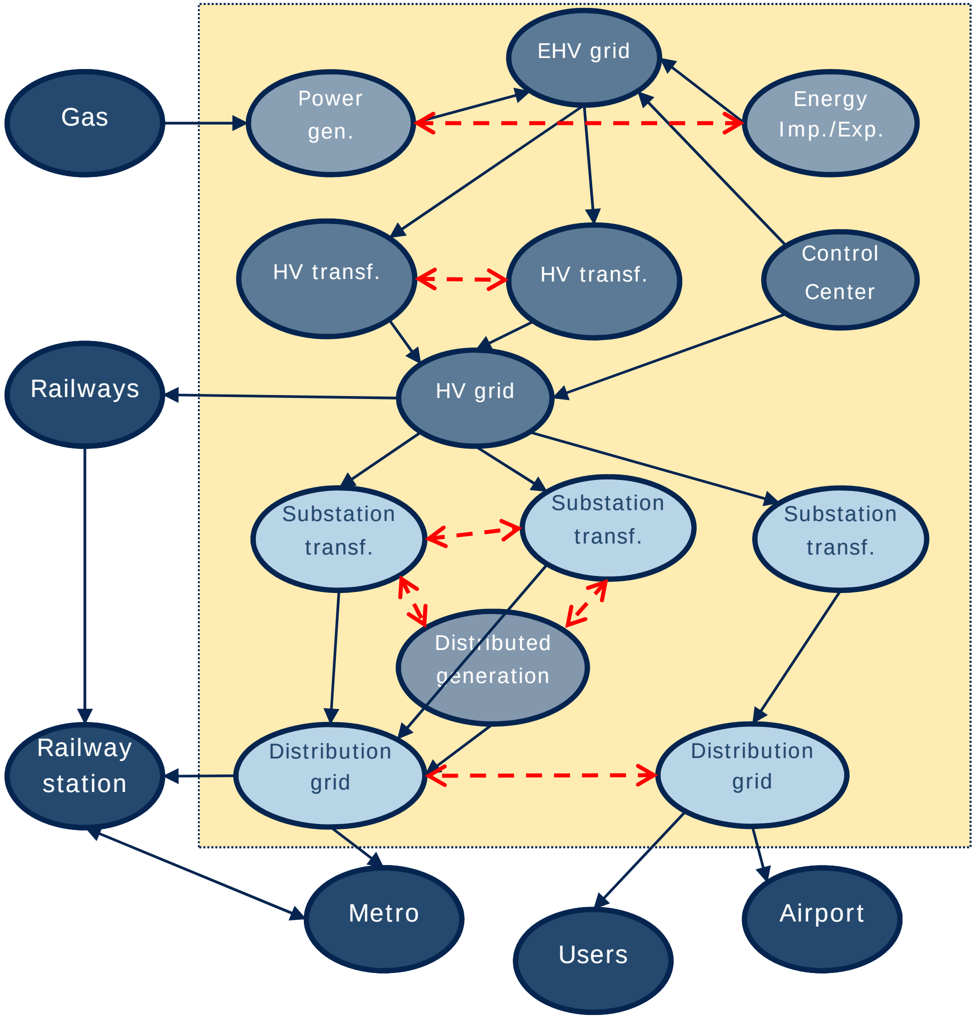
Vulnerable Nodes under the DMCI formalism



Extended DMCI for heterogeneous CI
Functional modelling of the Electrical Grid

- Logical Interdependencies
  - Re-balance grid disturbances (e.g. distributed gen. variability, generation vs import/export)
  - Change of grid settings at transmission and distribution level

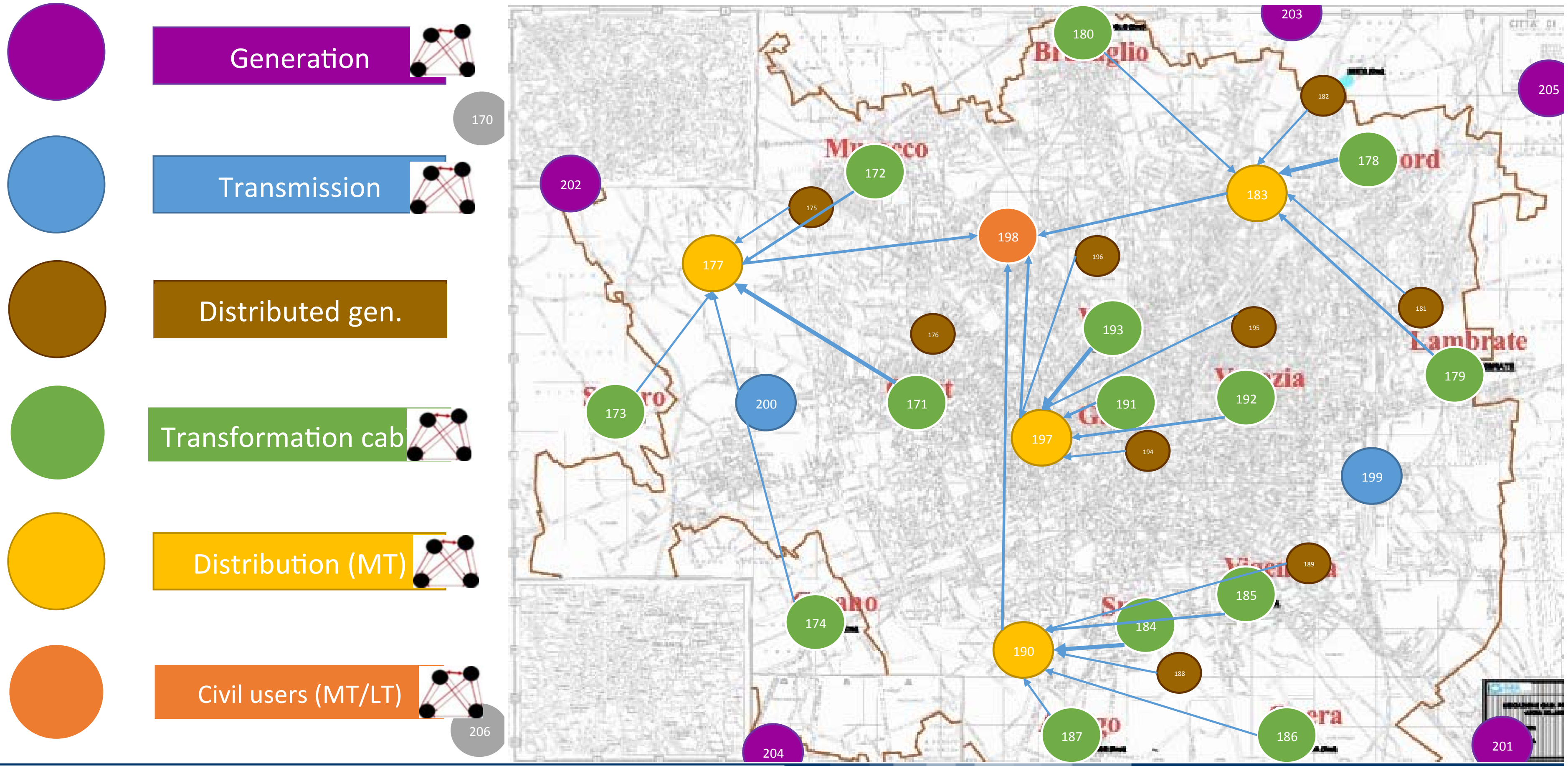
Vulnerable Nodes under the DMCI formalism



Pilot study in the metropolitan area of Milan, Italy

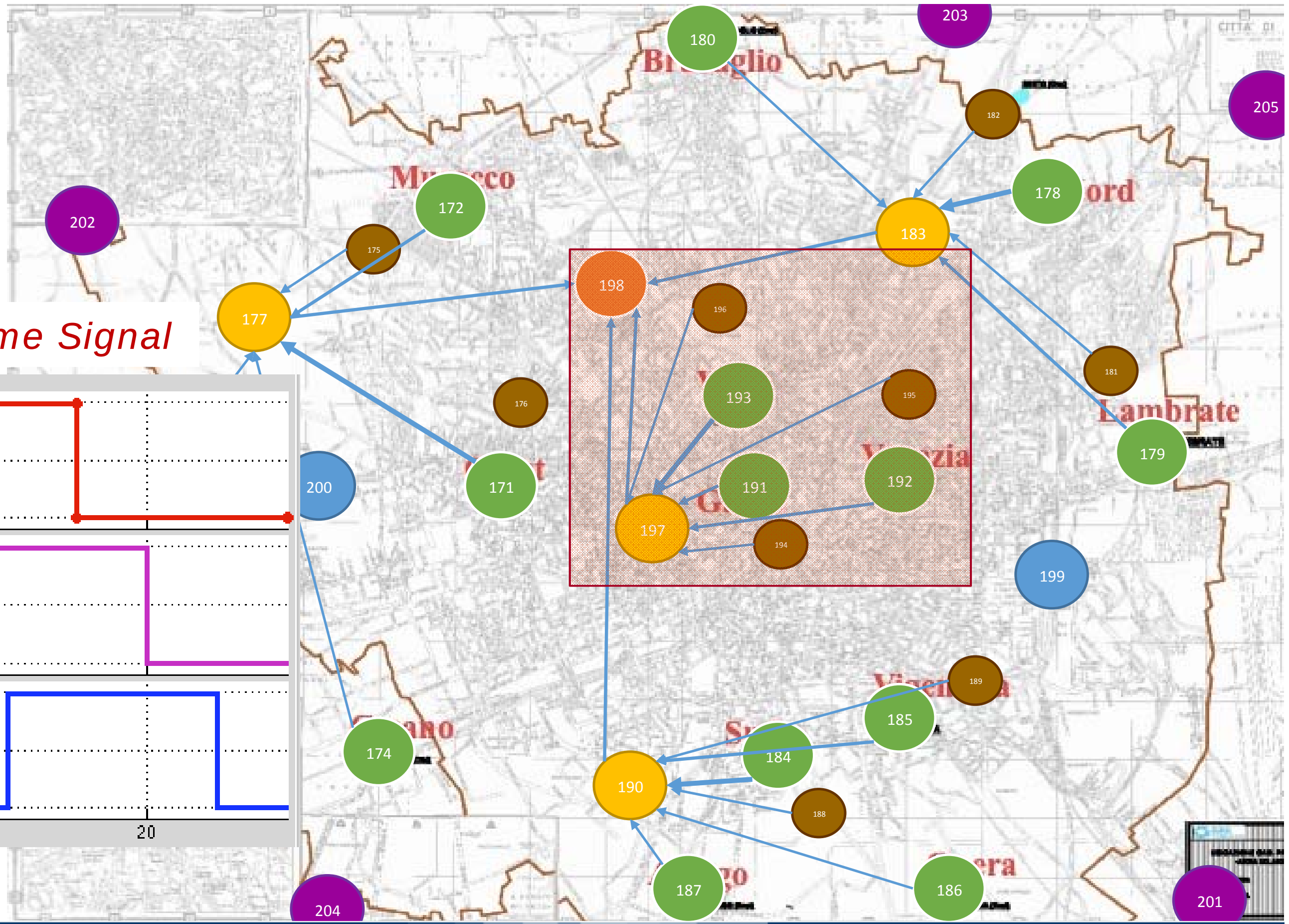
Extension to the Energy Network

- Includes **Electricity** and **Gas distribution** networks
- Modelled by a total of additional **38 vulnerable nodes**

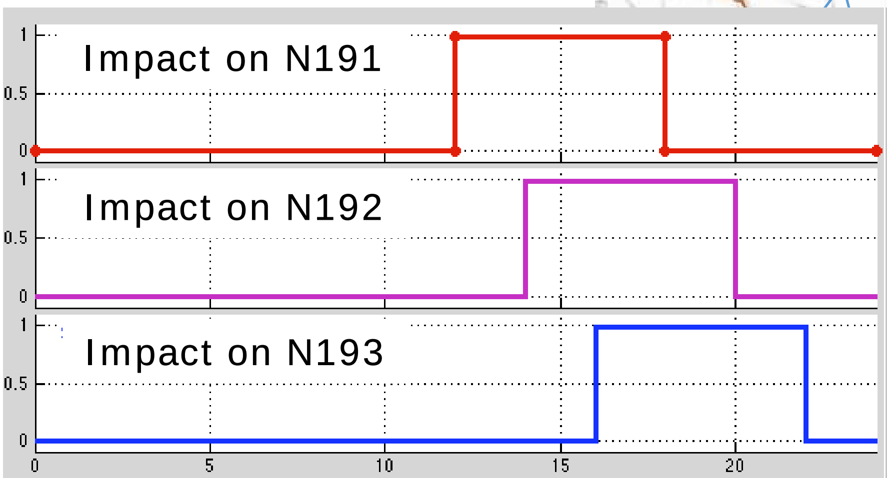


Pilot study in the metropolitan area of Milan, Italy
Scenario Settings for the test

- Cascading failure takes place on the **Electric Distribution Grid**
- Spare capacity is available through transformation cabins and grid connections

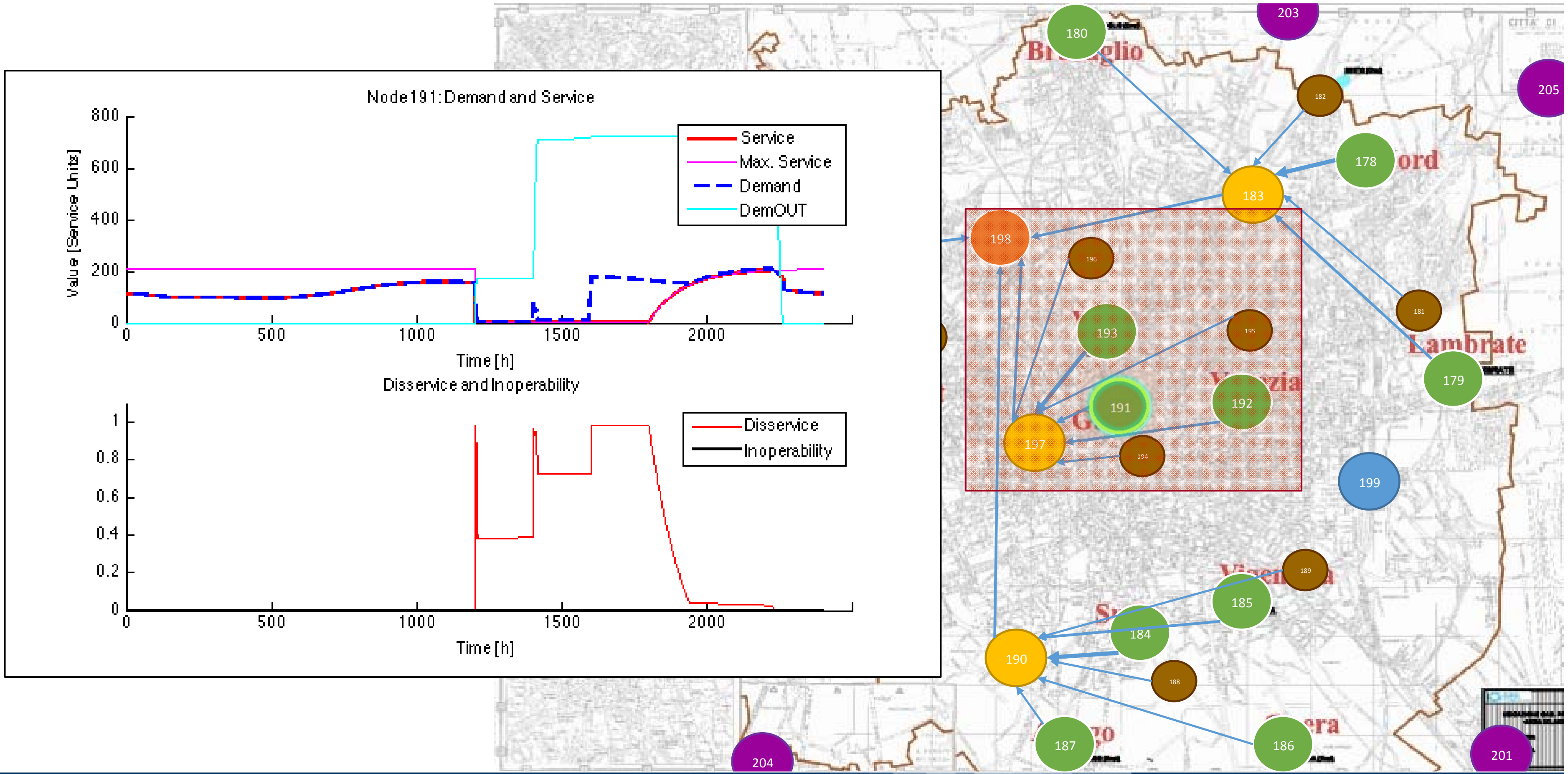


Multiple Step Threat Node's Time Signal



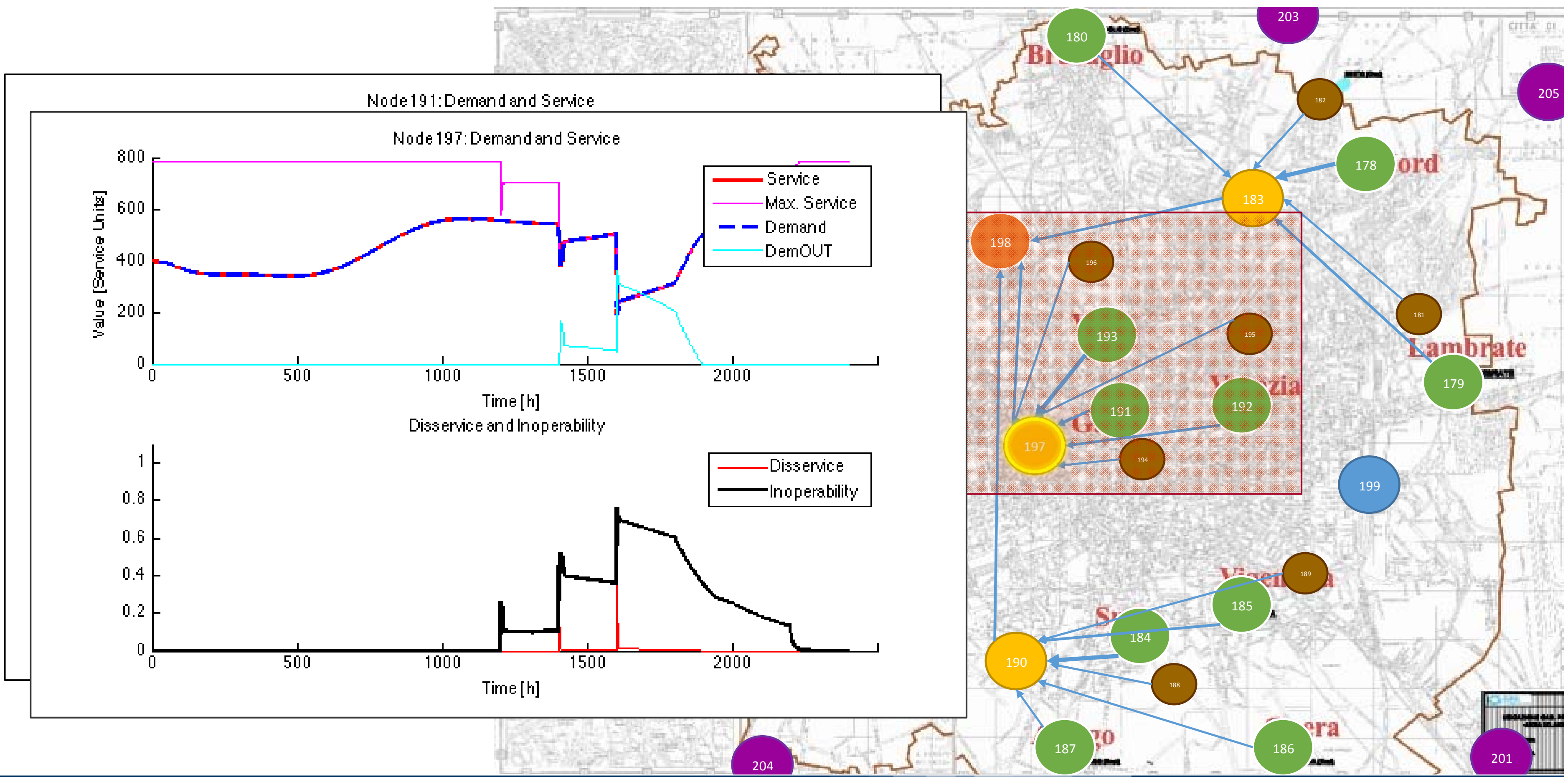
Pilot study in the metropolitan area of Milan, Italy
Analysis of results

- Actual Operator’s response strategy modelled trough a set of logical interdependencies among electricity nodes
- Dynamic analysis of **system resilience**



Pilot study in the metropolitan area of Milan, Italy
Analysis of results

- Identification of **cascading effects**
- Dynamic analysis of **Electricity system resilience** modelled trough logical interdependencies



Extension of DMCI to heterogeneous CI systems
Conclusions

- Test findings:
  - Logical int. modelling in DMCI can be used to simulate system balancing capabilities also for the Electricity Grid
  - Experts were satisfied with the approximation of Electricity system behaviour in the context of “system-of-system” analysis
  - Parameter setting is not simple

- On going developments:
  - New Impact and Resilience measures
  - GIS integration, for data input (CI shape files) and reporting

  - Simulation of full blackout scenarios in the pilot area
  - Extension of DMCI implementation to Telecom infrastructure

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Thank You!

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DMCI modelling approach
Vulnerable Nodes

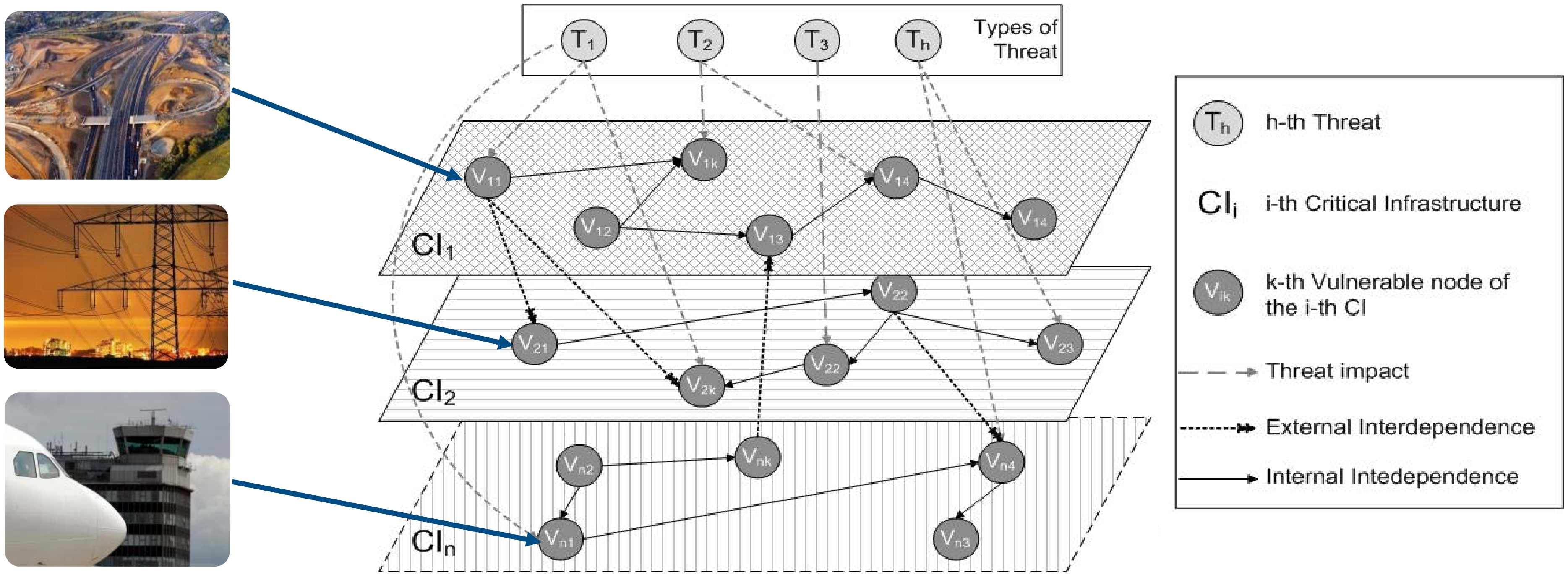
- Homogeneous: uniform in structure and function with respect to service demand.
- Service self-providing: a system able to supply a value added service through its own means.
- Vulnerable: exposed to disruptive events (Threats) that may affect its functional integrity.

Node Parameters:
- Node ID (k)
- Name
- Critical Infrastructure
- Maximum capacity $C_{max}(k)$
- Nominal demand $D_{std}(k,t)$
- Functional integrity dynamic parameters $T_{buffer}(k)$, $T_{prop}(k)$,...

Node State Variables:
- Functional Integrity, F(k,t)
- Inoperability, I(k,t)
- Delivered Service, S(k,t)
- Actual Demand, $D_{act}(k,t)$
- Service Disruption, diss(k,t)
- Service Disruption time, $T_{diss}(k,t)$

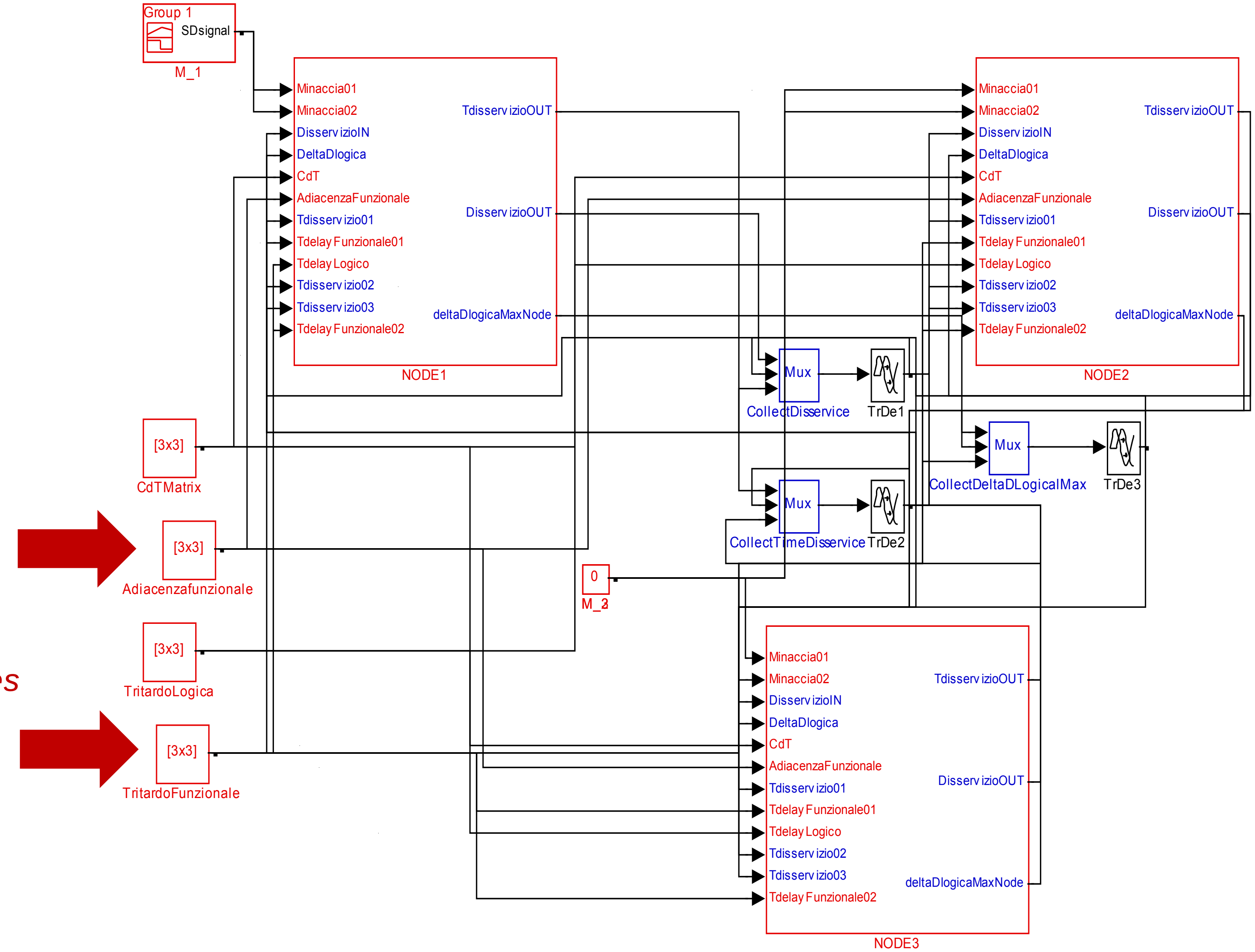
DMCI modelling approach
Modelling of vulnerability and interdependency

- Disruptive events are modelled by **threat nodes,** characterised by time-variant intensity and have specific impact potential on different vulnerable nodes.
- Implementation of both **functional** and **logical** interdependencies thanks to the use of service demand and service capacity parameters.
- Propagation of **inoperability** and **demand variations** throughout CI and between CIs via internal and external interdependencies modelling.



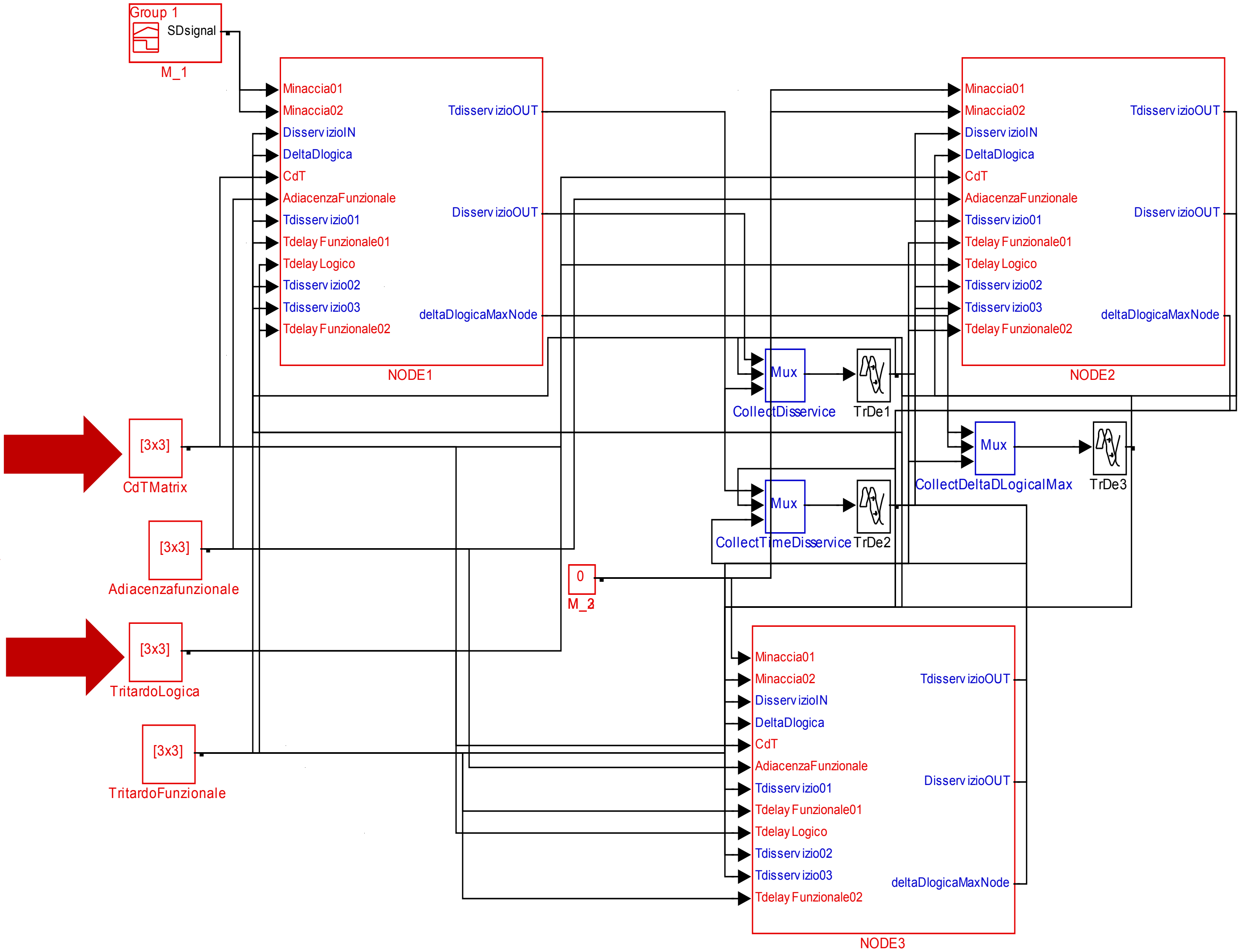
DMCI Modularization
Simulink® implementation

Cyber and Functional Interdependencies



DMCI Modularization
Simulink® implementation

Logical Interdependencies



DMCI Modularization
Simulink® implementation

Single or multiple Threats