FFI Norwegian Defence Research Establishment

Modelling Total Defence Systems to Inform National Resilience Objectives – A Norwegian Case Study

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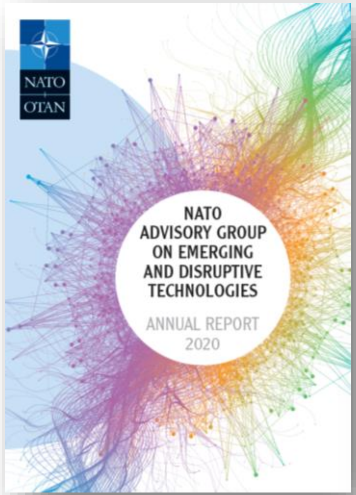
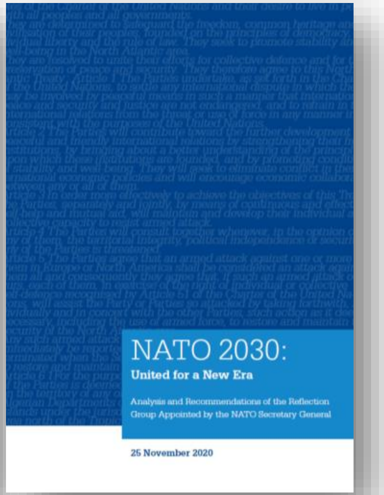
Security situation looking out towards 2040

- The Russian invasion of Ukraine and the 2020-2022 Covid-19 pandemic have affected all sectors in our society
- The war in Ukraine has created lasting changes in Europe's security environment
- The security situation is exacerbated by:
  - revisionist authoritarian states seeking to disrupt the current rule-based international order;
  - non-state actors who seek to inflict terror or gain profits through criminal acts;
  - substantial and accelerated technological change affects all policy areas and sectors;
  - the broad use of all instruments of power that is changing our understanding of security
  - the impacts of climate change





The need for strengthening national resilience

Allies will develop a proposal to establish, assess, review and monitor resilience objectives to guide nationally-developed resilience goals and implementation plans

Defence of Norway and the Total Defence Concept

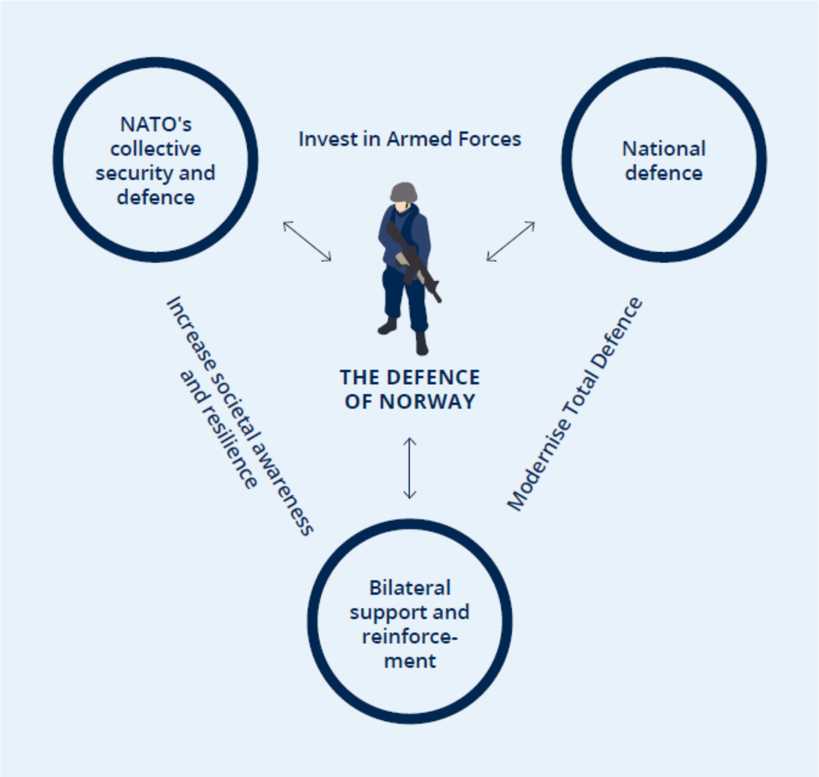


Photo: Norwegian Ministry of Defence

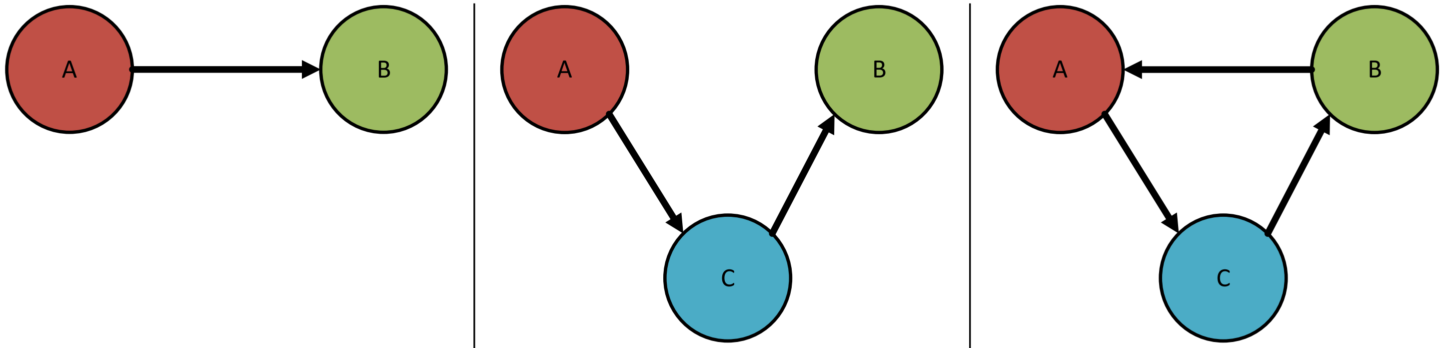
- Three lines of effort:
  - National defence
  - NATO’s collective security and defence
  - Bilateral support and reinforcements

- The three lines of efforts are underpinned by the Total Defence concept
  - Comprehensive whole-of-society approach
  - Resilient critical infrastructures and resilient societies are a vital part of the total defence

Analytical methods

Proposed methodology:

- Framework for describing total defence systems that is grounded in theory for complex systems
- Model for describing potential cascading consequences that follow disruptive events
- Method for mapping and quantifying interdependencies between the functions that constitute the total defence system



first order dependency | second order dependency | interdependency

Framework for infrastructure planning and resilience policies

Objective:

- Propose a framework that aid governments with the development of more coherent and effective national resilience policies

The framework:

- System-of-systems approach that is grounded in theory for complex sociotechnical systems
- Based on work domain analysis
- Consists of an abstraction hierarchy and a part-whole decomposition
- The framework is formative
- Promotes design for adaptation where actors within the system are allowed to adapt their behavior as they find appropriate without violating the system's constraints

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Abstraction-decomposition space for critical infrastructure systems: A framework for infrastructure planning and resilience policies

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Abstract

The objective of this work has been to propose a framework that will aid governments with the development of more coherent and effective infrastructure planning and resilience policies through a system-of-systems approach that is grounded in theory for complex sociotechnical systems. The framework has been developed by using a work domain analysis (WDA). The WDA consists of an abstraction hierarchy analysis and a part-whole decomposition. Together, the abstraction hierarchy and the part-whole description form the abstraction-decomposition space (ADS) for which the system constraints apply. By imposing constraints, the WDA promotes design for adaptation where actors within the system are allowed to adapt their behaviour as they find appropriate without violating the system's constraints. The proposed ADS consists of five levels of abstraction and four levels of decomposition. By applying the ADS, it will aid decision making related to the overall purposes of the critical infrastructure system, the values and priority measures that are used to assess the system's progress towards the functional purposes, as well as formulation of infrastructure needs that are necessary to achieve the functional purposes. The framework is formative in the sense that it reveals how work can be done in the critical infrastructure system. This is important because it is not feasible to prescribe, describe and risk assess all possibilities for action that are available in complex sociotechnical systems, especially when dealing with unforeseen events. Future research should focus on finding science-based yet useful in practice ways for establishing values and priority measures that encompass sustainability issues and resilience standards.

Keywords:
resilience, adaptation, critical infrastructures, national security, work domain analysis

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Abstraction hierarchy

1. **Functional purposes** – The overall purposes of the system

2. **Values and priority measures** – The values that are assessed and used to measure the system's progress towards the functional purposes

3. **Purpose-related functions** – The generalised functions of the system that are necessary to achieve the functional purposes

4. **Infrastructure-related processes** – The functional capabilities of the system's assets that enable the purpose-related functions

5. **Assets** – The system's assets that undertake the infrastructure-related processes

Decomposition level / Abstraction level	Whole system	Sectors	Sub-sectors	Types of entities
Functional purposes				
Values and priority measures				
Purpose-related functions				
Infrastructure-related processes				
Assets				

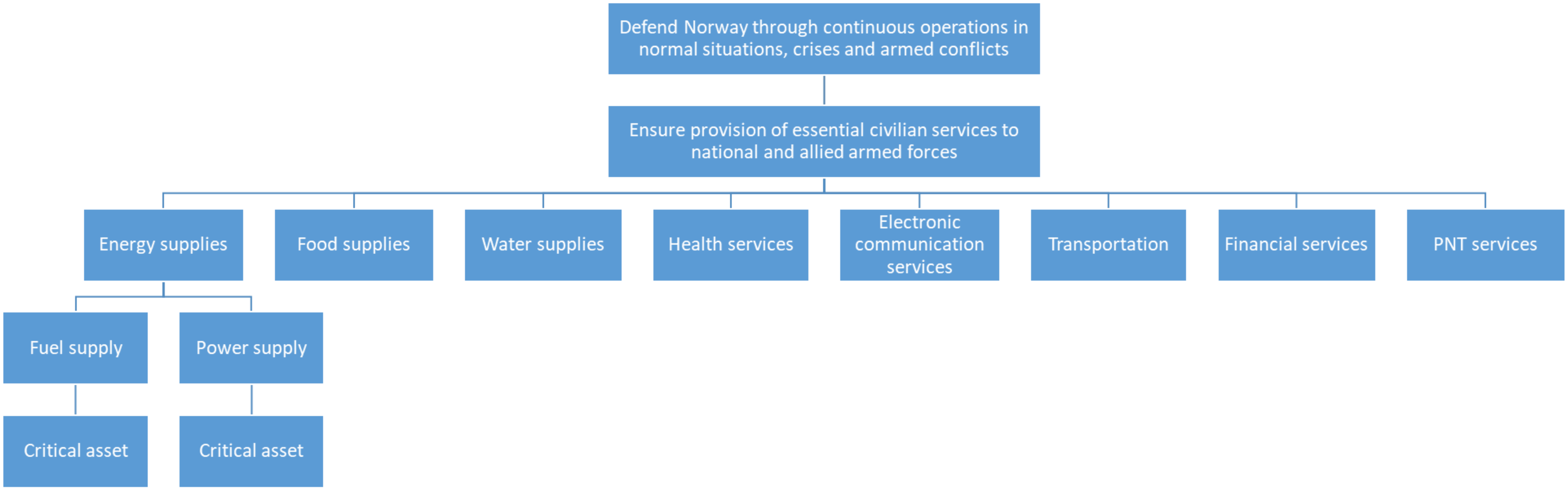
Values and priority measures

- Two types of criteria:
  - Levels of services
  - Resilience criteria
- Values and priority measures should be invariants or relatively stable properties of the work domain
- Provide guidance for reasoning from first principles when the system is confronted with stressful, unanticipated events.

Values and priority measures:

- System level:
  - Ensure provision of essential civilian services to national and allied armed forces
- Sector level:
  - Resilient energy supplies
  - Resilient food resources
  - Resilient water resources
  - Resilient ability to deal with mass casualties and disruptive health crises
  - Resilient civil communications systems
  - Resilient transportation
  - Resiliente financial services
  - Resilient PNT services

Abstraction hierarchy for the system of civil total defence functions



Comparison of methods for modelling cascading consequences

	Agent-based	Network topology	Network flow	Input-output
Functional entities	Agents	Graphs	Flow networks	Linear systems
Model inputs	Agents, environment, interactions	Nodes, links	Node, links, capacity, demands	Interdependency matrix, perturbation
Model outputs	Emergent phenomena of distributed decision making	Characteristic path length, clustering	Flow distribution on capacitated networks	Total effect of linear interdependencies
Aspects considered	Decision rules, agent interactions	Network connectivity	Demand and supply	Ripple effects
Computational cost	Large	Small, moderate	Large	Small, moderate
Accessibility of input data	Difficult	Medium	Difficult	Easy

Dynamic inoperability input-output model (DIIM)

Discrete form where *k* is the time step parameter:

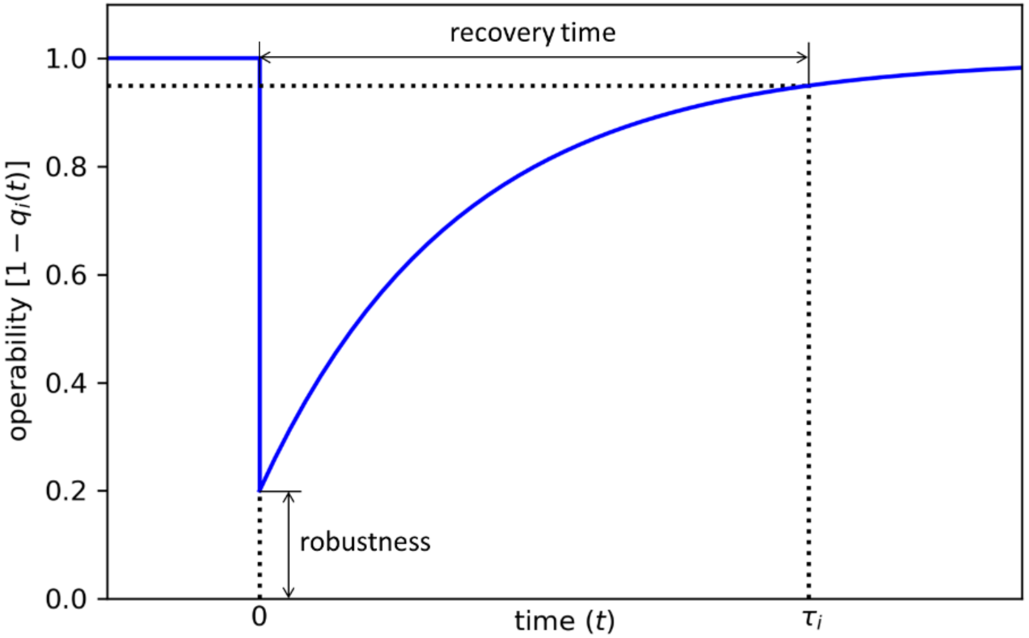
$$\boldsymbol{q}(k+1) - \boldsymbol{q}(k) = \boldsymbol{K}[\boldsymbol{A}^{*}\boldsymbol{q}(k) + \boldsymbol{c}^{*}(k) - \boldsymbol{q}(k)]$$

Infrastructure resilience coefficient matrix:

$$\boldsymbol{K} = \mathrm{diag}(k_i); k_i \in [0,1)^n$$

Dynamic recovery ($\boldsymbol{q}(0) > 0$, $\boldsymbol{c}^{*} = 0$):

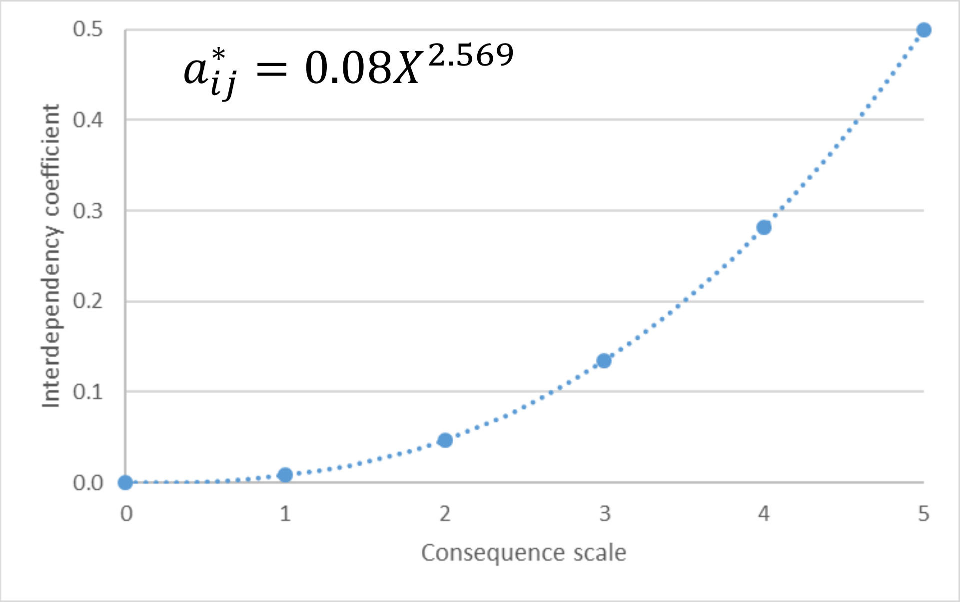
$$\boldsymbol{q}(t) = e^{-\boldsymbol{K}(\boldsymbol{I}-\boldsymbol{A}^{*})t}\boldsymbol{q}(0)$$



Resilience in this work is interpreted as the ability of the system to sustain or restore its basic functionality following a risk source or a disruptive event

Estimation of interdependency matrix (A*) from expert assessments

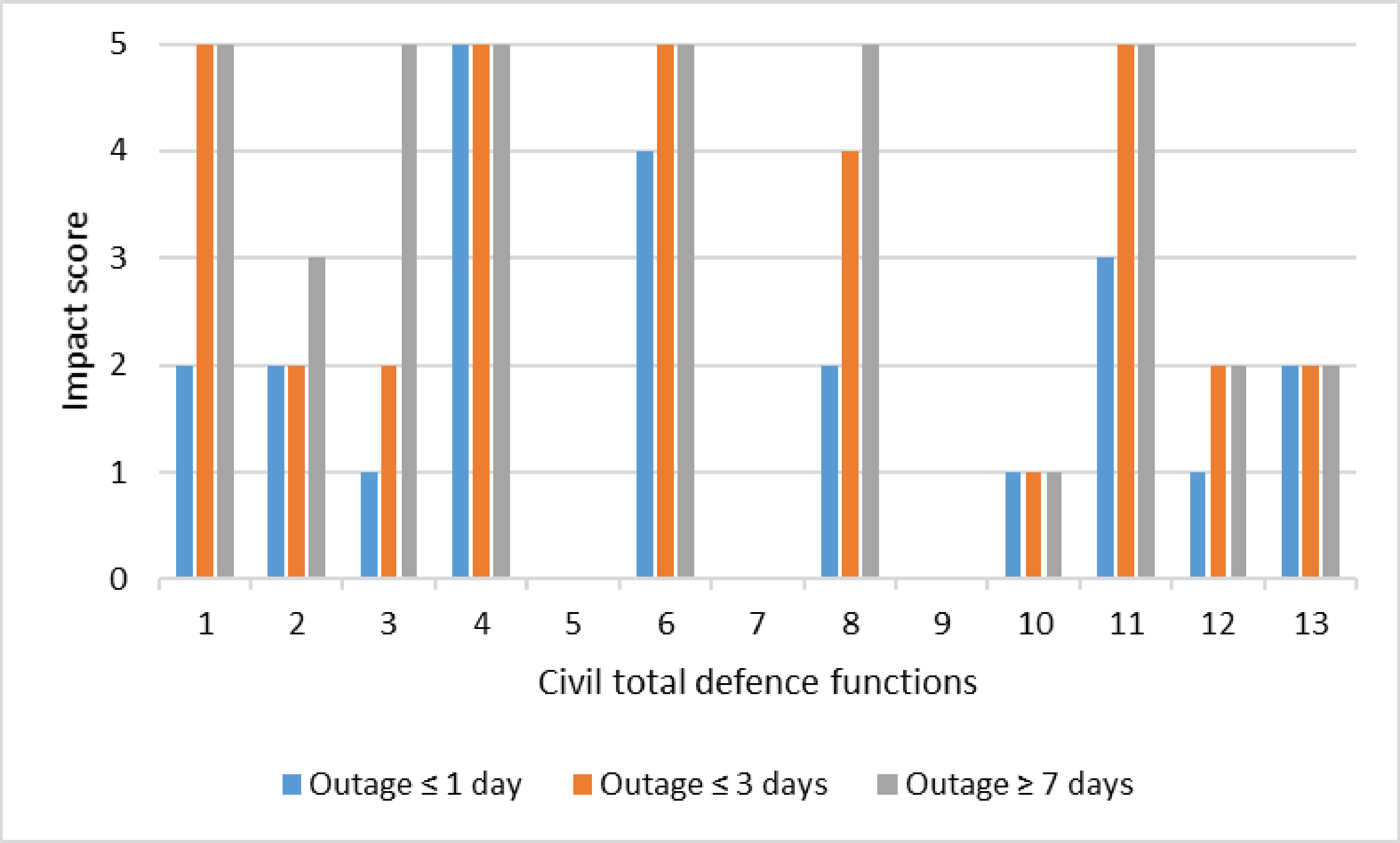
Scale	Impact
0	None
1	Insignificant (very limited degradation)
2	Minor (some degradation)
3	Moderate (significant degradation)
4	Major (only some services provided)
5	Severe (unable to provide services)

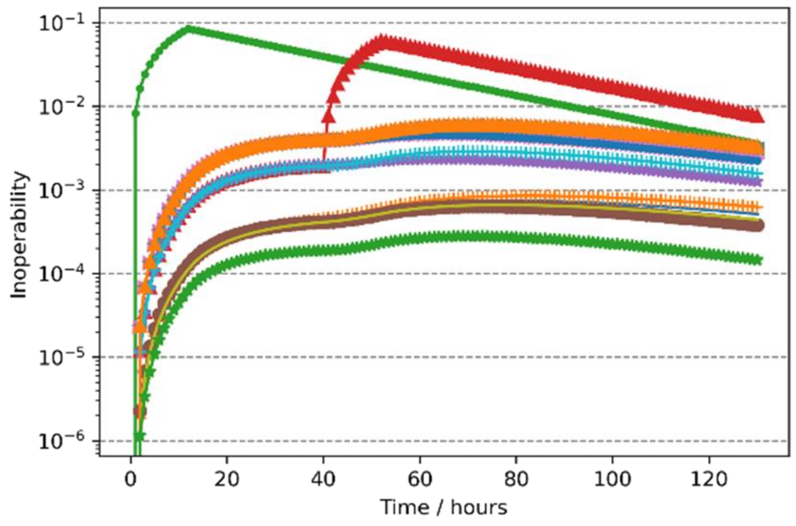


- "On a scale from 0–5, how would you rate the direct impact on TDF_i occurring as a result of lack of services provided by TDF_j for the geographical region under study?"
- The experts were asked to consider the following service outage scenarios: (*i*) $\leq$ 1 day; (*ii*) 1–3 days; (*iii*) $\geq$ 7 days

Fitted to data from Setola, R., De Porcellinis, S., & Sforna, M. (2009). Critical infrastructure dependency assessment using the input-output inoperability model. *International Journal of Critical Infrastructure Protection*, *2*, 170-178.

Interdependency mapping for Norwegian case study





Fictitious modelling results

Impact assessment (resilience loss)

Resilience loss metric (Bruneau *et al.*, 2003):

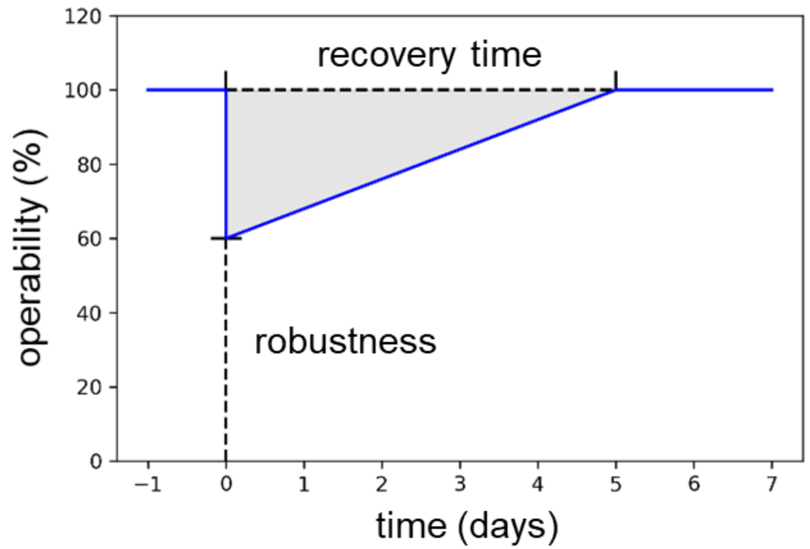
$$RL = \int_{0}^{t_{\mathrm{R}}} (1 - P(t))\mathrm{d}t$$

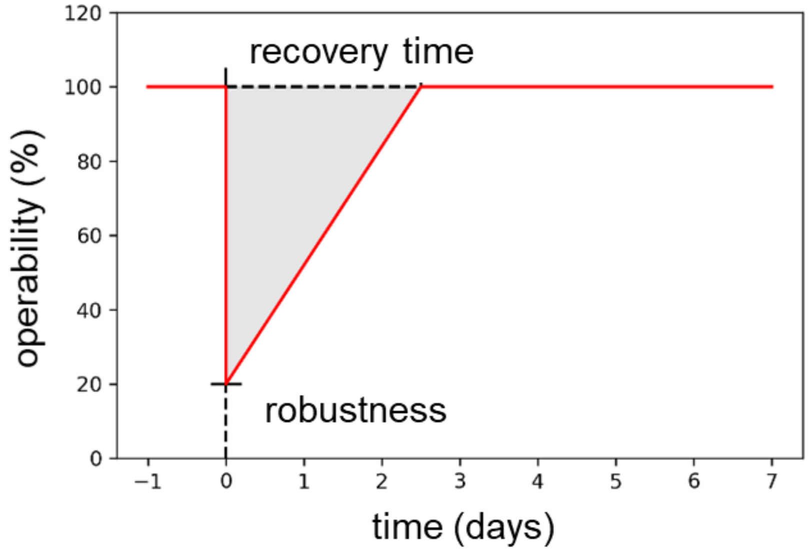
Impact for each total defence function (TDF):

$$Q_i = \int_{0}^{t_{\mathrm{R}}} q_i(t)\mathrm{d}t$$

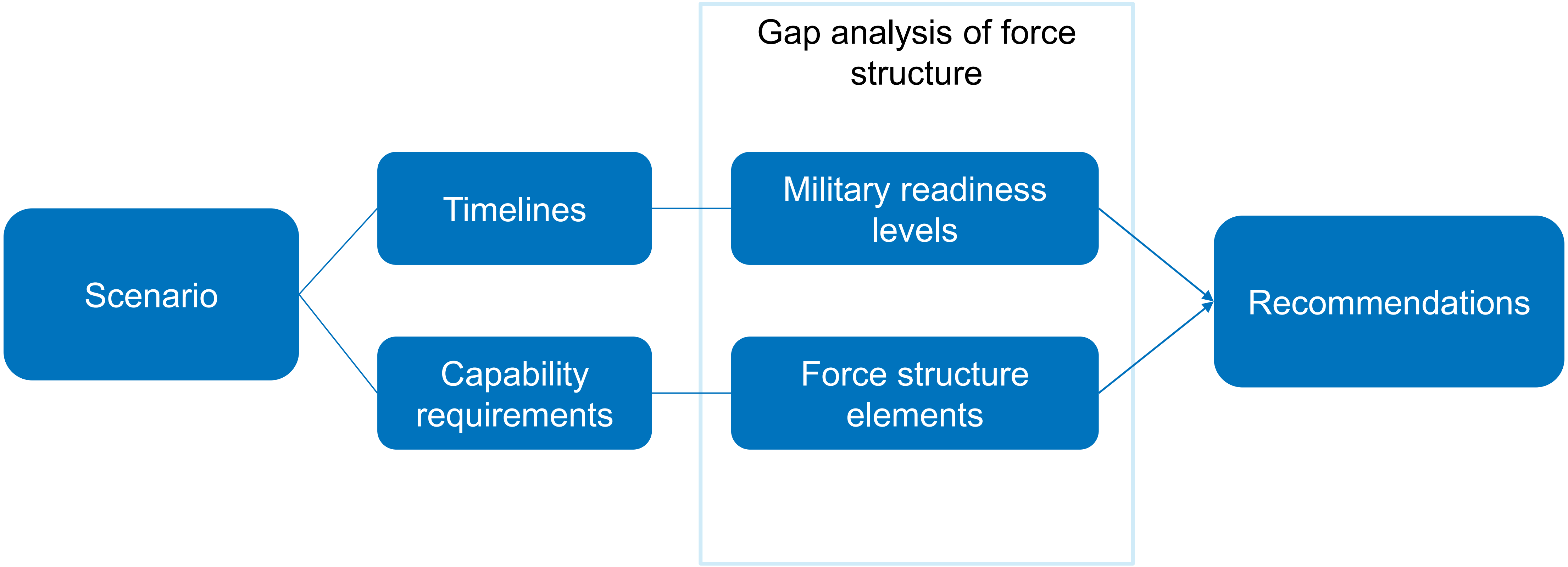
Impact for the whole system of TDFs:

$$Q_{\mathrm{tot}} = \sum_{i} Q_i$$





Linkage to scenario and capability analyses of defences forces



Conclusions

Findings:

- Proposed a practical-in-use system-scale and cross-sector functional approach for modelling total defence systems that is grounded in theory for complex systems
- The total defence system is described by using an abstraction-decomposition space for critical infrastructure systems, taking into account NATO's seven baseline requirements
- By mapping the interdependencies between the system's functions, cascading effects following disruptive events can be investigated by using DIIM
- The modelling results can be used to aid resilience assessments of the total defence system for current and future defence scenarios

Limitations:

- The system is modelled at a high level of abstraction (each TDF is treated as a single entity)
- The use of DIIM for modelling cascading effects (interdependencies are treated as constant in time)
- Need to take into account that the interdependencies likely will change for armed conflict scenarios compared to the peacetime situation

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