FORESEE: Future proofing strategies FOr RESilient transport networks against Extreme Events

H2020-MG-7-1-2017: Resilience to extreme (natural and man-made events)

An algorithm to determine optimal risk reducing intervention programs on networks

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Head of the Infrastructure Management Group, ETHZ

https://www.bernerzeitung.ch/jahrhunderthochwasser-2005-und-heute-der-vergleich-in-bildern-362263069287

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Results

1. Burkhalter, M., Moghtadernejad, S., Hackl, J., Toribio-Dia, C., Antonio Moli Diaz, A, Martani, C., Adey, B.T., Jimenez Redondo, N., Pardi, L., Di Gennaro, F., Robles Urquijo, I., Beltran-Hernando, I., (2020), Final versions of the algorithms to determine optimal restoration and risk reduction intervention programs for transportation networks, Deliverable 4.7, EU Grant number 769373, pages 171, DOI: https://doi.org/10.3929/ethz-b-000503443.

2. Burkhalter, M., Adey, B.T., (accepted in 2022), Digitalising the determination of railway infrastructure intervention programs: A network optimisation model, Infrastructure Systems.
3. Burkhalter, M., Adey, B.T., (published on-line 2021), Required accuracy of information when determining optimal railway intervention programs, Infrastructure Asset Management, DOI: https://doi.org/10.1680/jinam.20.00032
4. Burkhalter, M., Adey, B.T., (2021), Quantifying net-benefits of intervention programs to enable their digitalized generation, Infrastructure Asset Management, 8(3), pp. 141–154, DOI: 10.1680/jinam.20.00020
5. Burkhalter, M., Adey, B.T., (2020), Modelling the complex relationship between interventions, interventions costs and the service provided when evaluating intervention programs on railway infrastructure networks, Infrastructures, 5(12) 113, 20 pages, DOI:10.3390/infrastructures5120113.

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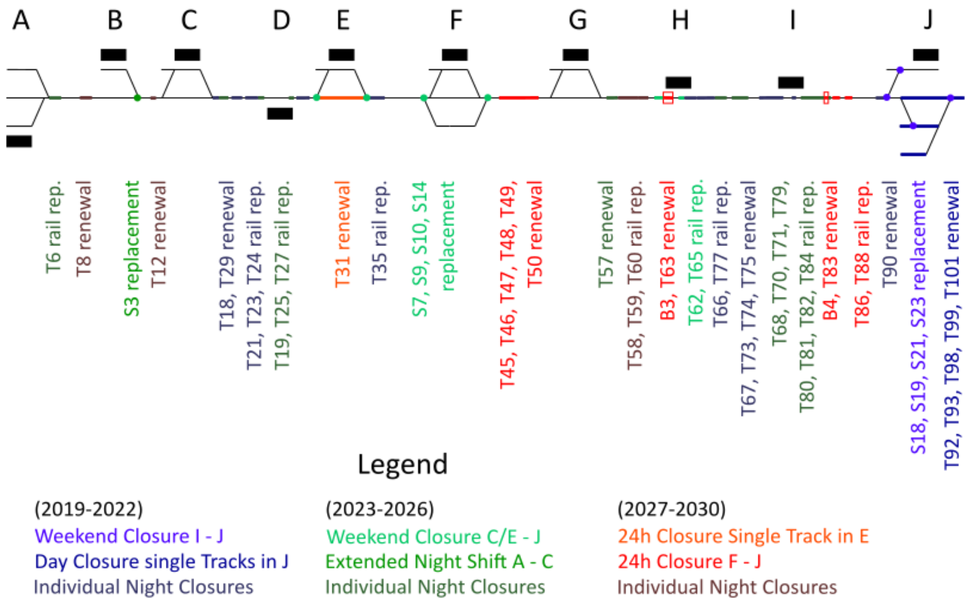
What does the algorithm do?

- Plans risk reducing interventions on networks taking into consideration
  - The interventions required per asset according to their optimal individual life-cycles
  - The possible savings from grouping interventions
  - The restrictions on the possibility of executing multiple interventions at the same time
  - The traffic configurations that would need to be in place during a project with one or more interventions, and
  - The consequences of moving interventions away from their optimal time of execution, in terms of additional life cycle costs or increased risk.



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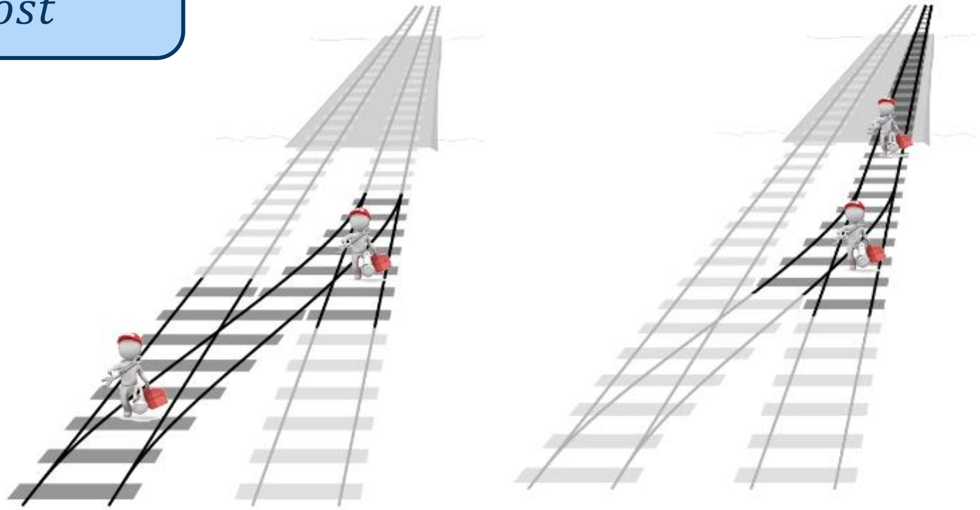
What does the algorithm do?

Optimal intervention program:

$$Max\ Net\ Benefit = Benefit - Cost$$

- Benefit:
  - Reduction in future expected impacts
- Cost:
  - Impacts during the execution of the interventions



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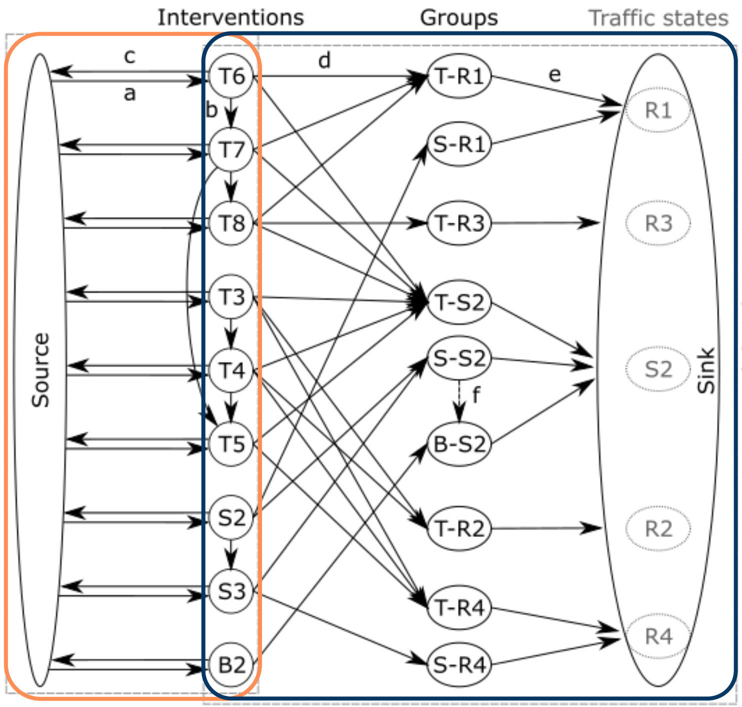
What does the algorithm do?

- **Mixed integer linear program**

$$Max\ Z = \underbrace{\sum_{u \in V} \sum_{v \in V} \delta_{u,v} \cdot NB_{u,v}}_{\text{Asset level}} + \underbrace{\sum_{u \in V} \sum_{v \in V} \gamma_{u,v} \cdot NB_{u,v}}_{\text{Network level}}$$



- Subject to:
  - Flow constraints
  - Capacity constraints
  - Budget constraint
  - Structural constraints

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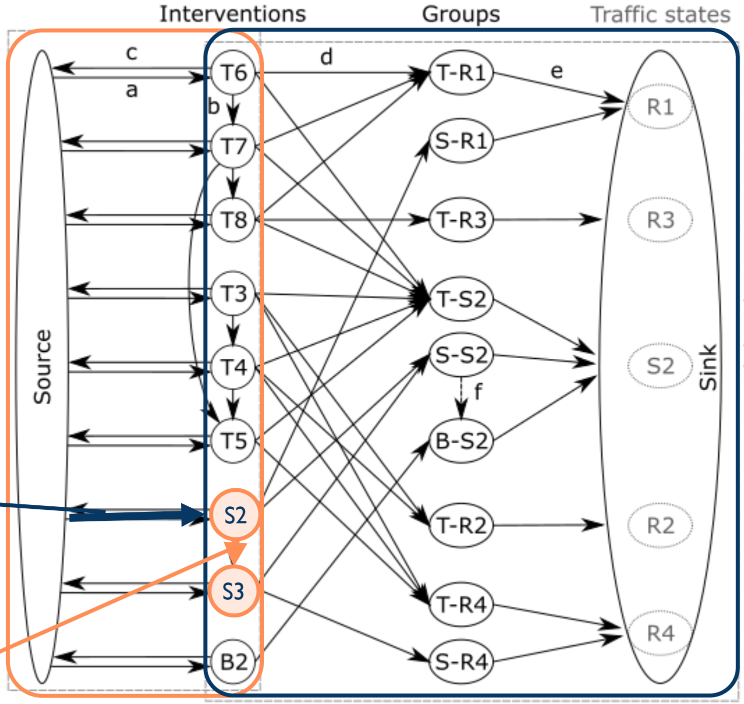
Asset level Network level

- Asset Level (Intervention Selection, Asset level costs)
- Nodes: Specific interventions on specific assets
- Edges: Selection of the intervention

Cost = fix + variable intervention costs

Cost = variable costs



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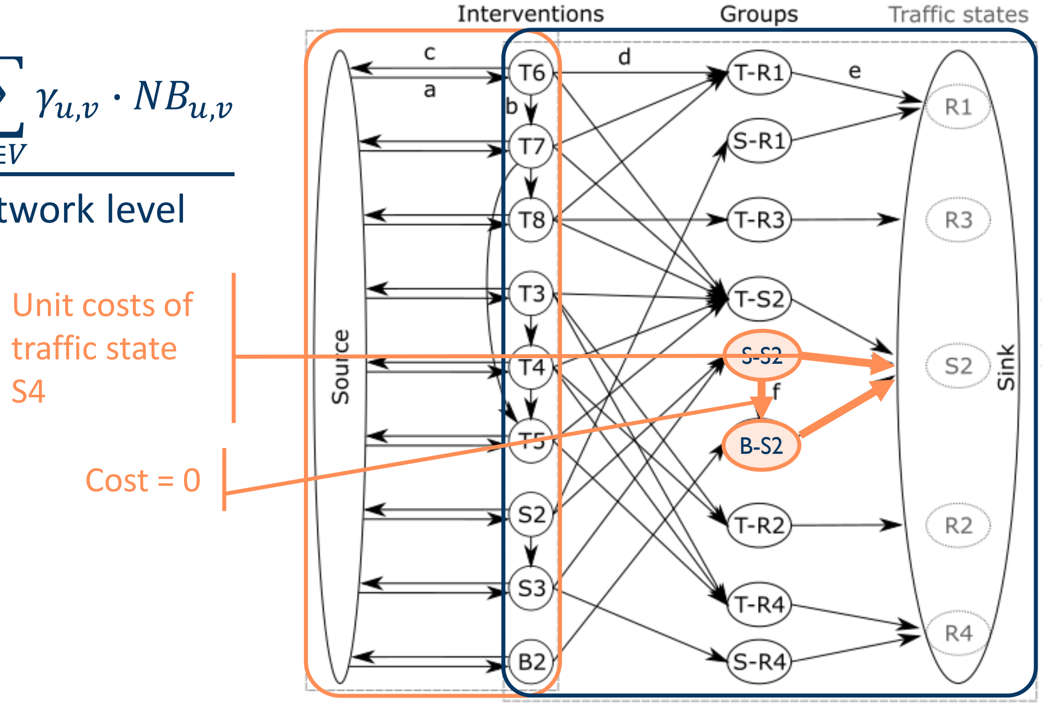
- Network Level (Traffic configuration, Duration of disturbance, Network level costs)
- Nodes: Specific groups of interventions
- Edges; Required duration of the traffic states, Real valued flow



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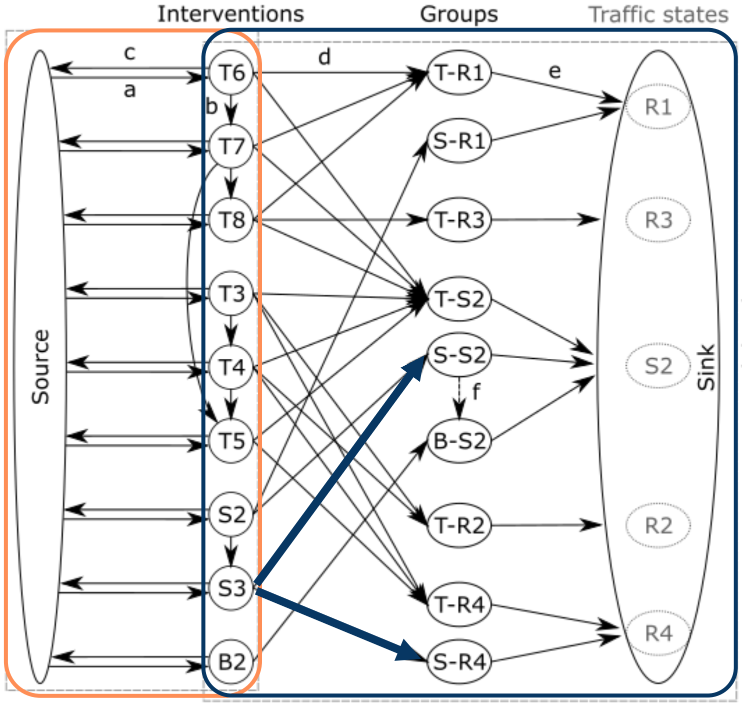
- Level interaction
  → Duration of selected interventions

$$\sum_{v} \delta_{v,u} \cdot d_u = \sum_{v} \gamma_{u,v}$$



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Input data

- Infrastructure assets, possible risk reducing interventions, variable unit costs and percentages of fixed costs per intervention,
- The type of intervals possible, the costs per traffic configuration, the number and type of vehicles using the lines
- The condition of the assets
- The risk associated with each asset in each condition state
- The optimal asset level intervention strategies
- The possible type of restoration interventions, variable unit costs and percentages of fixed costs per intervention, amount of down time expected
- The consequences of failure for each type of asset, including approximate material damage, approximate number of injuries and fatalities

https://www.railfreight.com/railfreight/2021/07/20/belgium-germany-estimated-costs-for-flood-damage-repairs-reach-billions/?gdpr=accept

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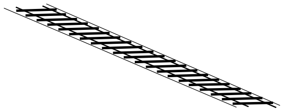
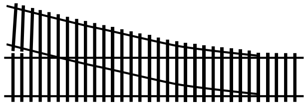
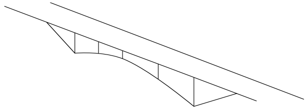
Demonstration



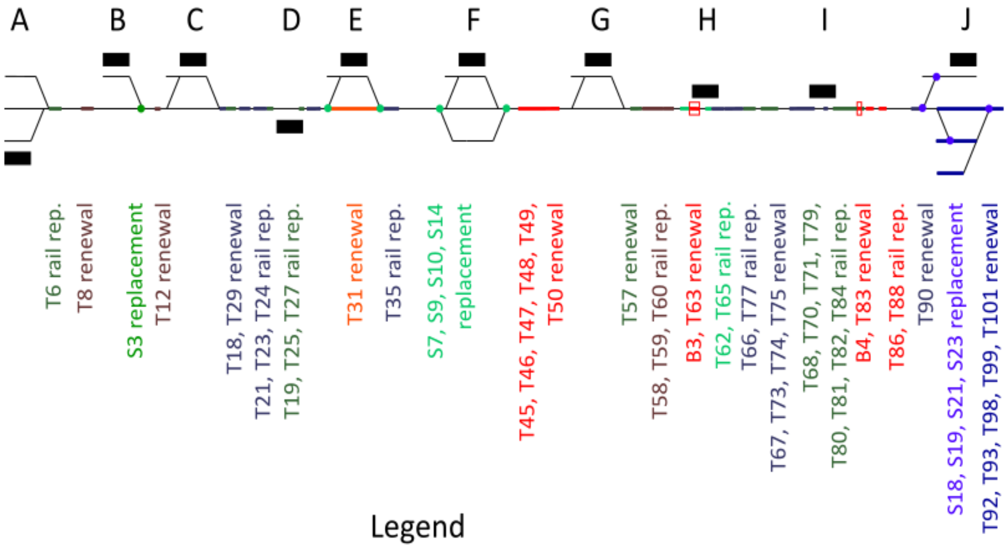


20km of track (101 segments)	23 Switches
Track renewal Rail replacement	Switch replacement



4 Bridges
Bridge renewal

Intervention program
- 12-year planning period (2019-2030)
- 3 times 4-year periods



Legend

(2019-2022)	(2023-2026)	(2027-2030)
Weekend Closure I - J	Weekend Closure C/E - J	24h Closure Single Track in E
Day Closure single Tracks in J	Extended Night Shift A - C	24h Closure F - J
Individual Night Closures	Individual Night Closures	Individual Night Closures

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Conclusion

- The algorithm can be used to plan risk reducing interventions on networks in a digital environment, taking into consideration all of the issues confronting infrastructure asset managers, including
  - The interventions required per asset according to their optimal individual life-cycles
  - The potential savings of grouping interventions together
  - Restrictions on the possibility of executing multiple interventions at the same time due to potentially large effects on the provided service, e.g. train movements
  - The traffic configurations that would need to be in place during a project with multiple interventions, and
  - The consequences of moving interventions away from their optimal time of execution, in terms of additional life cycle costs or increased risk.

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Future proofing strategies FOr RESilient transport networks against Extreme Events

H2020-MG-7-1-2017: Resilience to extreme (natural and man-made events)

An algorithm to determine optimal restoration programs for transportation networks

Dr. Saviz Moghtadernejad, ETH Zurich

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What does the algorithm do?

- The objective function to be minimized is the costs:
  1. Direct costs of executing the physical interventions
  2. Indirect costs due to the inadequate service by the network.

$$Min\ Z^R = \sum_{t\in T}\left[\sum_{n\in N^s}\sum_{i\in I(n|s)} \delta_{n,i,t}\,.\,C_{n,i} + \gamma \sum_{p\in P_{od}^{s\setminus g},e\in P} \Pi(t|x_{e,t}) - \Pi^0(t|x_{e,0}) + \sum_{p\in P_{od}^{g}} \Lambda(t)\right]$$

Direct costs — Indirect costs

- This is a bi-level optimization where the indirect costs depend on the link traffic flow:

$$x_{e,t} \in \min Z^T = \sum_{e\in\varepsilon^s}\int_0^{x_{e,t}} C_e^T(\omega)d_\omega$$

Subject to:

- Budget constraint
- Resource constraints
- Traffic flow constraints
- The number and type of interventions in a time period

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Input data

- Infrastructure assets, and the GIS map of the network
- Origin-Destination matrix of the network
- The condition of the assets, and their related capacity losses after the hazard
- The possible type of restorative interventions, variable unit costs and fixed costs per intervention, amount of down time expected
- The indirect costs per traffic configuration, the number and type of vehicles using the lines (mean fuel consumption, operation costs, etc.)
- Available budget and work crews

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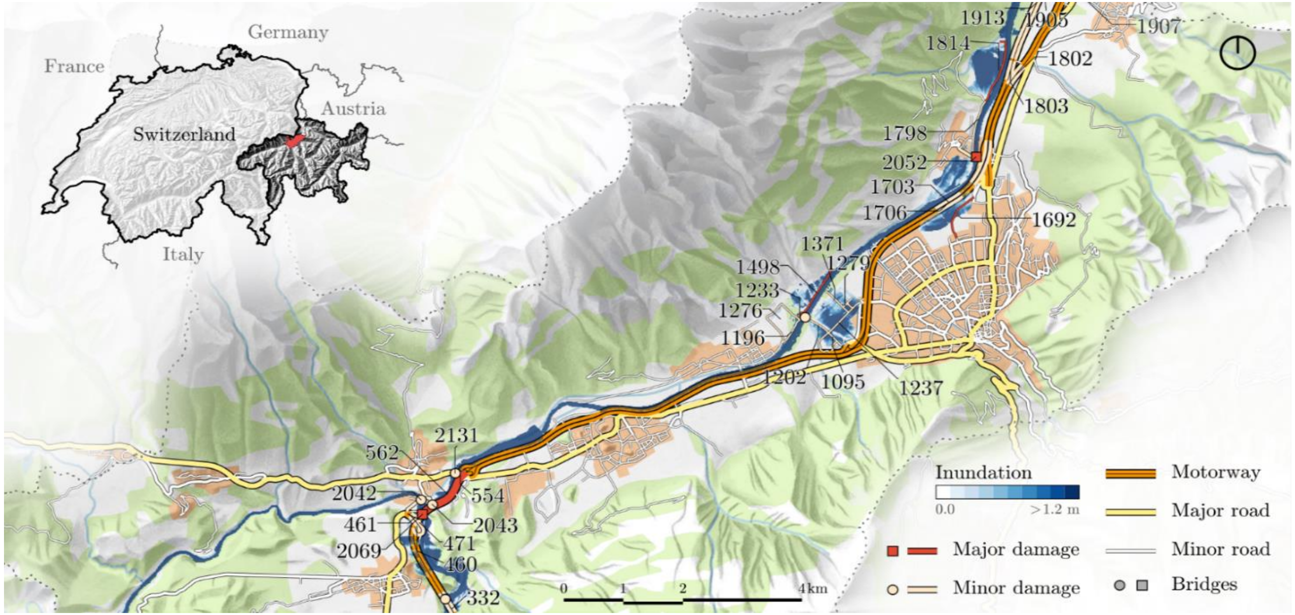
Demonstration



Description	Capacity Loss - (%)		Number of damaged segments	
	Road	Bridge	Road	Bridge
No damage	0	0	1,987	111
Minor damage	70	50	20	3
Major damage	100	100	4	2

	State	Priority	Recovery (%)
Road	Minor	High	100
		Normal	100
		Low	30
	Major	High	100
		Normal	100
		Low	10
Bridge	Minor	High	100
		Normal	100
		Low	20
	Major	High	100
		Normal	100
		Low	10

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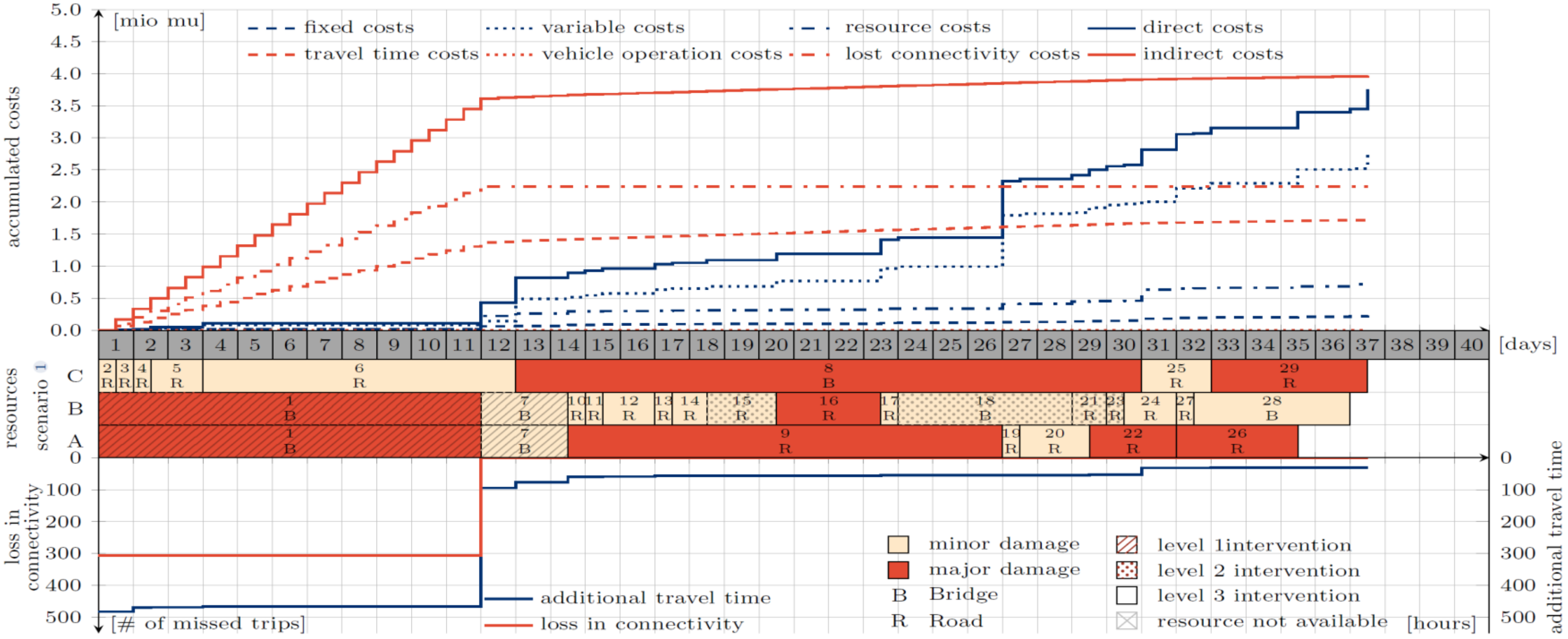

Costs		
Direct	Indirect	Total
$3.75 \times 10^6\,mu$	$3.95 \times 10^6\,mu$	$7.7 \times 10^6\,mu$

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Conclusion

- This algorithm has the flexibility to be used in real-world situations and for a variety of infrastructure types.
- It can provide estimations on the time required to restore the desired level of service following an extreme event.
- It can be used to identify objects whose failure will result in relatively large disruptions to service.
- It can identify when it is advantageous to execute less extensive interventions in the interest of speeding up the restoration of service.

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