Propagation of cyber incidents in an insurance portfolio

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Cyber Risk: Actuarial Modeling

Outline

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Cyber-risk

- Cyber-risk: inappropriate use of numerical tools and information systems.
- A cyber incident can be voluntary (cyber attack) or not (accidents may happen).
- For hacking, hackers use vulnerabilities in information systems, from outside or from inside.
- Various types of attacks (ransomware, phishing, classic frauds...)
- Strike states, companies, people.
- Huge costs : estimated to 1% of the global GDP.
- In France, numbers of ransomwares reported to ANSSI multiplied by 3 between 2019 and 2020.

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Wannacry

- Ransomware Wannacry : worldwide cyber attack in May 2017.
- Use the vulnerability "EternalBlue".
- Approximatively 200 000 infected computers across 150 countries over approximatively one week.
- Estimation of the cost : hundreds of million dollars, billions according to some estimations. ($100 millions for the NHS).

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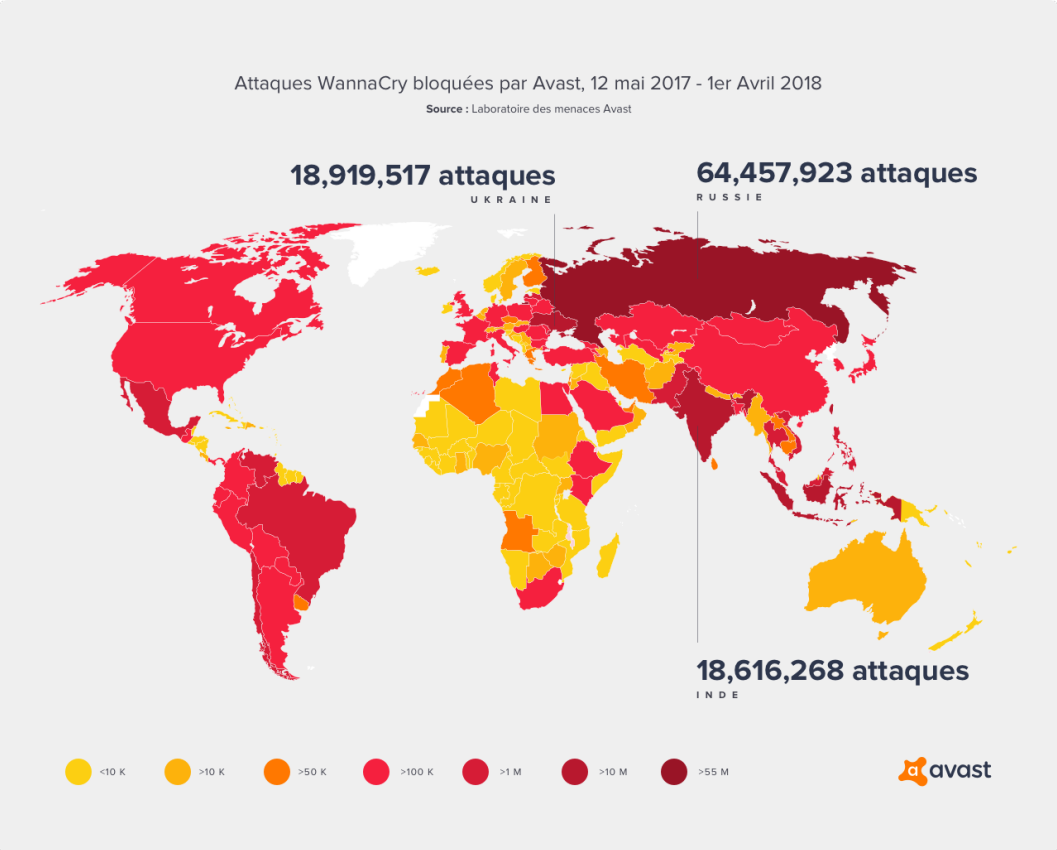
Wannacry in maps



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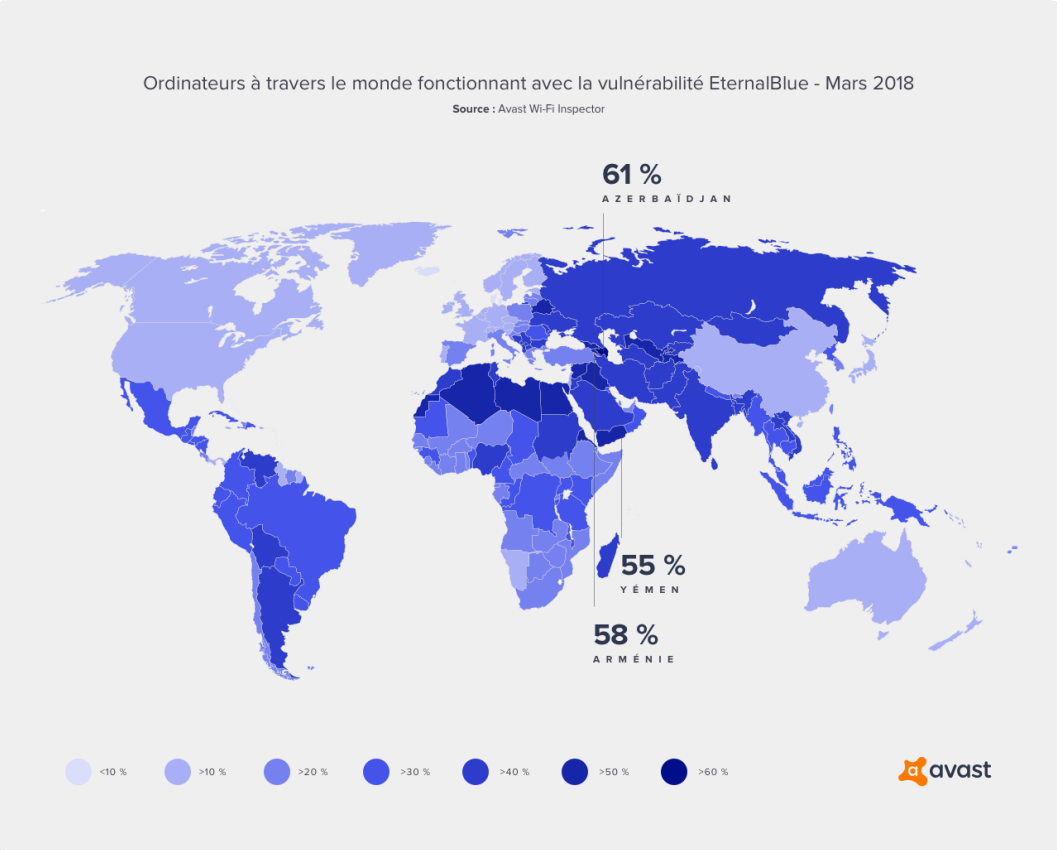
Wannacry in maps



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NotPetya

Le Point Tech & Net

Actualité > Tech & Net

Cyberattaque mondiale NotPetya: Londres et Washington accusent la Russie

AFP

Modifié le 15/02/2018 à 23:49 - Publié le 15/02/2018 à 13:07 | AFP

- June 2017. Uses the same vulnerability EternalBlue.
- Strikes mostly Ukraine, but also Saint Gobain ($384 millions losses), Auchan and SNCF.

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Cyber insurance products

- Typically, there are four dimensions:
  - financial reparation
  - immediate assistance to restart the activity
  - protection against regulation issues caused by leaks of data
  - crisis communication
- And a fifth dimension, essentially for SME: prevention and risk analysis.

Cyber-risk specificities

- Similarities with operational risk...
- ... but specificities in the structure of cyber events.

1. The risk is new and evolves fast.
2. "Silent cyber": non-cyber policies may content guarantees that can be triggered by cyber events if not excluded.
3. Accumulation risk : potential concentration of incidents which leads to loss of mutualization.
4. Specificity of the repair needed after a cyber event.

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Loss of mutualization : when there is no independence

- Example in insurance : natural catastrophes and portfolios with spatial correlations:

- Cyber risk: how to define proximity?

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The approach

- Objectives
  - To model and control the dynamics of the infected policyholders in an insurance portfolio
  - To quantify and calibrate the implementation of countermeasures.
- Model composed of three modules :
  - environment module : the global dynamic of the cyber event (that can be described through compartmental epidemiological models)
  - repair/assistance module : duration of the assistance required
  - prevention and response module : reactivity in detecting the incident and to implement countermeasures.
- Help for an insurance company to quantify
  - how much should be the response capacity in order to sufficiently reduce the impact of a given scenario
  - how much is won if one increases the capacity of response (to fix the price of a partnership with a cyber security firm).

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The general model

- $t = 0$: start of the cyber-epidemic

Micro modeling of the cyber-epidemic

For a policyholder, we define

- T = Time of infection (possibly equal to $+\infty$),
- U = Duration of the assistance required after infection,
- C = Time at which policyholder becomes immune.

- Policyholders are assumed independent (contagion comes from outside the portfolio).
- We assume T independent of C.

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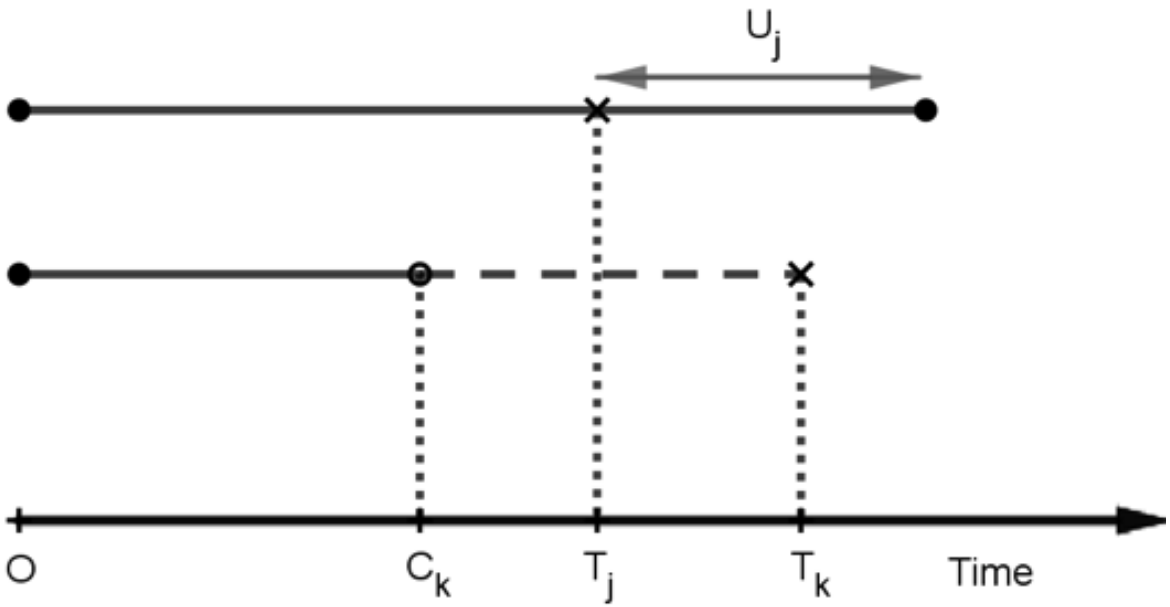
Chronology of the cyber events



Three variables to be modeled

- Module "environment" : T models the severity of the infection in the global population (epidemiological model).
- Module "repair" : U depends of the type of infection (ransomware, malware, data-corruption...). It is the duration of immediate assistance.
- Module "prevention and response" : C describes the ability to react to the crisis, the reactivity to identify the incident and to implement countermeasures.

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Impact on the portfolio

- Policyholders assumed to be i.i.d., characterized by $(T_i, U_i, C_i)_{1 \leq i \leq n}$.
- We define $\delta_i := 1_{T_i \leq C_i}$.
- Different counting processes

$$\begin{aligned}
\mathfrak{N}_t &= \sum_{i=1}^{n} \delta_i 1_{T_i \leq t} && : \text{cumulative number of infected} \\
\mathfrak{R}_t &= \sum_{i=1}^{n} \delta_i 1_{T_i + U_i \leq t} && : \text{number of recovered} \\
\mathfrak{I}_t &= \mathfrak{N}_t - \mathfrak{R}_t && : \text{number of currently infected}
\end{aligned}$$

- Different quantities of interest :

$$\sup_{t \geq 0} \mathfrak{I}_t, \text{ or } \int_0^\infty \mathfrak{I}_t dt = \sum_{i=1}^{n} \delta_i U_i.$$

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Hazard rate function

- Hazard rate function is a natural quantity to model duration variables.
- Definition :

$$\lambda_T(t) = \lim_{dt \to 0^+} \frac{1}{dt} \mathbb{P}(T \in [t, t+dt] | T \geq t).$$

- Link with the density function f_T and the survival function $S_T = \mathbb{P}(T \geq t)$:

$$\lambda_T(t) = \frac{f_T(t)}{S_T(t)}.$$

- For the variable T, λ_T is "calibrated" using a SIR model (but other models are possible).

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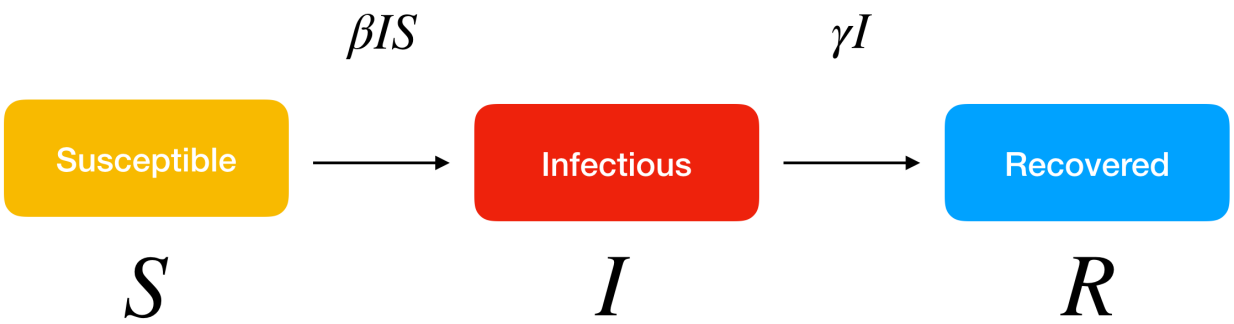
SIR model Flow Chart



- β : Infection rate
- γ : Recovery rate
- $\mathcal{R}_0 = N\beta/\gamma$: Basic reproduction number.
  If $\mathcal{R}_0 > 1$, an epidemic appears, otherwise it vanishes.

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SIR model

- SIR model : prey-predators model. Define:
  - $S(t) =$ "Susceptible" (those who are exposed in the global population);
  - $I(t) =$ "Infected" (and contagious);
  - $R(t) =$ "Recovered" or "Removed" (no longer contagious).
- Differential equations system :

$$\begin{aligned}\frac{dS(t)}{dt} &= -\beta S(t)I(t),\\ \frac{dI(t)}{dt} &= \beta S(t)I(t) - \gamma I(t),\\ \frac{dR(t)}{dt} &= \gamma I(t).\end{aligned}$$

- Constant size of the population : $N = S(t) + I(t) + R(t)$.

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From SIR to λ_T

- Number of susceptible at time t : $S(t)$.
- Number of new infections between t and $t + dt$: $\beta S(t)I(t)$.
- The probability for a policyholder to be infected between t and $t + dt$ (given that he has not been infected before t) is

$$\frac{\beta S(t)I(t)}{S(t)} = \beta I(t).$$

- Conclusion :

$$\lambda_T(t) = \lim_{dt \to 0^+} \frac{1}{dt} \mathbb{P}(T \in [t, t + dt] | T \geq t) = \beta I(t).$$

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Calibration

- Difficult calibration of SIR model in cyber epidemic (few available data).
- What is a reasonable β, and what is the exposure N in the global population?
- What do we know on Wannacry :
  - the total number of infected
  - the duration of the epidemic
  - the dynamics of the ransom payments (using bitcoins addresses used to pay the ransoms).

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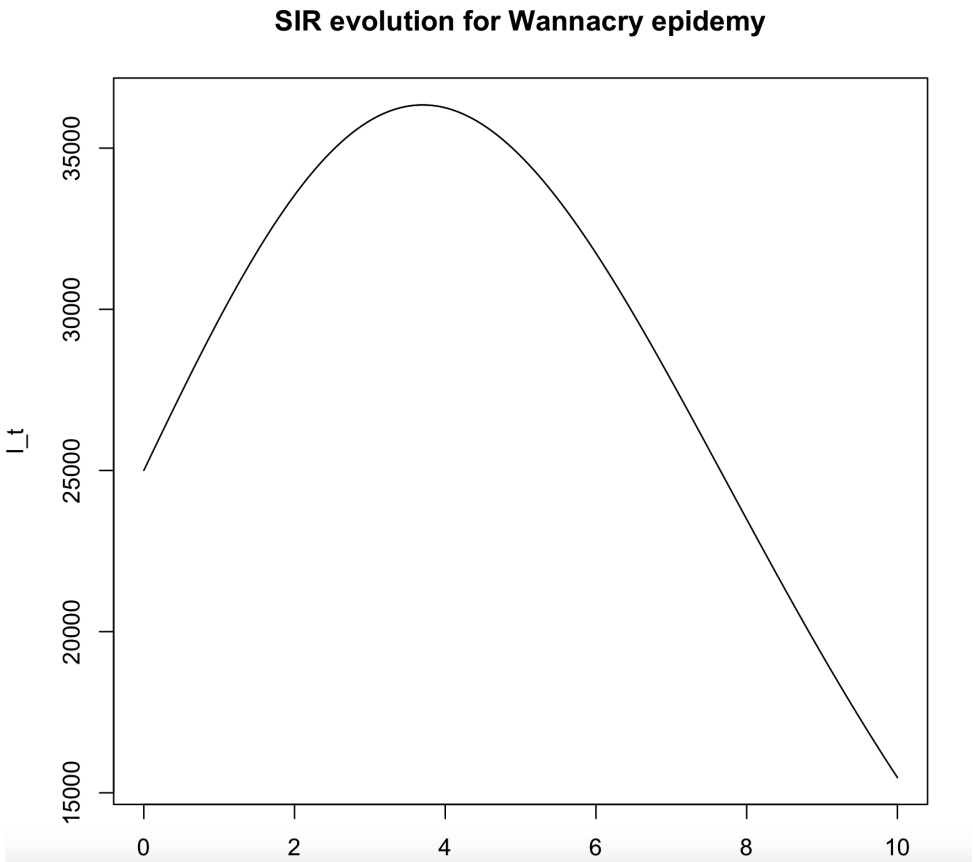
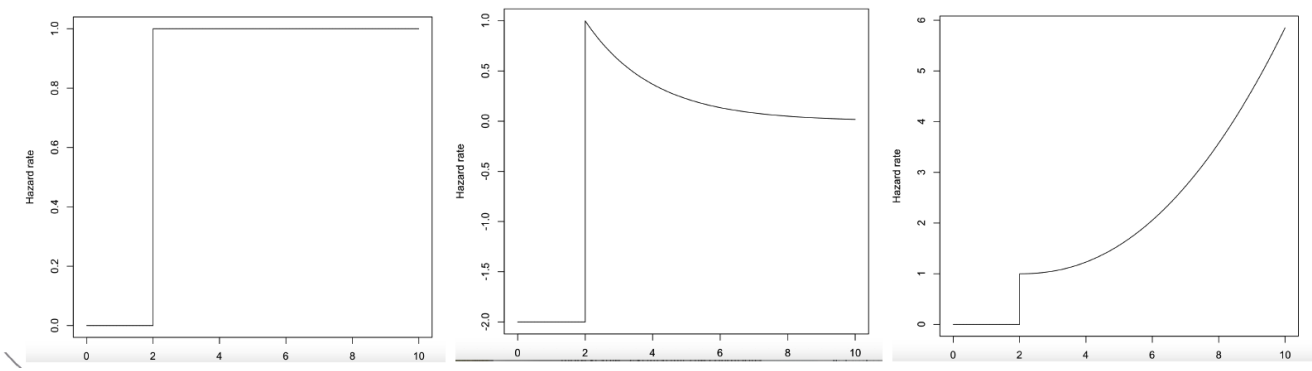
Example of epidemic dynamics of Wannacry type



Reaction

- Three examples of behavior (hazard rate) :



- From left to right "Exponential", "Pareto", "Weibull".
- In the three cases, three reaction delays, and different hazard rates.

What can we quantify with this model ?

- One can quantify :
  - the total number of infected policyholders on each scenario;
  - its evolution, and thus the impact of the different reactions ;
  - the risk of "saturation", i.e. the risk that the insurer is not able anymore to provide the promised technical assistance to his policyholders.
- Saturation : if a large number of policyholders are simultaneously victims of the attack, the insurer may not be able to assist them all (causing then an increase of the costs).

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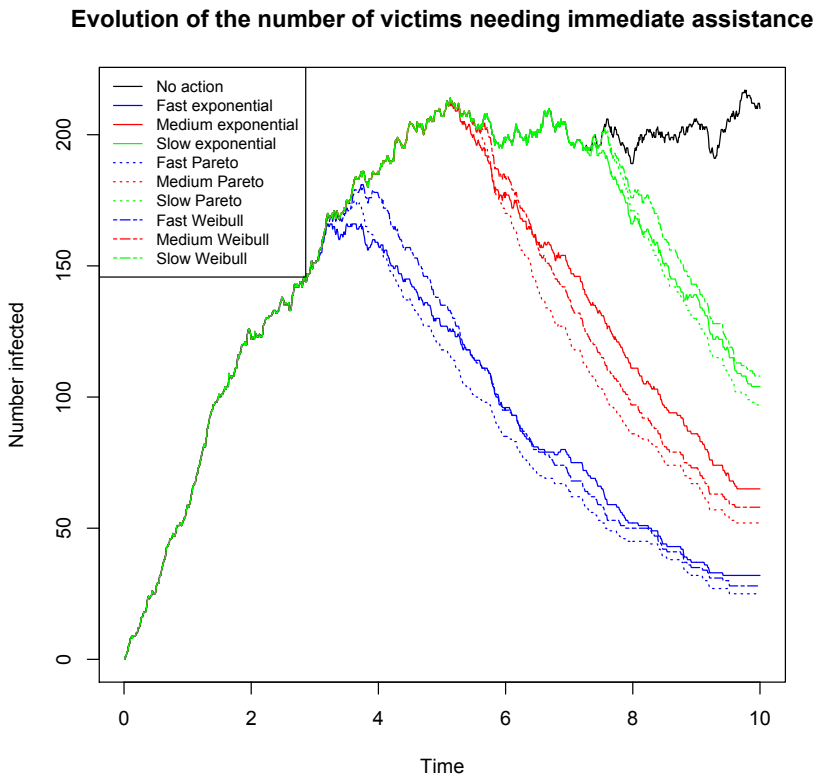
Simulation of a Wannacry-type scenario

- Simulation on a portfolio of 10 000 policyholders.



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Simulation results

- In this example, we see that the speed of reaction is crucial to reduce the peak.
- A late intervention still reduces the final number of policyholder infected.
- Regarding the way the three behaviors affect the peak: mixed picture.
- In Hillairet and Lopez (2021): if one assumes a shape on the cost of intervention (which may be dependent on the current number of policyholders needing assistance), one can determine the cost of concluding a partnership with a certain capacity of response.

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Multi-group SIR models

- Aim:Take into account connexions between members of different types on the portfolio that can contaminate themselves.
- Multi-group SIR: consider B **subpopulations**:

$$\frac{dS_i(t)}{dt} = -\left\{\sum_{j=1}^{B} \beta_{i,j} I_j(t)\right\} S_i(t)$$

$$\frac{dI_i(t)}{dt} = \left\{\sum_{j=1}^{B} \beta_{i,j} I_j(t)\right\} S_i(t) - \gamma_i I_i(t)$$

$$\frac{dR_i(t)}{dt} = \sum_{i=1}^{B} \gamma_i I_i(t).$$

- $\beta_{i,j}$ materializes how j contaminates i.
- Allows to introduce network effects.

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Multi-group SIR models

- Multi-group SIR: consider B subpopulations:

$$\frac{dS_i(t)}{dt} = -\left\{\alpha_i(t) + \sum_{j=1}^{B} \beta_{i,j} I_j(t)\right\} S_i(t)$$

$$\frac{dI_i(t)}{dt} = \left\{\alpha_i(t) + \sum_{j=1}^{B} \beta_{i,j} I_j(t)\right\} S_i(t) - \gamma_i I_i(t)$$

$$\frac{dR_i(t)}{dt} = \sum_{i=1}^{B} \gamma_i I_i(t).$$

- $\alpha_i(t)$ represents an intensity of attacks in class i.
- Example: single initial burst $\alpha_i(t) = \alpha 1_{0 \le t < 1}$ for some i.

Multi-group SIR models

- Multi-group SIR: consider B subpopulations:

$$\frac{dS_i(t)}{dt} = -\left\{\alpha_i(t) + \eta_i(t)\sum_{j=1}^{B}\beta_{i,j}I_j(t)\right\}S_i(t)$$

$$\frac{dI_i(t)}{dt} = \left\{\alpha_i(t) + \eta_i(t)\sum_{j=1}^{B}\beta_{i,j}I_j(t)\right\}S_i(t) - \gamma_i I_i(t)$$

$$\frac{dR_i(t)}{dt} = \sum_{i=1}^{B}\gamma_i I_i(t).$$

- $\eta_i(t)$ represents how population i tends to protect itself against the threat.
- Example: $\eta_i(t) = \eta 1_{S_i(0)/S_i(t)\geq s}$.

Final number of victims

- $R_i(\infty)$ = final number of victims in class i, $\mathrm{R} = (R_1(\infty), ..., R_d(\infty))$.
- One can show that the vector R is the unique solution of a fixed point equation

$$\mathrm{R} = \Phi(\mathrm{R}),$$

where

$$\Phi_i(\mathrm{x}) = I_i(0) + S_i(0)\left\{1 - \exp\left(-\mathcal{A}_i - \sum_{k=1}^{d} \frac{\beta_{k,i}}{\gamma_i} x_k\right)\right\},$$

with $\mathcal{A}_i = \int_0^\infty \alpha_i(t)dt$.

- From R, one deduces the probability of being hit for each category present in the portfolio.

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Impact of the connectivity

- We consider different classes of matrices $\mathcal{B}$ for the matrix B.
- Each class $\mathcal{B}$ has some properties, and we simulate random matrices from this class, and look at the final impact.
- Two examples:
  - "Clustered" : the transmission is essentially intern to a class.
  - "Non-clustered" : the transmission is stronger from one class to another than within a given class.

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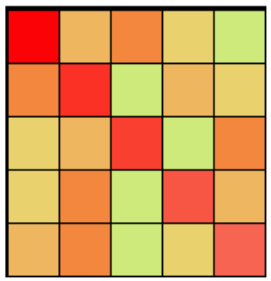
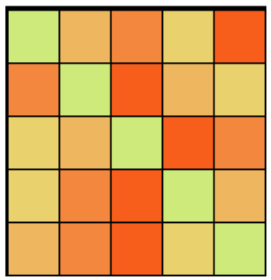
Two examples of matrices

- 5 classes.
- First class: 36% of the total population.
- 5-th class: 16% of the total population.
- Clustered:



- Non-clustered:



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Comparison with a reference scenario

- Reference scenario: one single class, infection similar to Wannacry, initialization through an attack function $\alpha_1(t) = \alpha_0 1_{0 \leq t \leq 1}$.
- Question: how much should we increase α to obtain the same number of victims as Wannacry depending on:
  - the class of matrices $\mathcal{B}$ (here "clustered", "non-clustered")?
  - the class in which the initial attack is performed?
- 100,000 simulations, $(E[\alpha] - \alpha_0)/\alpha_0$:

	Clustered	Non-Clustered
Attack on class 1	1.96	1.82
Attack on class 5	2.10	1.98

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A first conclusion

- Through this short example:
  - if, at first, a single class is attacked, communities tend to slow down the infection.
  - the more the communities are "separated", the stronger should be the attack to achieve the same level.
  - otherwise (non-clustered case), after some point there is an outbreak in the majority class.
- Other classes of matrices: possibility to look at some different shapes of networks as in Fahrenwaldt, Weber, Weske (2018) **Pricing of cyber insurance in a network model,** *ASTIN Bulletin*.
- -> To be investigated:
  - calibration of the network structure.
  - importance of the reaction (η_i in the differential system).
  - network effect on the "peak" of infections.

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References

- On contagion scenarii:

  

  Hillairet C., Lopez O. (2021) **Propagation of cyber incidents in an insurance portfolio: counting processes combined with compartmental epidemiological models**, in *Scandinavian Actuarial Journal* https://www.tandfonline.com/doi/abs/10.1080/03461238.2021.1872694.
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- Joint Research Initiative "Cyber-insurance: actuarial modeling" : https://sites.google.com/view/cyber-actuarial/home?authuser=0

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