Collective decision-making on networked systems: from social networks to smart homes

Angela Fontan
angfon@kth.se

Division of Decision and Control Systems
KTH Royal Institute of Technology, Sweden

KTH VETENSKAP OCH KONST

digital futures

Outline

- Background and motivating examples
- Problem: Collective decision-making in presence of antagonism
  - Social networks as signed networks
  - The notion of frustration
  - Analysis of proposed model for collective decision-making over signed networks
  - Application: Process of government formation over signed parliamentary networks
- Problem: Design of energy-efficient smart homes
  - Smart homes as cooperative networks
  - Application: Study of social influence at KTH Live-In Lab

Background

Context: Interpretation of urban systems as cyber-physical-human systems (CPHS)

[Control for Societal Scale Challenges: Road Map 2030, eds. Annaswamy, Johansson, Pappas (2023)]

Motivating examples

Characterize models of (human) decision-making within interconnected communities...
...and how they adapt during the interaction with smart technologies

1. From collaborative to antagonistic collective decision-making systems

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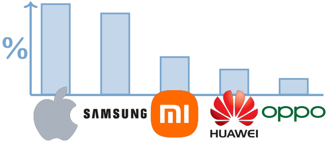
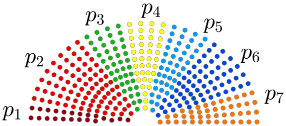
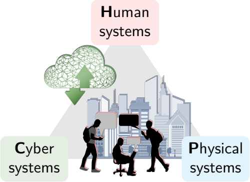
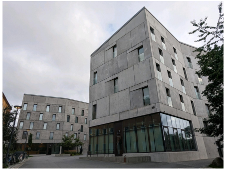




2. Design of energy-efficient smart homes
   - Building automation and control of energy-efficient smart homes
   - Integrated real-life experimental building infrastructure: KTH Live-In Lab





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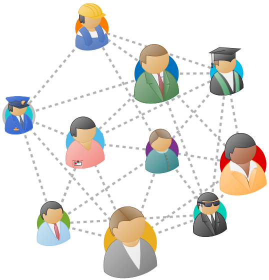
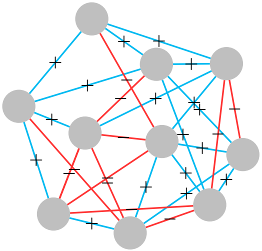
In collaboration with: Claudio Altafini, Linköping University, Sweden

Problem: Collective decision-making in presence of antagonism

Application: Social networks



$$\dot{x} = f(x, \text{network}, \pi)$$



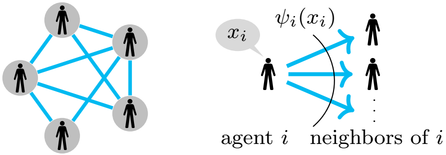
1. Model for collective decision-making
    - x: vector of opinions
    - equilibrium points: possible decisions
2. Signed networks
    - Positive weight: cooperative interaction
    - Negative weight: antagonistic interaction

Model for collective decision-making over cooperative networks

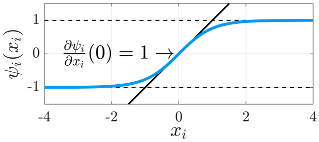
$$\dot{x} = -\Delta x + \pi A \psi(x)$$

- n agents, $x \in \mathbb{R}^n$ vector of opinions
- "inertia" of the agents: $\Delta = \mathrm{diag}\{\delta_1, \ldots, \delta_n\}$, $\delta_i > 0$
- interactions between the agents:

unsigned (connected) network $\mathcal{G}(A)$



$\psi(x) = [\psi_1(x_1) \ \ldots \ \psi_n(x_n)]^T$



- $\pi > 0$ scalar parameter

[Gray, Leonard, et al., IEEE TCNS (2018)]

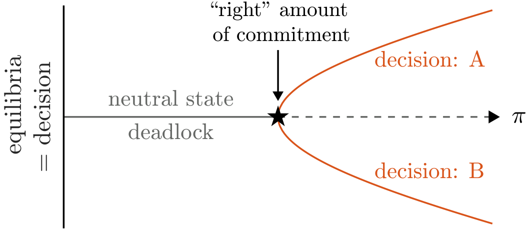
Model for collective decision-making over cooperative networks

$$\dot{x} = -\Delta x + \pi A \psi(x) \qquad (\star)$$

- π = "social effort" or "strength of commitment" among the agents
- equilibria = decisions

Assumption: $\delta_i = \sum_j a_{ij} \quad \Rightarrow \quad L = \Delta - A$: Laplacian of $\mathcal{G}(A)$

Task: Study qualitative behavior of $(\star)$ as social effort parameter π is varied

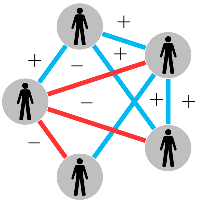


Model for collective decision-making over *signed networks*

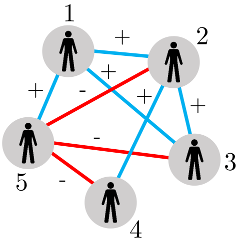
Task: Study the decision-making process in a community of agents where both cooperative and antagonistic interactions coexist

Model: $\dot{x} = -\Delta x + \pi A \psi(x)$, π: social effort between the agents

Assumptions: $\mathcal{G}(A)$ is a signed network



Signed networks and signed Laplacian matrix

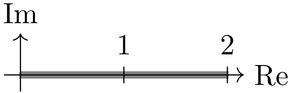


$$A = \begin{bmatrix} 0 & + & + & 0 & + \\ + & 0 & + & + & - \\ + & + & 0 & 0 & - \\ 0 & + & 0 & 0 & - \\ + & - & - & - & 0 \end{bmatrix} \begin{matrix} \Rightarrow \delta_1 \\ \\ \dots \\ \\ \Rightarrow \delta_5 \end{matrix} \qquad \mathcal{L} = \begin{bmatrix} 1 & - & - & 0 & - \\ - & 1 & - & - & + \\ - & - & 1 & 0 & + \\ 0 & - & 0 & 1 & + \\ - & + & + & + & 1 \end{bmatrix}$$

Signed Laplacian*:

$$L = \Delta - A$$

$$\Delta = \mathrm{diag}\{\delta_1, \dots, \delta_n\} : \ \delta_i = \sum_{j=1}^{n} |a_{ij}| > 0 \quad \forall\ i$$



$\Lambda(\mathcal{L})$ = spectrum of $\mathcal{L}$

Focus on:

normalized signed Laplacian: $\mathcal{L} = I - \Delta^{-1} A$

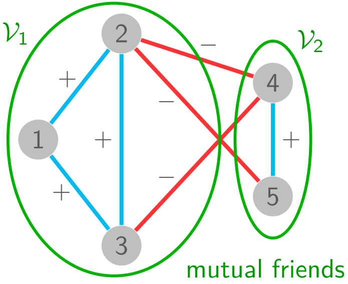
* "opposing" signed Laplacian [Shi, Altafini, Baras, SIAM Review (2019)]

Structural balance

A connected signed graph $\mathcal{G}(A)$ is structurally balanced if $\mathcal{V} = \mathcal{V}_1 \cup \mathcal{V}_2$ such that every edge:

- between $\mathcal{V}_1$ and $\mathcal{V}_2$ is negative
- within $\mathcal{V}_1$ or $\mathcal{V}_2$ is positive

[F. Harary, Mich. Math. J. (1953)]



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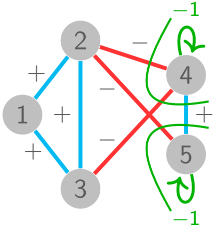
[F. Harary, Mich. Math. J. (1953)]

Lemma: $\mathcal{G}(A)$ is structurally balanced iff

- ▶ $\exists$ signature matrix $S = \mathrm{diag}\{s_1, \ldots, s_n\}$, $s_i = \pm 1$, s.t. $S\mathcal{L}S$ has all nonpositive off-diagonal entries
- ▶ $\lambda_1(\mathcal{L}) = 0$



$$\mathcal{L} = \begin{bmatrix} 1 & - & - & & \\ - & 1 & - & + & + \\ - & & 1 & + & \\ & + & + & 1 & - \\ & + & & - & 1 \end{bmatrix}$$

$$S = \mathrm{diag}\{1,\ 1,\ 1,\ -1\ ,\ -1\}$$

$$\Rightarrow S\mathcal{L}S = \begin{bmatrix} 1 & - & - & & \\ - & 1 & - & - & - \\ - & - & 1 & - & \\ & - & - & 1 & - \\ & - & & - & 1 \end{bmatrix}$$

Structural balance

A connected signed graph $\mathcal{G}(A)$ is **structurally balanced** if $\mathcal{V} = \mathcal{V}_1 \cup \mathcal{V}_2$ such that every edge:

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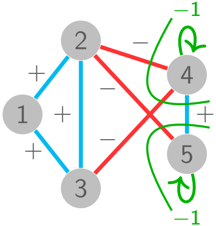

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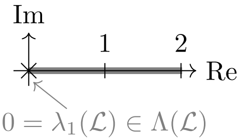
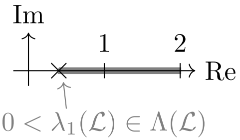
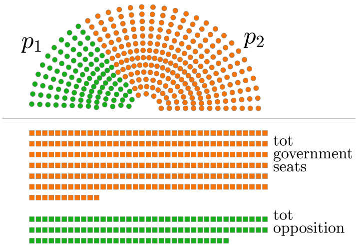
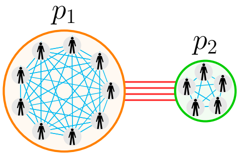
$\mathcal{G}(A)$ structurally balanced	$\mathcal{G}(A)$ structurally unbalanced
	

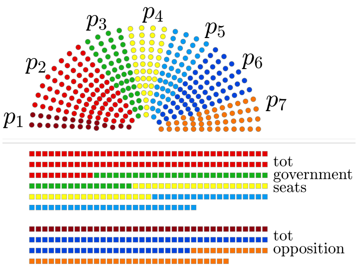
Example: Parliamentary systems

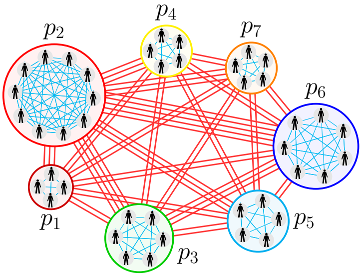
Structurally balanced network





Structurally unbalanced network





Frustration index and algebraic conflict

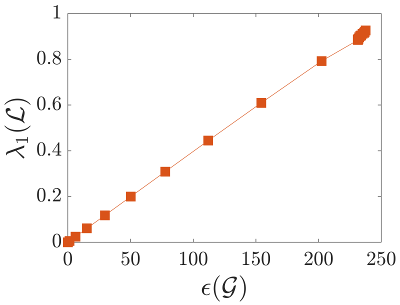
Task: characterize the graph distance from structurally balanced state

- Frustration Index
  (computation: NP-hard problem)

$$\epsilon(\mathcal{G}) = \min_{\substack{S=\text{diag}\{s_1,\dots,s_n\}\\ s_i=\pm 1}} \underbrace{\frac{1}{2}\cdot\sum_{i\neq j}\left[\,|\mathcal{L}| + S\mathcal{L}S\,\right]_{ij}}_{=e(S):\ \text{"energy functional"}}$$

- Algebraic Conflict

$$\xi(\mathcal{G}) = \lambda_1(\mathcal{L})$$



$\Longrightarrow$

$\lambda_1(\mathcal{L})$ good approximation of $\epsilon(\mathcal{G})$

[Fontan and Altafini, IEEE CDC (2018)]

Model for collective decision-making over signed networks

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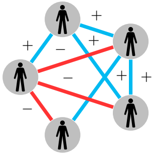
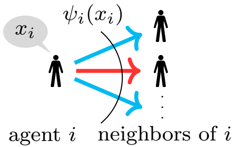
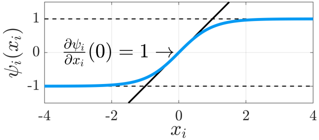
- n agents, $x \in \mathbb{R}^n$ vector of opinions
- "inertia" of the agents: $\Delta = \mathrm{diag}\{\delta_1, \ldots, \delta_n\}$, $\delta_i > 0$
- interactions between the agents:

signed (connected) network $\mathcal{G}(A)$





$\psi(x) = [\psi_1(x_1) \; \ldots \; \psi_n(x_n)]^T$



- $\pi > 0$ "social effort" (or "strength of commitment")

[Fontan and Altafini, IEEE TAC (2021)]

Task

$$\dot{x} = -\Delta x + \pi A\psi(x) = \Delta(-x + \pi H\psi(x)) \qquad (\star)$$

- Normalized adjacency matrix $H = \Delta^{-1}A = I - \mathcal{L}$
- Dynamical interpretation: $(\star)$ is monotone $\Leftrightarrow$ $\mathcal{G}(A)$ is structurally balanced $\Leftrightarrow$ $\lambda_1(\mathcal{L}) = 0$

Investigate how:

- the social effort parameter π affects the existence and stability of the equilibrium points of the system $(\star)$
  Tool: bifurcation theory ($\mathcal{L} = I - H$ has simple eigenvalues)
- the presence of antagonistic interactions affects the behavior of $(\star)$
  Tool: signed networks theory (frustration)

Bifurcation analysis: Structurally balanced networks

$$\dot{x} = \Delta(-x + \pi H \psi(x)), \quad x \in \mathbb{R}^n$$

$\pi < 1$: $x = 0$ only eq. point (GAS)
Not enough commitment: Deadlock

$\pi = 1$: pitchfork bifurcation

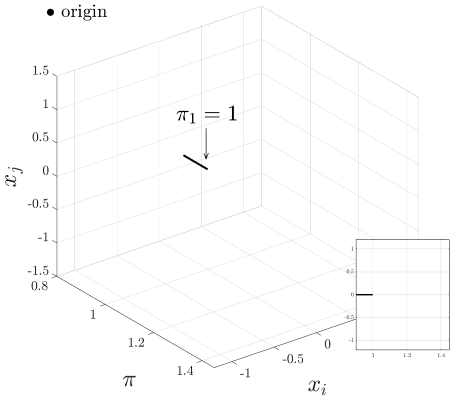
- $x = 0$ saddle point
- new equilibria: x^*, $-x^*$ (loc. AS $\forall \pi > 1$)

Right commitment: Two alternative decisions x^*

$\pi = \pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$: pitchfork bifurcation

- new equilibria (stable/unstable for $\pi > \pi_2$)

Overcommitment: Several decisions



Bifurcation diagram

[Fontan and Altafini, IEEE TCNS (2018)]

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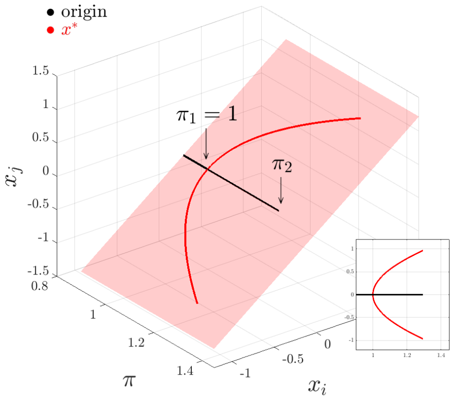

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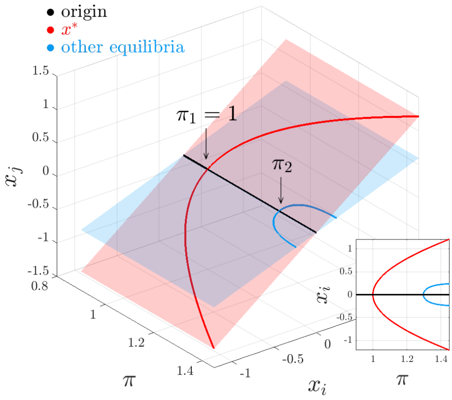


Bifurcation diagram

[Fontan and Altafini, IEEE TCNS (2018)]

Bifurcation analysis: Structurally unbalanced networks

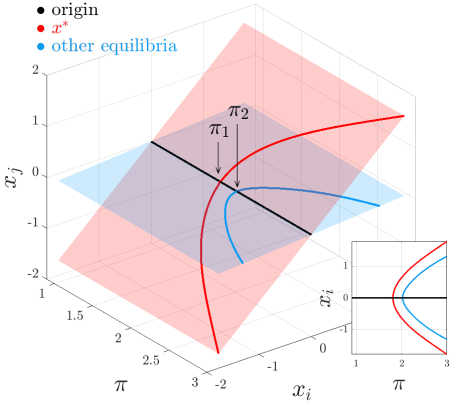
$$\dot{x} = \Delta(-x + \pi H \psi(x)), \quad x \in \mathbb{R}^n$$

With: $\pi_1 = \dfrac{1}{1-\lambda_1(\mathcal{L})}$, $\pi_2 = \dfrac{1}{1-\lambda_2(\mathcal{L})}$

$\pi < \pi_1$: Not enough commitment
Deadlock

$\pi = \pi_1$: Right commitment
Two alternative decisions x^*

$\pi = \pi_2$: Overcommitment
Several decisions



Bifurcation diagram

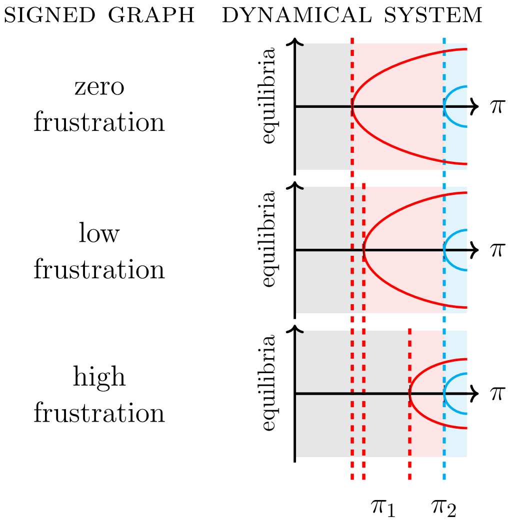
[Fontan and Altafini, IEEE TAC (2021)]

Interpretation of the results as we vary the frustration

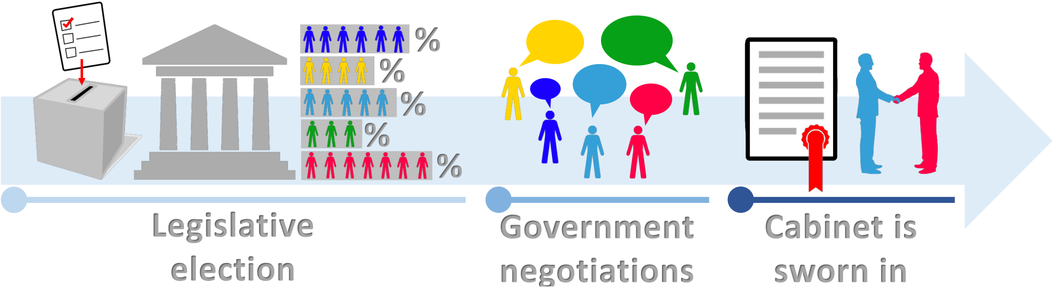
- $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$ depends on the frustration ($\lambda_1(\mathcal{L}) \approx$ frustration)
- $\pi_2 = \frac{1}{1-\lambda_2(\mathcal{L})}$ depends on the topology, independent from the frustration

Then, the higher the frustration:

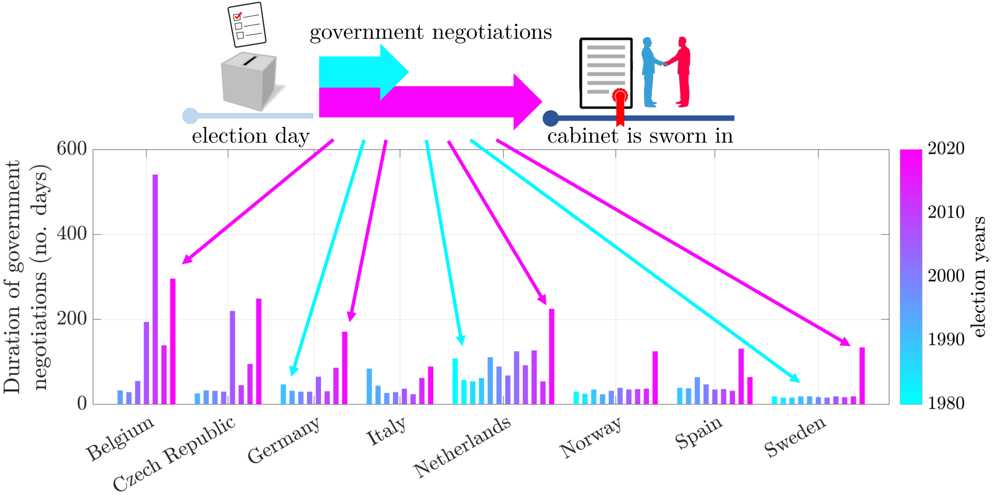
- the higher the social effort needed to achieve a decision
- the smaller the interval for which only two alternative decisions exist



Application: Government formation in parliamentary democracies



Duration of government negotiation phase



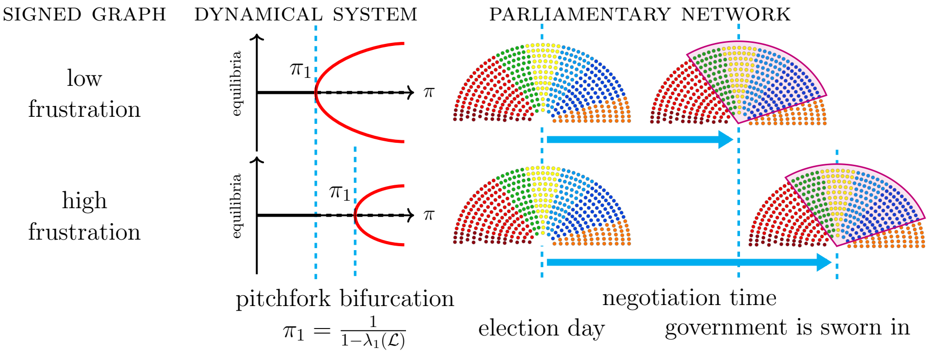
Question: can we use our model to explain this behavior?

Dynamics of the formation of a government

- Signed network: parliament
- Social effort: duration of the government negotiation phase
- Decision: vote of confidence of the parliament

$\lambda_1(\mathcal{L}) \sim$ frustration $+$ $\pi_1 \sim$ duration of negotiations $+$ $\pi_1 = \frac{1}{1-\lambda_1(\mathcal{L})}$

$\Rightarrow$ duration of negotiations $\sim$ frustration

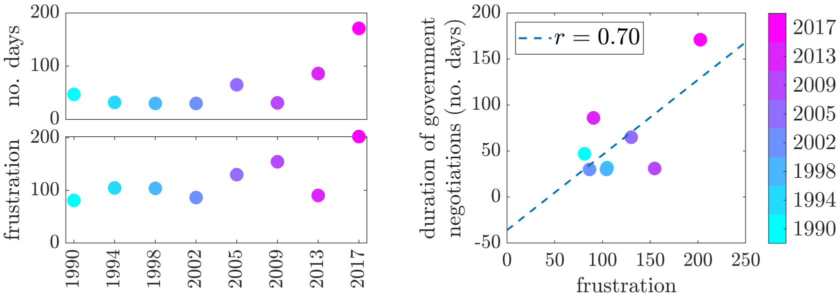


Frustration vs duration of government negotiations

Task: show that the government formation process is influenced by the frustration of the parliamentary network

- Data: elections in 29 European countries (election years: 1978 - 2020)
- Method: Pearson's correlation index (r), frustration vs duration of negotiations

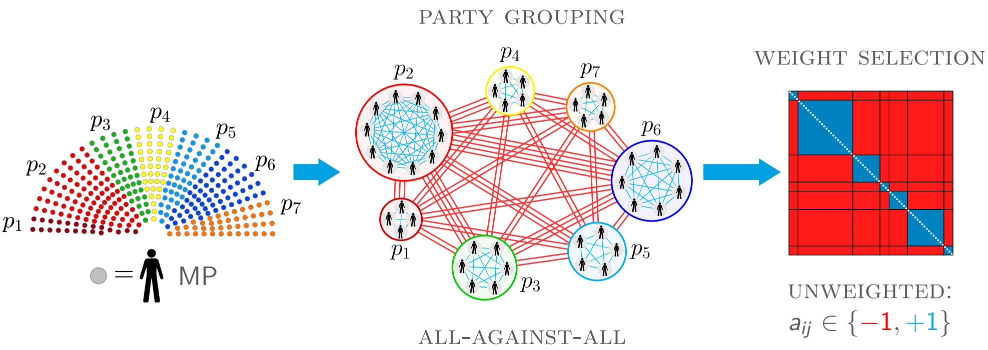
Example: German elections



[Fontan and Altafini, Scientific Reports (2021)]

Construction of the parliamentary networks

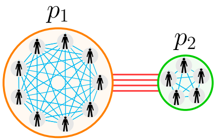
Definition: complete, undirected, signed graph in which each MP is a node



collaboration: MPs belong to the **same** party

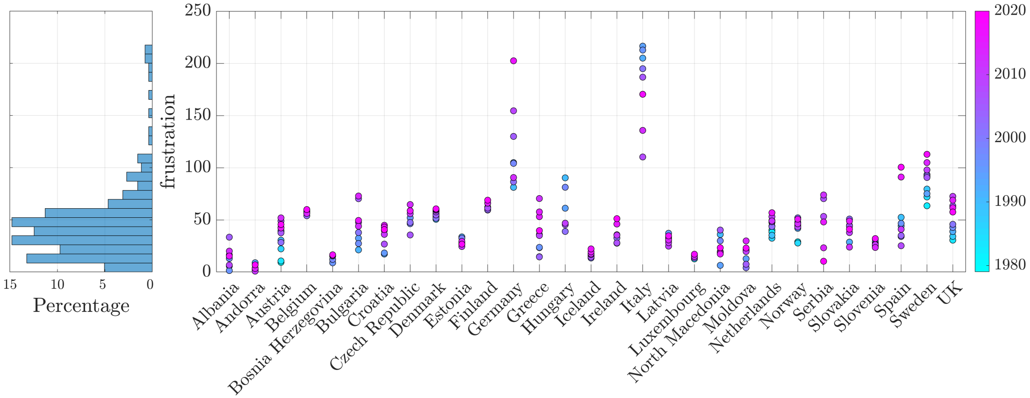
rivalry: MPs belong to **different** parties

Are the parliamentary networks structurally balanced?



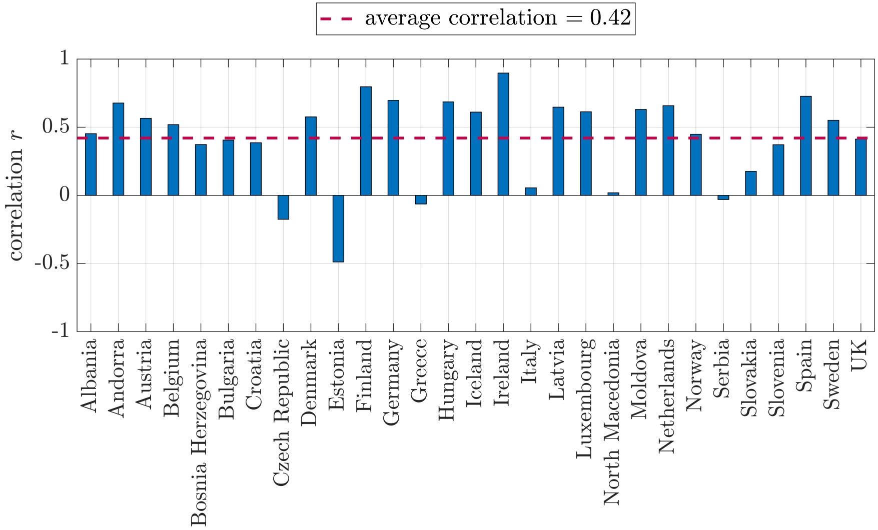
Structurally balanced parliamentary network

The parliamentary networks have (in general) nonzero frustration..

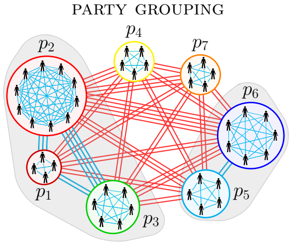


Correlation for all 29 European countries

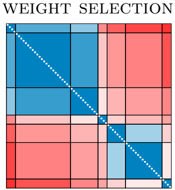
Duration of the government negotiations vs frustration of the parliamentary networks

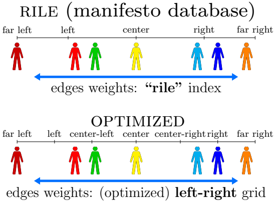


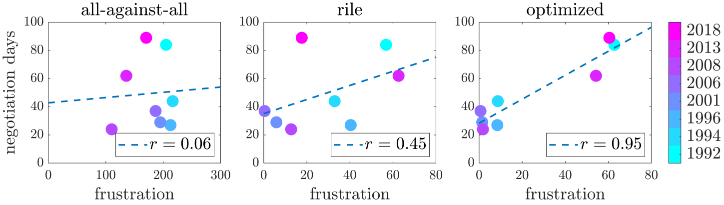
More complex scenarios: Coalitions and ideological differences



PRE-ELECTORAL COALITIONS
collaboration: MPs belong to the same party or pre-electoral coalition
rivalry: otherwise







Example: Italian elections

Results on average correlation for all 29 European countries:
0.42 (all-against-all), 0.32 (rile), 0.69 (optimized)
⇒ Frustration correlates well with duration of government negotiations

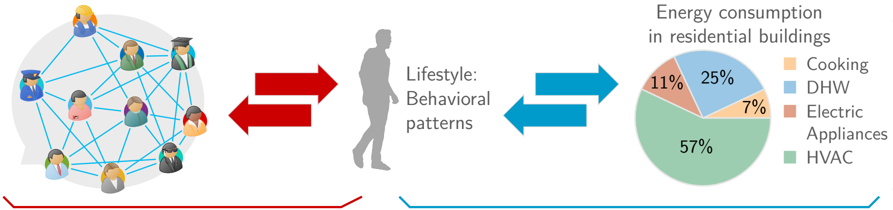
Outline

- Motivating examples
- Problem: Collective decision-making in presence of antagonism
  - Social networks as signed networks
  - The notion of frustration
  - Analysis of proposed model for collective decision-making over signed networks
  - Application: Process of government formation over signed parliamentary networks
- Problem: Design of energy-efficient smart homes
  - Smart homes as cooperative networks
  - Application: Study of social influence at KTH Live-In Lab

In collaboration with: M. Farjadnia, J. Llewellyn, C. Katzeff, M. Molinari, V. Cvetkovic, and K. H. Johansson, KTH Royal Institute of Technology, Sweden

Problem: Design of energy-efficient smart homes

- Context: Building sector accounts for more than 40% of the final energy use
- Challenges for control in smart buildings:
  The behavior of occupants have large effects on building energy use



Data-driven control of HVAC systems [Farjadnia et al., Eur. J. Control (2023)]

Social interactions towards a sustainable lifestyle [A. Fontan et al., IFAC WC (2023)]

Bidirectional interactions between tenants and environmental conditions [M. Farjadnia, A. Fontan, et al., IEEE CCTA (2023)]

[Fontan et al., IFAC WC (2023); Farjadnia et al., IEEE CCTA (2023); Farjadnia et al., Eur J Control (2023)]

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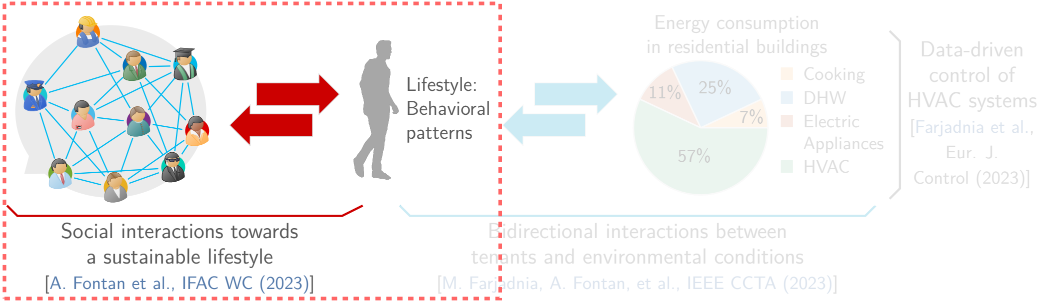


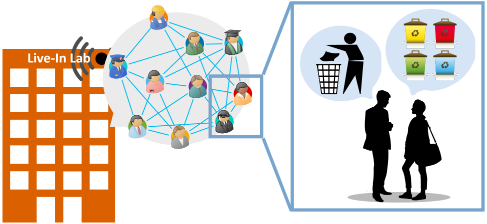
[Fontan et al., IFAC WC (2023); Farjadnia et al., IEEE CCTA (2023); Farjadnia et al., Eur J Control (2023)]

Problem formulation

Design longitudinal experimental study of social influence in behavioral changes towards sustainability, to be implemented in the KTH Live-In Lab

Combining several factors..

- Modeling household and energy use behavior
  [Wilson and Dowlatabadi (2007), Peng et al. (2012);..]
- Planning ad hoc social interventions on habits
  [Steg and Vlek (2009); Frederiks et al. (2015);..]
- Designing new technologies and infrastructures (flexible Live-In Laboratories)
  [Intille et al. (2006); Das et al. (2020);..]



..and proposing a social network perspective:

Experimental design as collective (household) decision-making process with interconnected tenants of KTH Live-In Lab as the decision-makers

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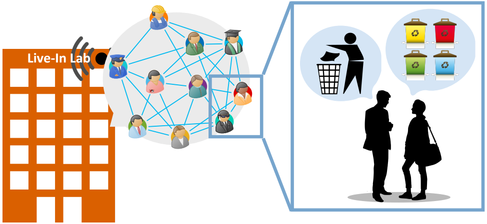


..and proposing a social network perspective:

Experimental design as collective (household) decision-making process with interconnected tenants of KTH Live-In Lab as the decision-makers

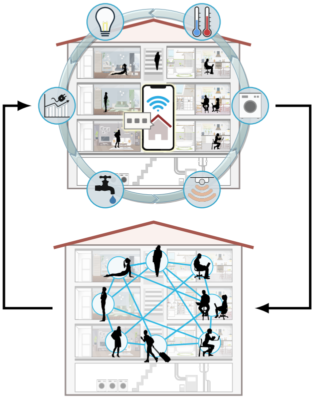
Exploring diffusion of sustainable behaviors: Smart homes as social networks

Approach Observe how tenants' sustainability scores change over time given that:

- Tenants are encouraged to exchange opinions with their neighbors
- Tenants can observe the average household sustainability score

Experimental campaign based on the interpretation:

- Smart home: Social network of interacting tenants
- Lifestyle choices: Decisions $\sim$ sustainability score
- Intuition: Feedback on global state (household) to reduce observed discrepancy between lifestyle choices and opinions on environmental responsibility



Experimental setup

Campaign run at the KTH Live-In Lab, state-of-the-art platform of building testbeds

- Apartments with extensive sensing, data collection, and control capabilities
- Redesignable apartment layout allowing various experimental environments
- Interaction capability with and between occupants
  (experiments involving 4 apartments and 5 tenants)

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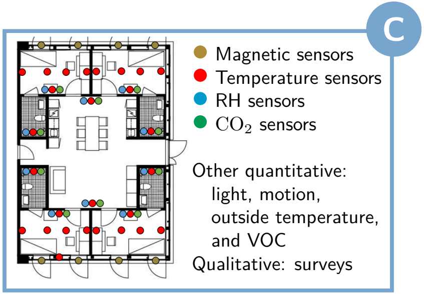

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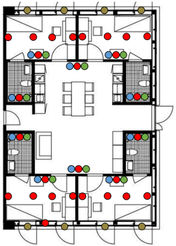

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- Temperature sensors
- RH sensors
- CO_2 sensors

Other quantitative:
light, motion,
outside temperature,
and VOC
Qualitative: surveys

P

H

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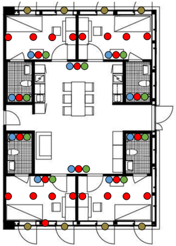

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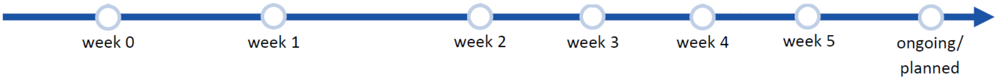
Preparatory phase of the project (winter 2022-spring 2023)

- Small group of participants
- Short time period



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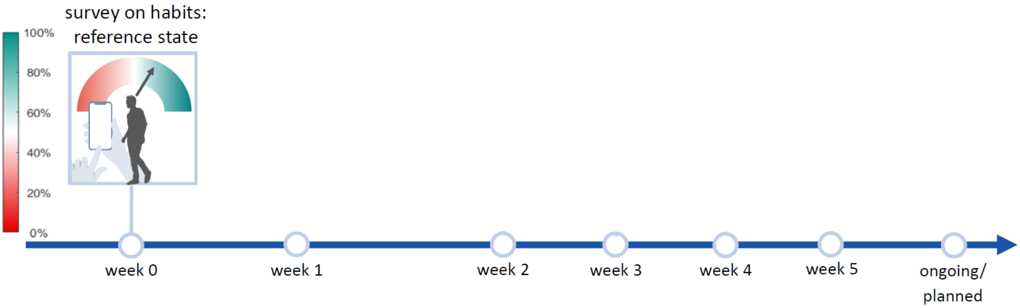

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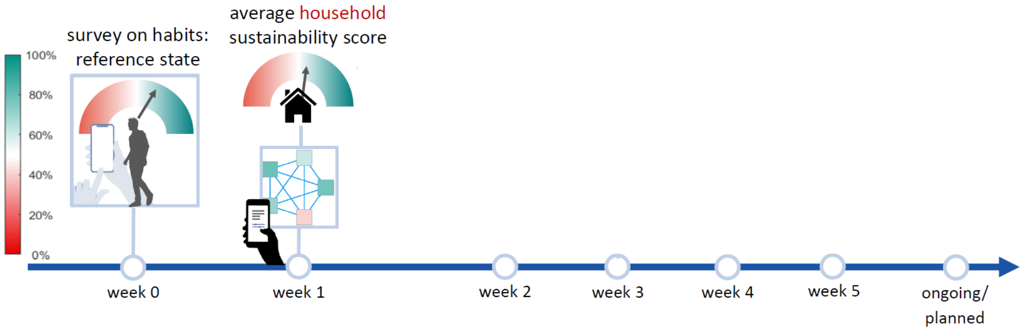

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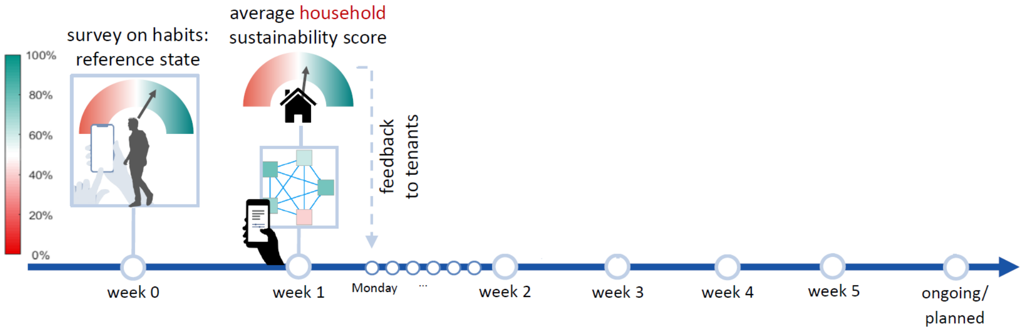

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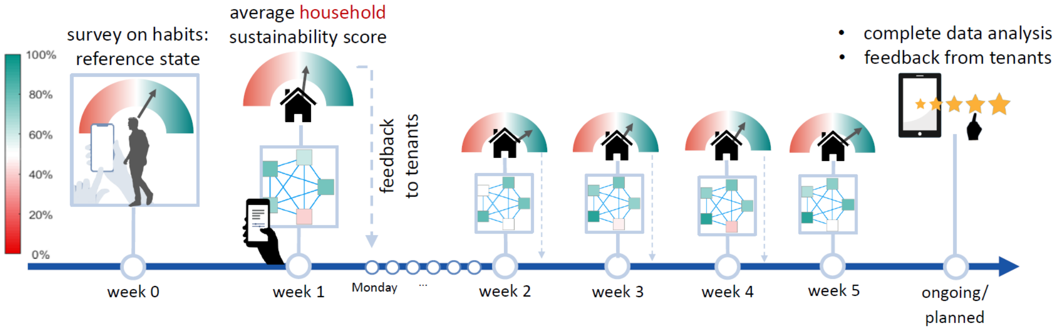

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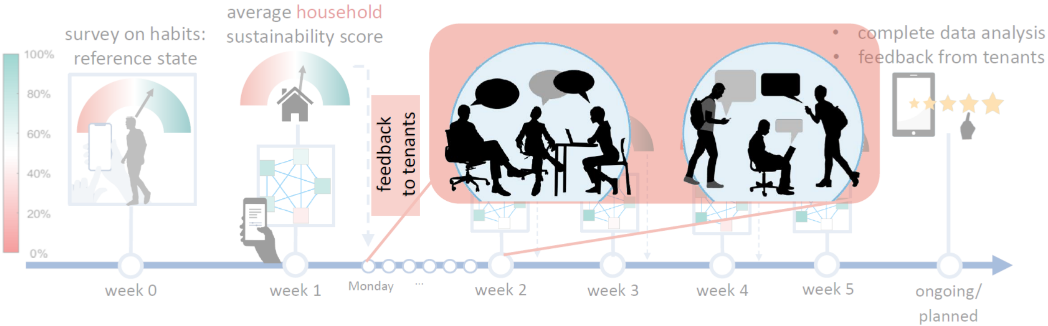
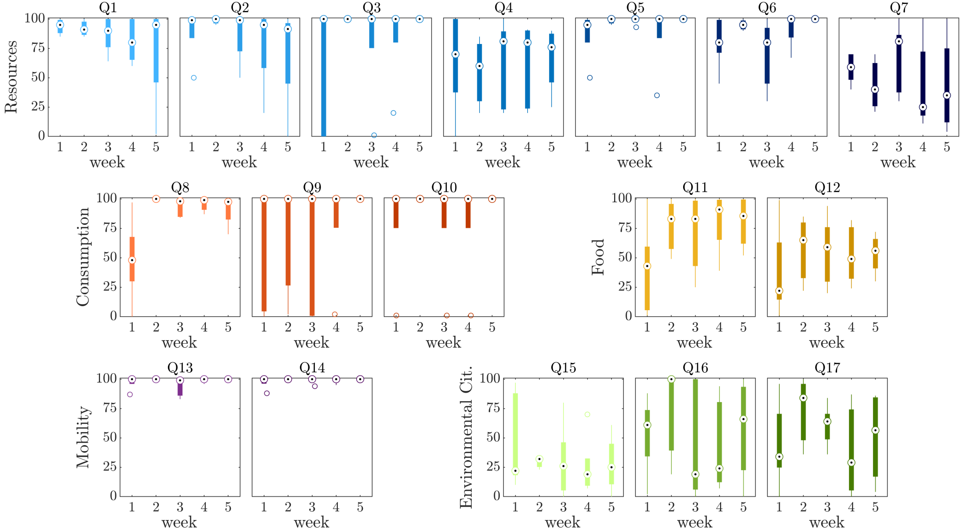


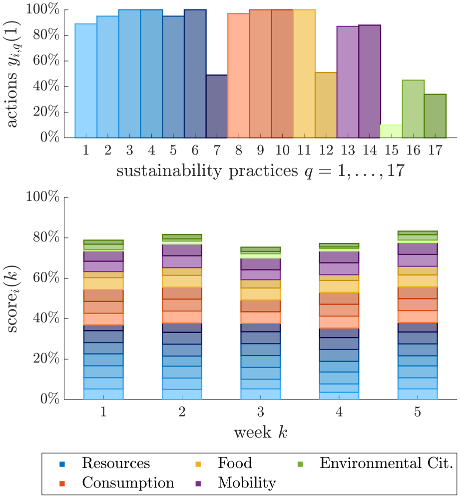
Preliminary results (I/II)

Summary of actions on sustainability practices Q# (grouped in 5 dimensions)

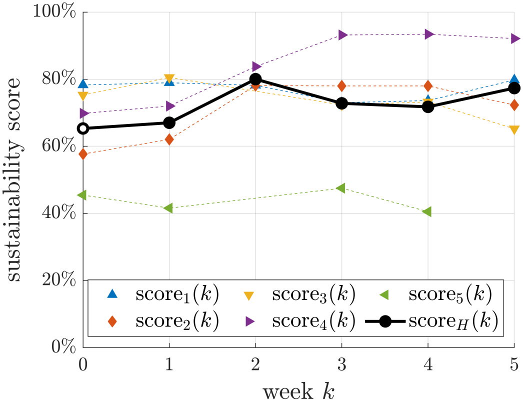


Preliminary results (II/II)

Actions $y_{i,q}(k)$ and sustainability score of tenant i of the KTH Live-In Lab



Sustainability scores of all tenants and average household sustainability score



Conclusions

Context Urban systems as CPHS

Focus Human decision-making within interconnected communities

Two motivating applications

1. Political decision-making
   - Government formation process as collective decision-making system over signed parliamentary networks
   - We show that the frustration of the parliamentary networks correlates well with the duration of government negotiation phase
2. Decision-making in smart homes
   - Smart homes as social networks
   - Design of experimental study, to investigate the dynamics of tenants' sustainability scores
   - Ongoing/future directions (to implement at the KTH Live-In Lab):
     - Theoretical analysis on impact of campaigns and incentives design
     - Compare surveys' data with sensor data collected at KTH Live-In Lab

Thank you for your attention!

Angela Fontan, angfon@kth.se, angelafontan.github.io