Imperial College London

Aggregation and control of smart refrigerators:
semi-autonomous control of heterogeneous appliances

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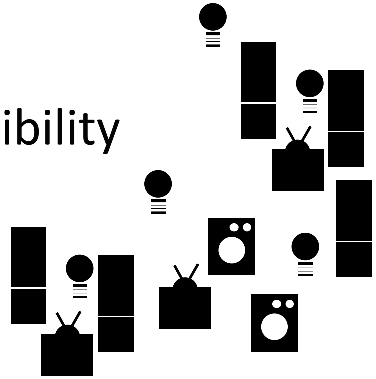
General: the long tail of flexibility

Many small appliances can collectively provide significant flexibility



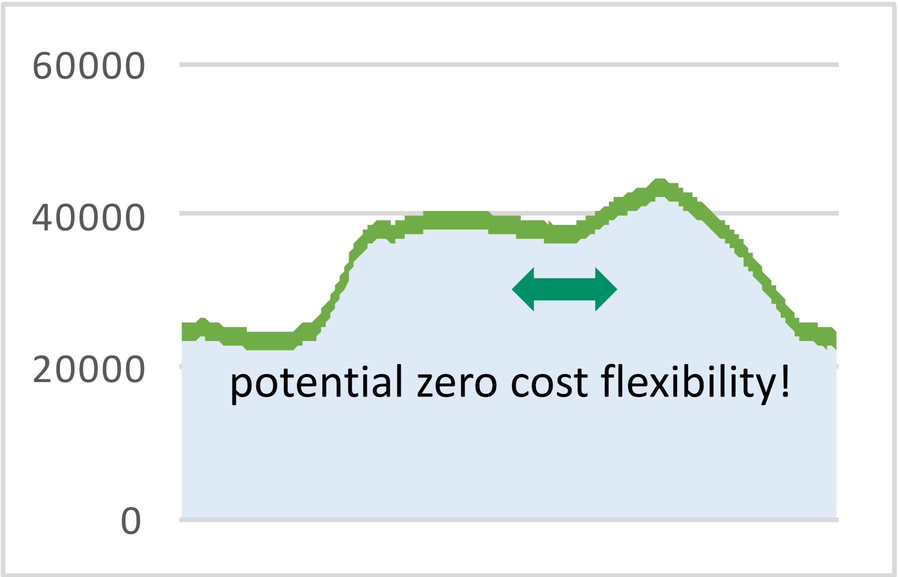
Constraints/challenges

- Primary service should be preserved (within limits), and without much user interaction
- Small per-device flexibility contribution, so controller/comms budget is small
- Significant heterogeneity

Opportunities

- Very large number of devices, so large-number statistics apply (at least at regional/national levels)
- Regular consumption patterns allow for aggregate prediction

Flexible refrigeration: from ‘what’ to ‘how’



The opportunity

- Refrigerators represent 5-15% of system load (est. 2-3GW in GB)*
- Load shifting for ~30 minutes is free* **secondary use**

The challenge

- **Maintain cooling performance:** Secondary use (flexibility) should not compromise the primary use (cooling) of devices.
- **Robustness and scalability:** Reliance on real-time communication may result in bottlenecks and single points of failure
- **Controllability:** Ensure sufficient control over power consumption, and avoid *unwanted interactions.*

The demand response control spectrum

Our approach: semi-autonomous control

- *Collective goals* are set centrally
- *Actions* are decided locally, with reference to expected *group behaviour*

Direct dispatch of flexible resources

Goals and actions are decided centrally, or in a distributed fashion

V
- Controllability

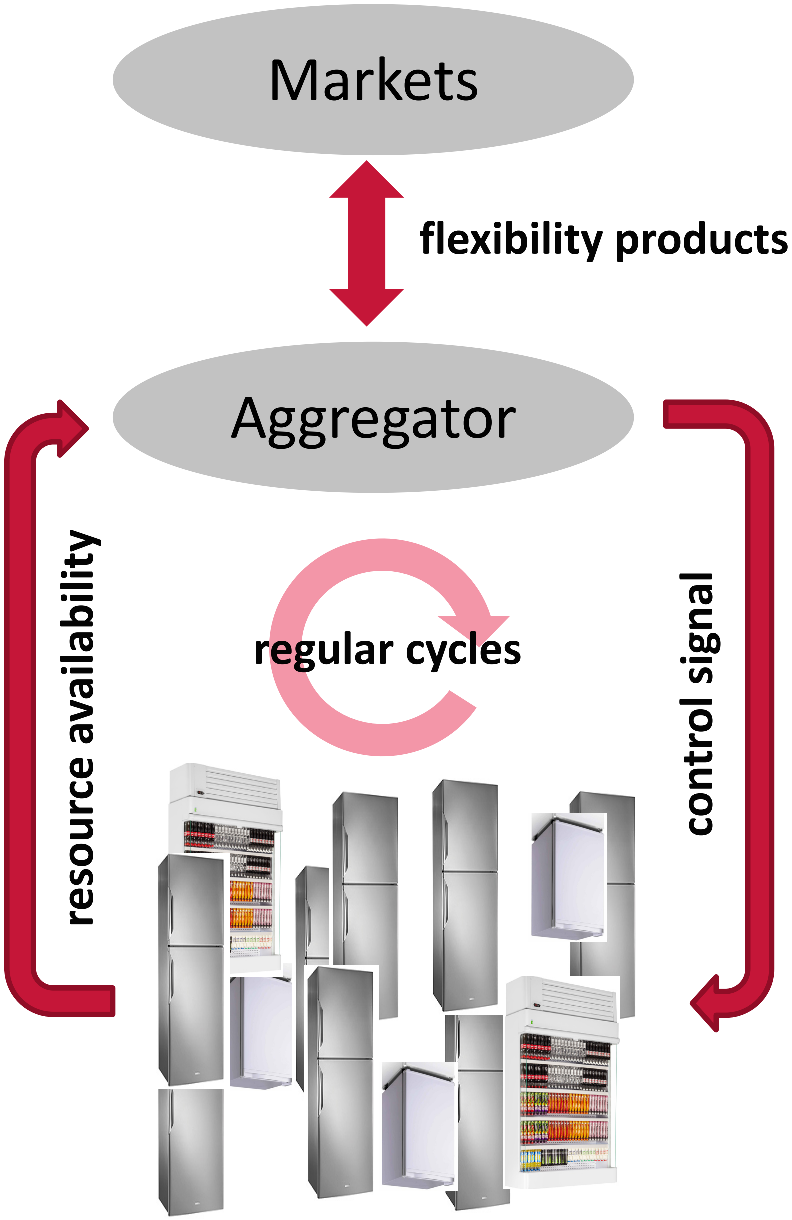
✗
- Requires real-time communication
- Limited autonomy
- Privacy concerns

Indirect control using incentives

Decentralised actions on the basis of a non-local control signals.

Useful taxonomy of indirect control in Heussen *et al.*, *IEEE PES ISGT Europe 2012*

High-level approach



Markets

flexibility products

Aggregator

resource availability

regular cycles

control signal

Model of collective flexibility

Aggregate load dispatch

“Semi-autonomous control”

Characteristics (details in following slides)

- Appliances ...
    - receive a signal of control intent (not price)
    - always give priority to local constraints (e.g. temperature)
    - act stochastically on the basis of an inferred (sub)population response
- The aggregator ...
    - constructs a model of aggregate appliance capabilities
    - offers aggregate services to the market
- On short time scales, appliances act autonomously
- On long time scales, appliances exchange aggregate control models with an aggregator

Control through the law of large numbers

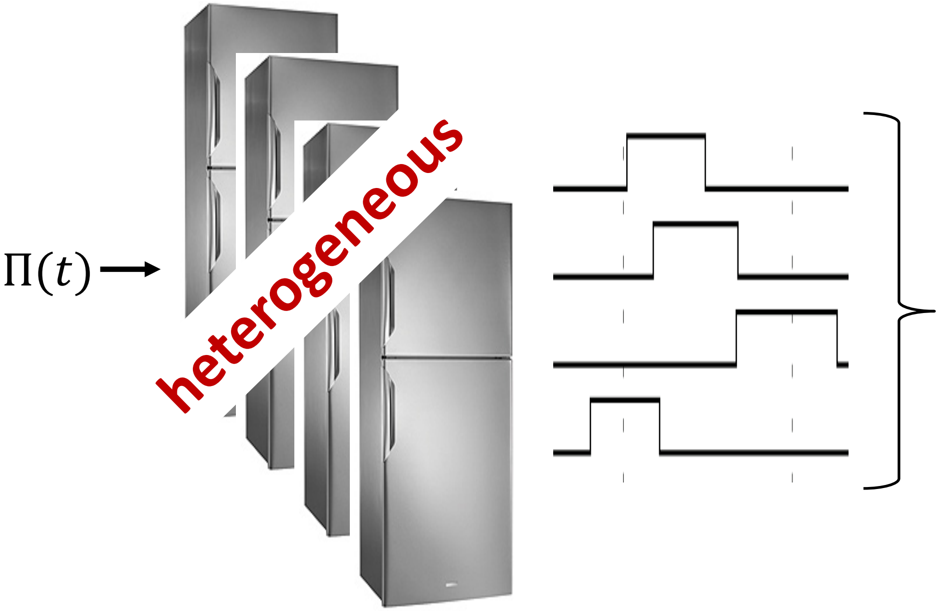
$$E[P^a(t)] = \overline{P_0^a}$$

control intent **modulates power consumption of all appliances**

$\Pi(t) = 1$ for steady state

power consumption of appliance *a* (a random process)

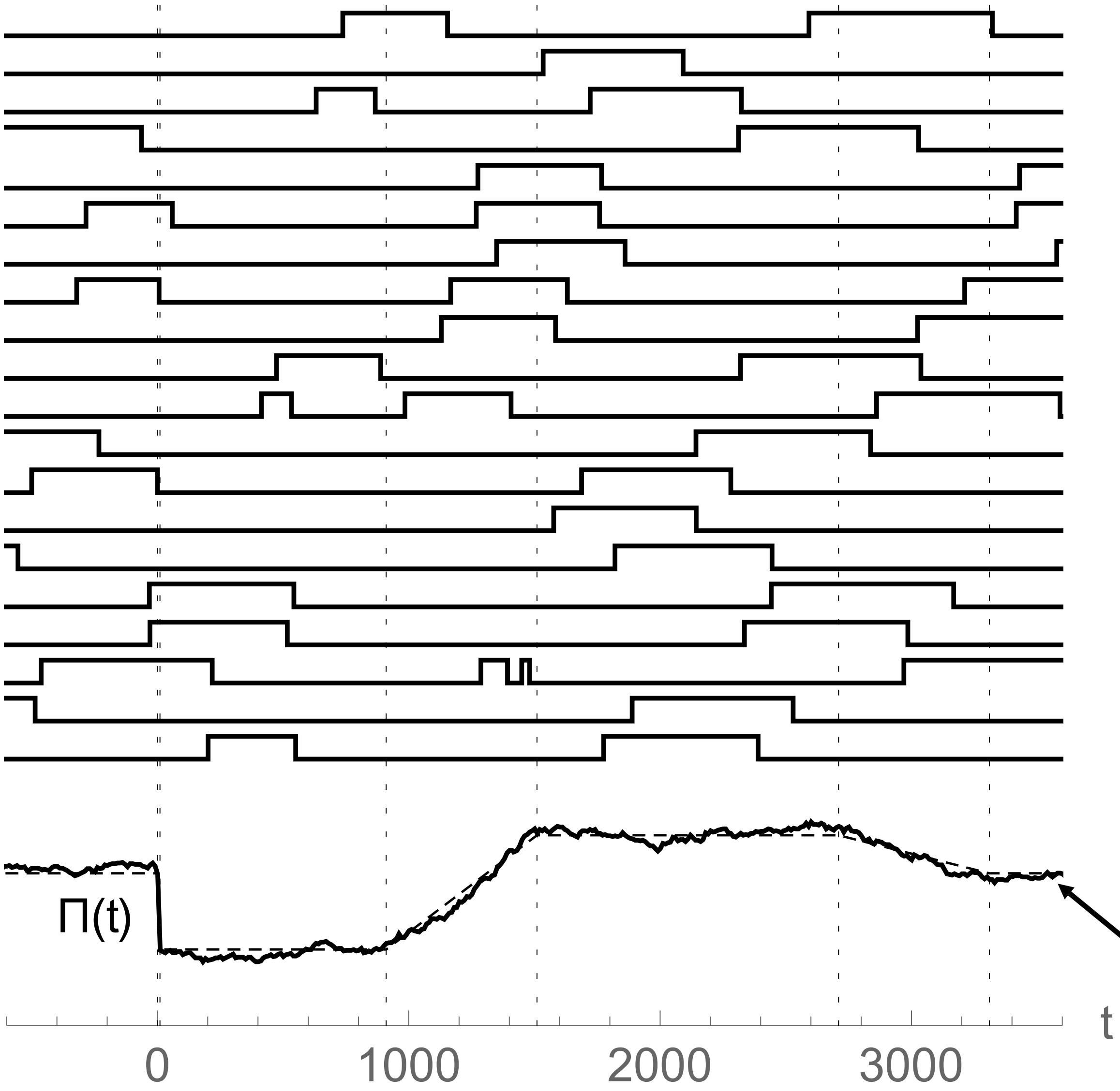
steady state power consumption of appliance *a*



$$P^{total} = \sum_a P^a(t) = P_0^{total} \times \Pi(t) + \mathcal{O}(N^{-1/2})$$

Simon Tindemans, Vincenzo Trovato, Goran Strbac, “Decentralised control of thermostatic loads for flexible demand response.”, *IEEE Transactions on Control Systems Technology*, (2015)

Aggregate convergent response



Collectively, **fridges track the reference signal $\Pi(t)$** – even when each appliance is different!

N=1000 domestic refrigerators

Controller implementation

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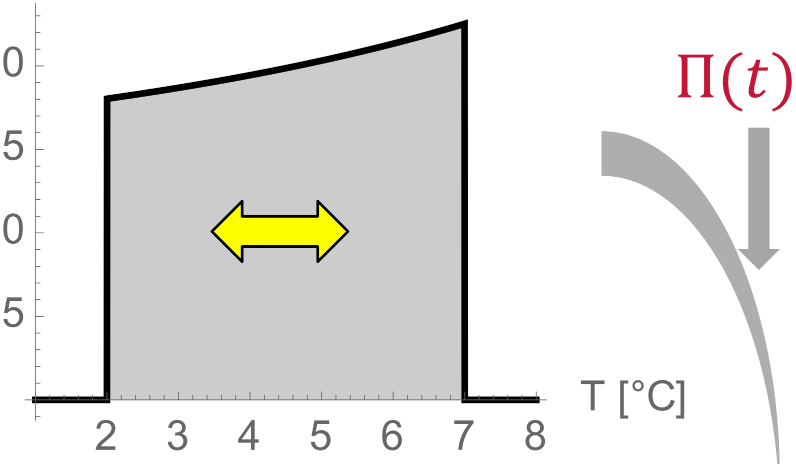
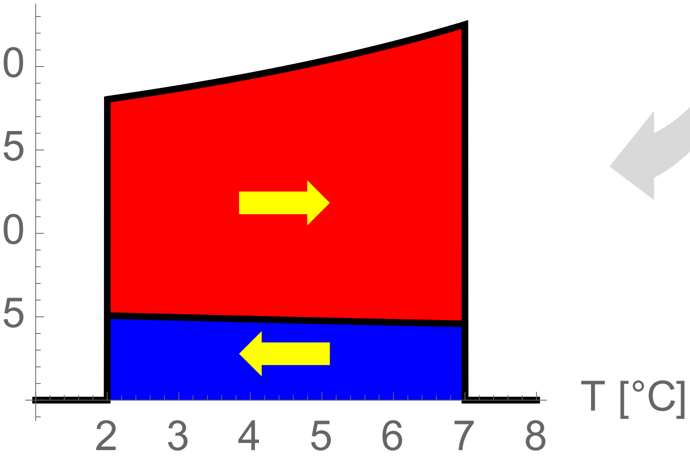
1. Each appliance knows its **state** and **model**

$$\frac{dT(t)}{dt}=\begin{cases}-\alpha(T(t)-T_{on}) & \text{(on)}\\ -\alpha(T(t)-T_{ambient}) & \text{(off)}\end{cases}$$

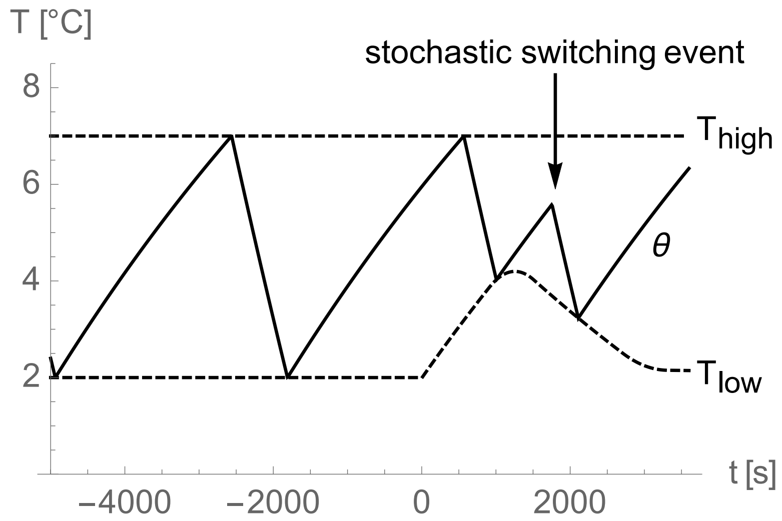
2. **Construct a *homogeneous* 'virtual population'** with random temperatures.



3. **Manipulate the 'virtual population'** to control its (virtual) power consumption in line with $\Pi(t)$.



4. **Determine device-specific actions,** based on the actual device temperature



Controller implementation

1. Each appliance knows its **state** and **model**

2. **Construct a *homogeneous* ’virtual population’** with random temperatures.

Each appliance considers itself as a random representative of a population...

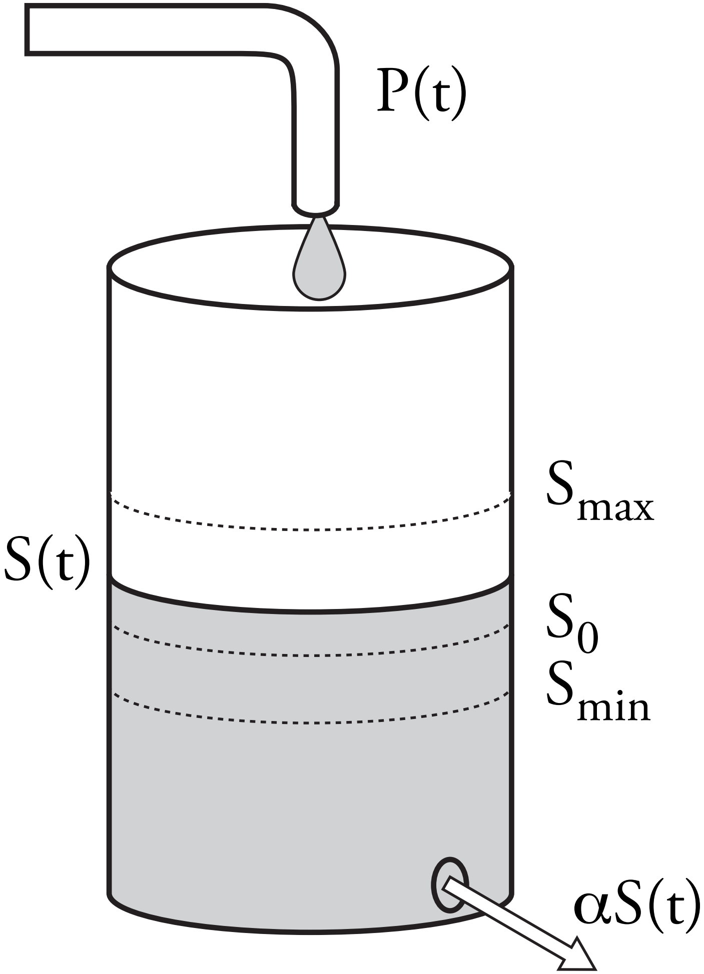
4. **Determine device-specific actions,** based on the actual device temperature

3. **Manipulate the ‘virtual population’** to control its (virtual) power

...and takes actions in line with population objectives

The leaky storage unit

Six-parameter model to describe the flexibility of a homogeneous population



$$\frac{dS(t)}{dt} = P(t) - \alpha S(t)$$

with constraints:

$$P_{min} \leq P(t) \leq P_{max}$$

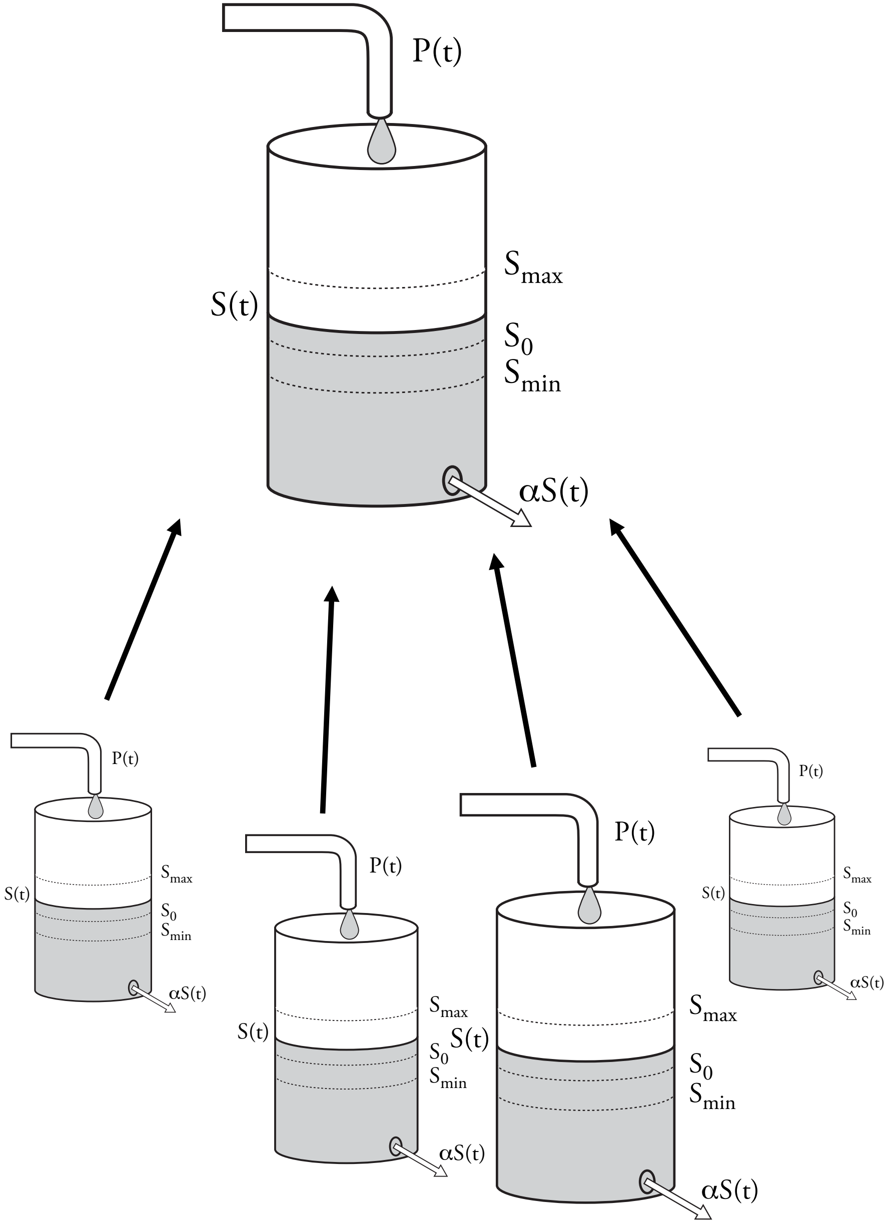
$$S_{min} \leq S(t) \leq S_{max}$$

preserve the food! →

$$\int_0^T S(t)dt = S_0$$

Vincenzo Trovato, Simon H. Tindemans, Goran Strbac, *"The Leaky Storage Model for optimal multi-service allocation of thermostatic loads. "*, IET Generation, Transmission & Distribution (2016)

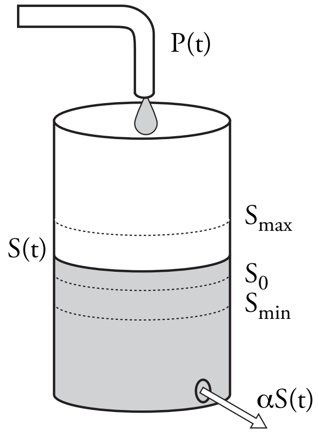
Aggregation of leaky storage units

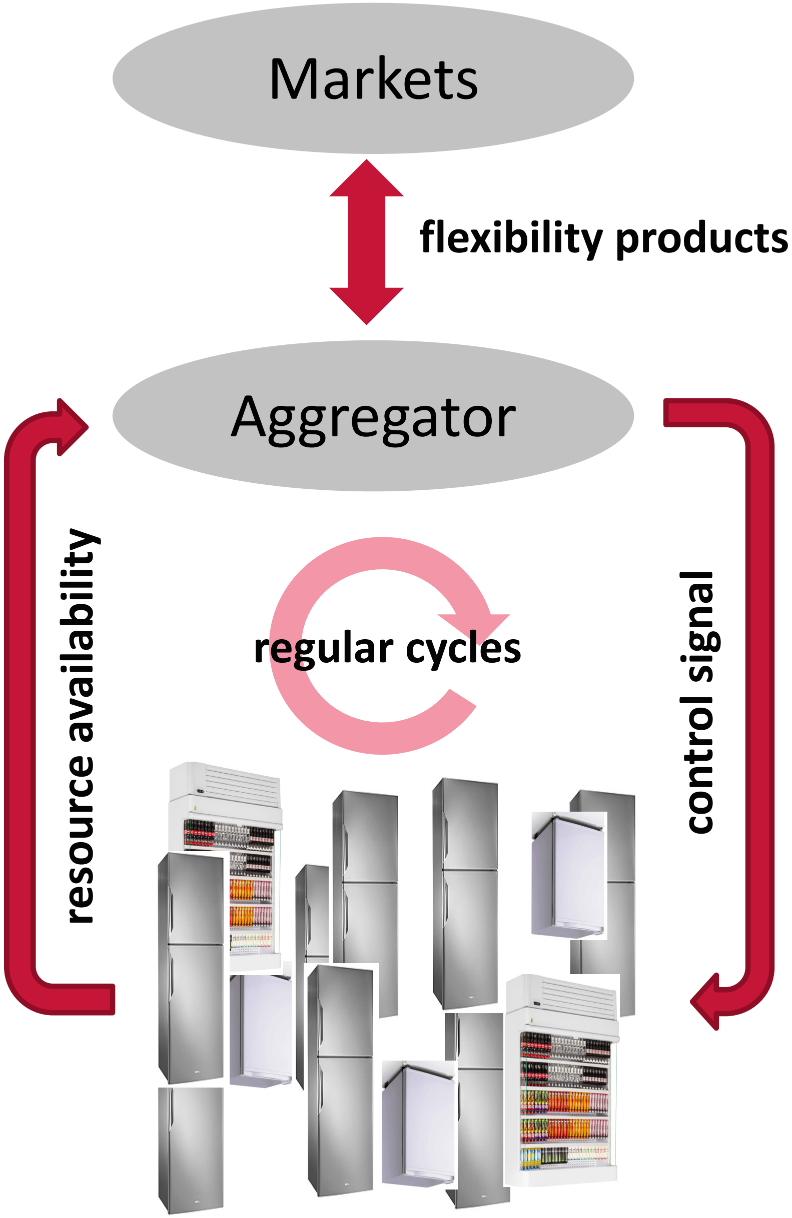


Heterogeneous models are merged into a conservative **envelope flexibility model**.

The model is **sufficient and linear**, for easy embedding in dispatch models.

Model of collective flexibility





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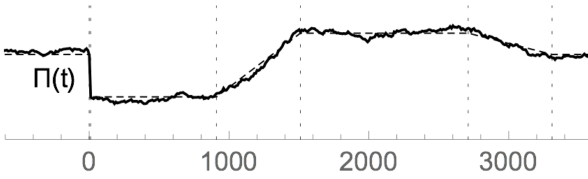
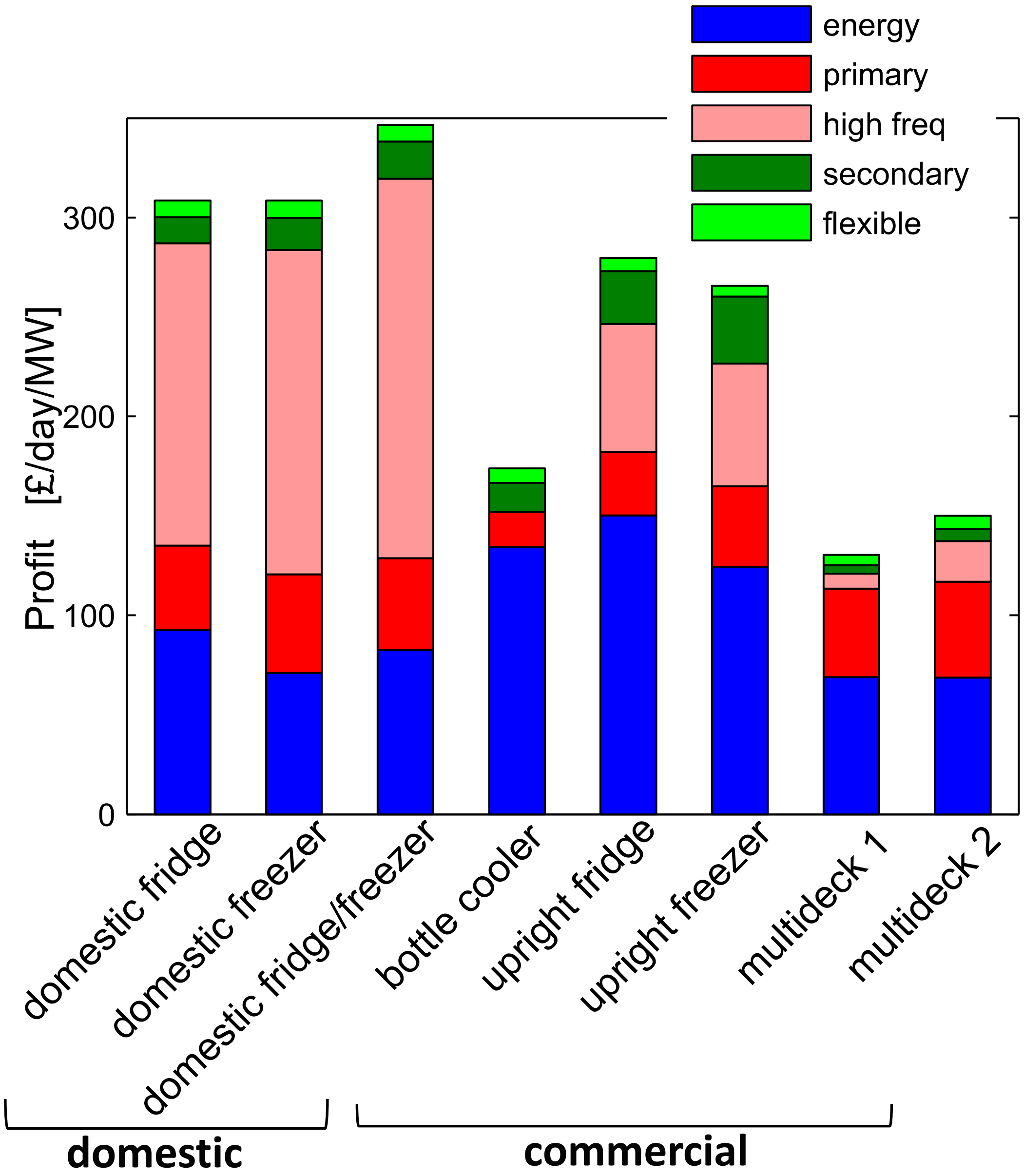
Aggregate load dispatch



Case study:
Optimal use of different device classes

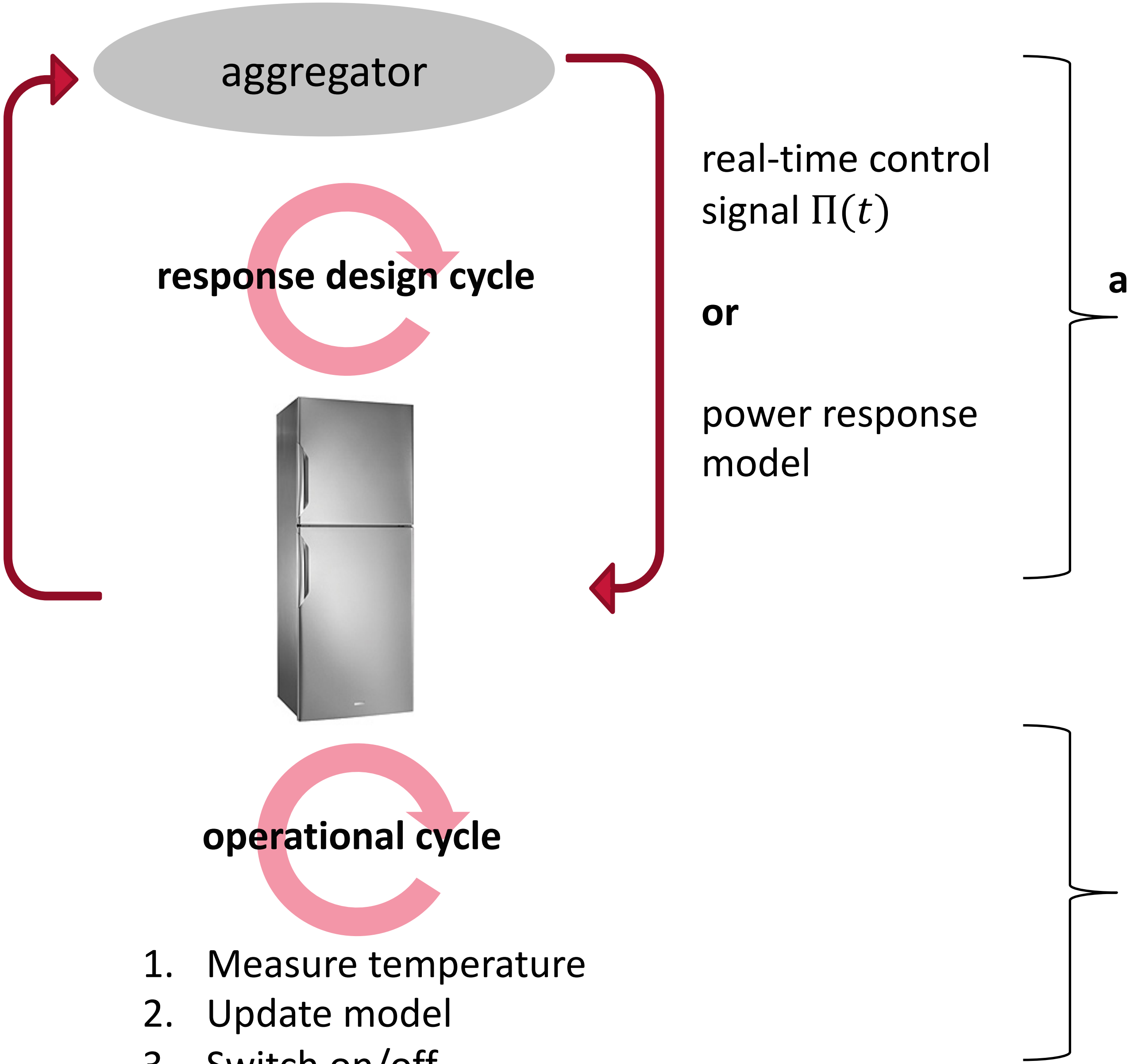


Service allocations reflect physical characteristics:

- Slow thermal time constants are good for energy arbitrage
- Low duty cycles in domestic appliances leave headroom for high frequency response.

Communication requirements

Robust ‘semi-autonomous’ operation



Significant changes in:
- thermal model
- constraints

aggregator

real-time control signal $\Pi(t)$

or

power response model

response design cycle

ahead of time

operational cycle

1. Measure temperature
2. Update model
3. Switch on/off

real time

Summary and outlook

We have developed an end-to-end control scheme for TCLs that is

- **Nondisruptive**: fridges respect local constraints at all times and are free to respond to individual cooling requirements
- **Decentralised**: (semi-)autonomous operation does not require real-time command and control infrastructure
- **Accurate:** accurate control over aggregate power consumption, despite on/off character of fridges and population heterogeneity

Open questions and further development

- **Robustness:** How sensitive is this scheme to model misspecification?
- **The limit of large but not infinite numbers**: mean field feedback effects
- **Local knowledge:** How much does an appliance need to know about the (sub-)population?
- **Wider applicability** to other appliances.
- **Practical demonstration**

Want to know more?

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- **Decentralised control of thermostatic loads for flexible demand response.**
  Simon Tindemans, Vincenzo Trovato, Goran Strbac
  IEEE Transactions on Control Systems Technology (2015)
- **The Leaky Storage Model for optimal multi-service allocation of thermostatic loads.**
  Vincenzo Trovato, Simon Tindemans, Goran Strbac
  IET Generation, Transmission & Distribution (2016)
- **A Stochastic Approach to “Dynamic-Demand” Refrigerator Control.**
  David Angeli, Panagiotis-Aristidis Kountouriotis
  IEEE Transactions on Control Systems Technology, 20(3), pp.581–592.
- **Distributed Control of Micro-Storage Devices With Mean Field Games.**
  Antonio De Paola, David Angeli, Goran Strbac
  IEEE Transactions on Smart Grid, (2016).
- **Nondisruptive decentralized control of thermal loads with second order thermal models**
  Simon Tindemans, Goran Strbac
  2016 *IEEE PES General Meeting, Boston.*