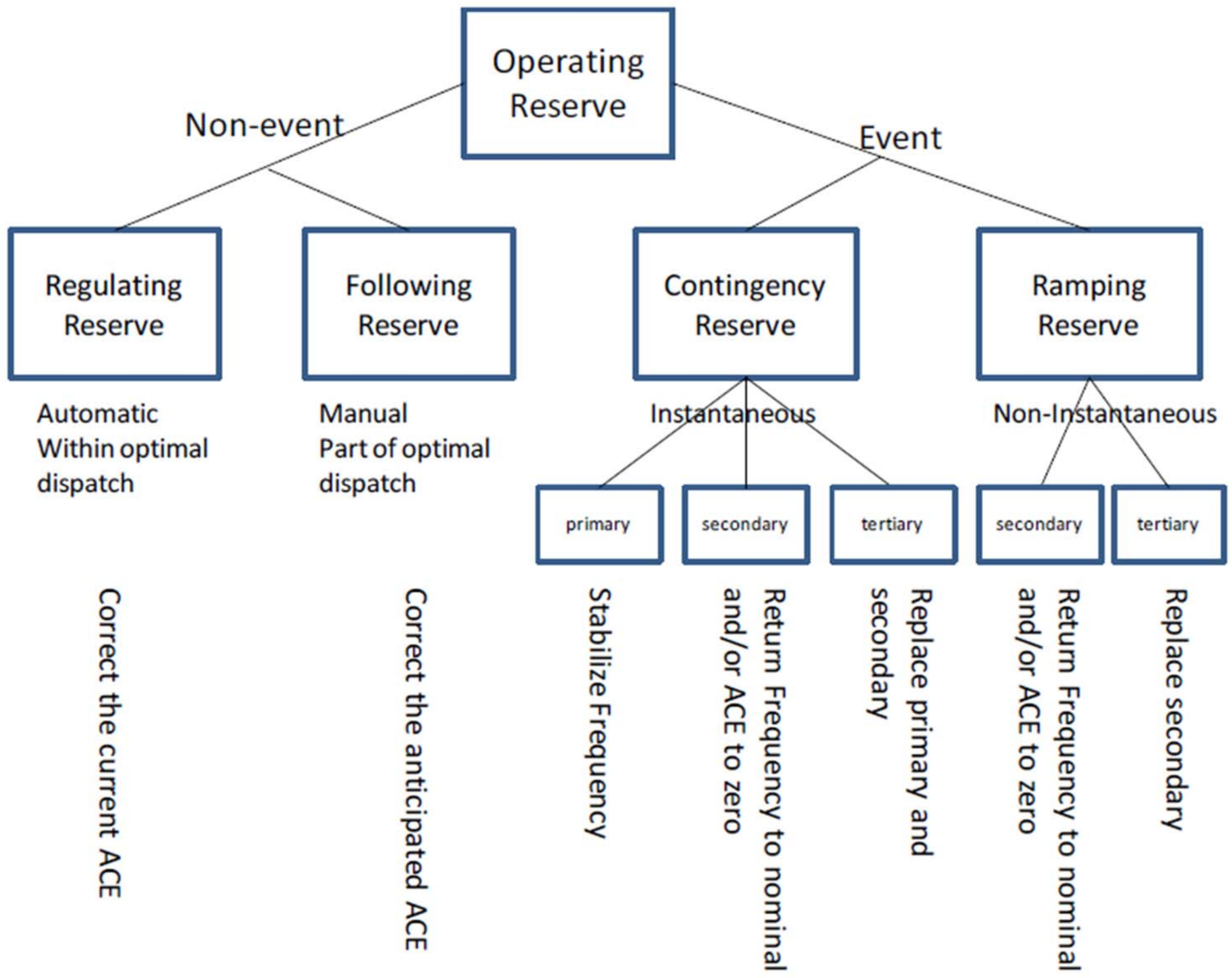
Institute for Energy Engineering (IIE-UPV) &
Universidad Politécnica de Cartagena

Demand Modelling for Ancillary Services

Finland, May 2014

- **State of the Art: Demand-Side in Ancillary Services**

- **Objective: to develop tools for increasing Demand participation in Ancillary Services:**
  - Figure source: NREL (USA), report NREL/TP-5500-51978

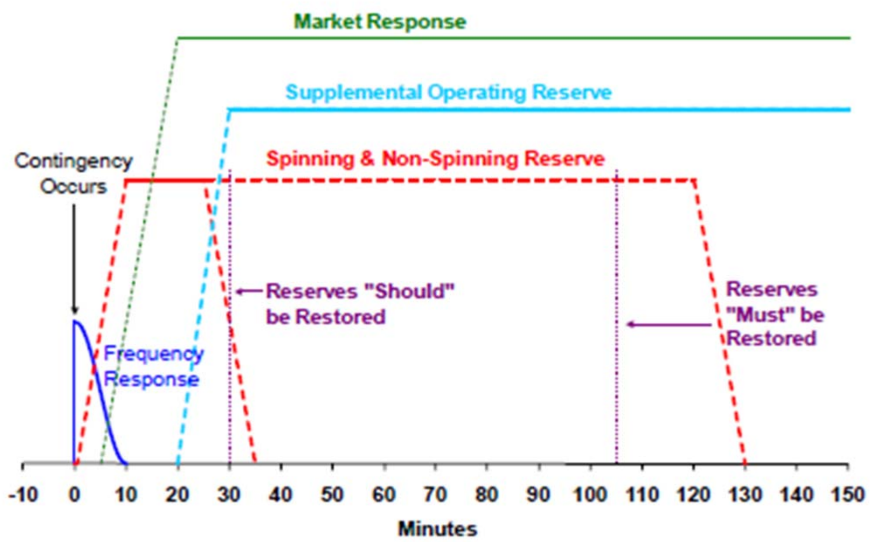


Objective: Reserve deployment

- Figure source: NREL (USA), report NREL/TP-5500-51978

Time for simulation of load response

Response time and duration



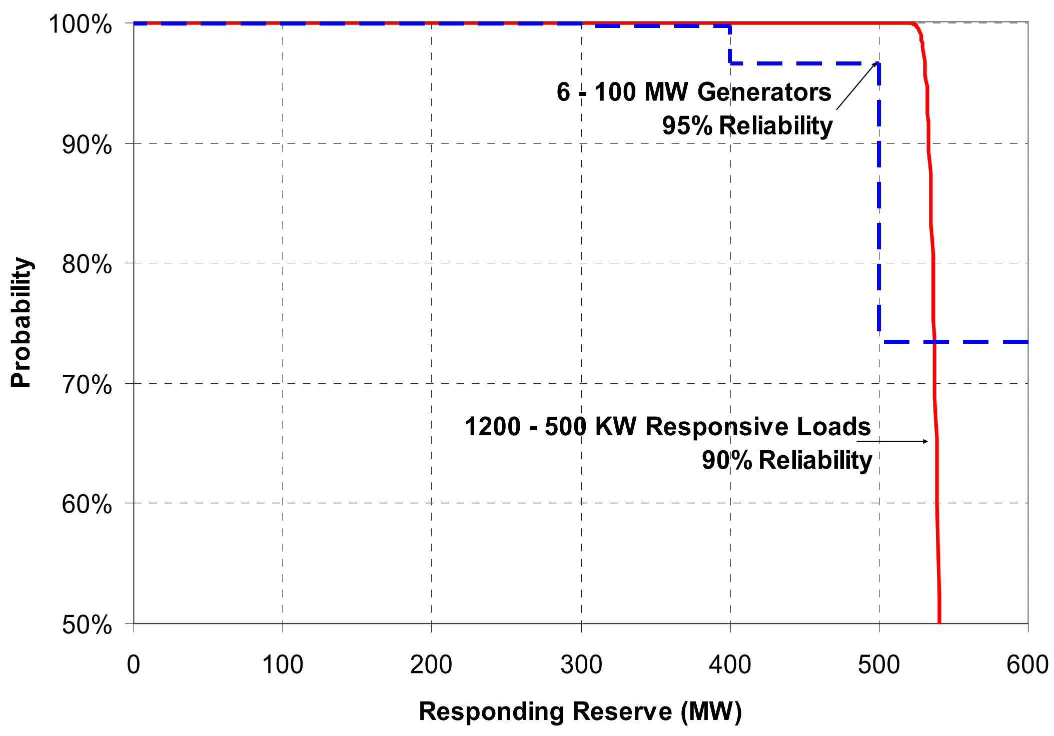
Time (min)

Customer revenues

- **Barriers:**
  - Legislative: e.g. services only opened to generators
  - Monitoring: e.g. sampling rates (4 s)
  - Aggregation: minimum size (MW) or unable
  - Complexity of response: 10000 customer eq. 1 generator
  - Verification of response: customer baselines/non-intrusive monitoring
    - Figure source: Adapted from Mac Donald et al. , LBLN report 5958E

ISO/ RTO	Min Size (MW)	Rules of Regulation Services			Rules of Spinning Reserves	
		Aggregation	Symmetric Bid?	Energy period	**Aggregation**	Energy Period
CAISO	0.5	No	No	60 min	No	30 min
ERCOT	0.1	No	No	NA	No	NA
MISO	1	No	Yes	60 min	**Yes**	60 min
PJM	0.1	**Yes**	Yes	NA	**Yes**	NA
NYISO	1	No	Yes	NA	No	60 min
ISO-NE	NA	NA	NA	NA	**Yes**	NA

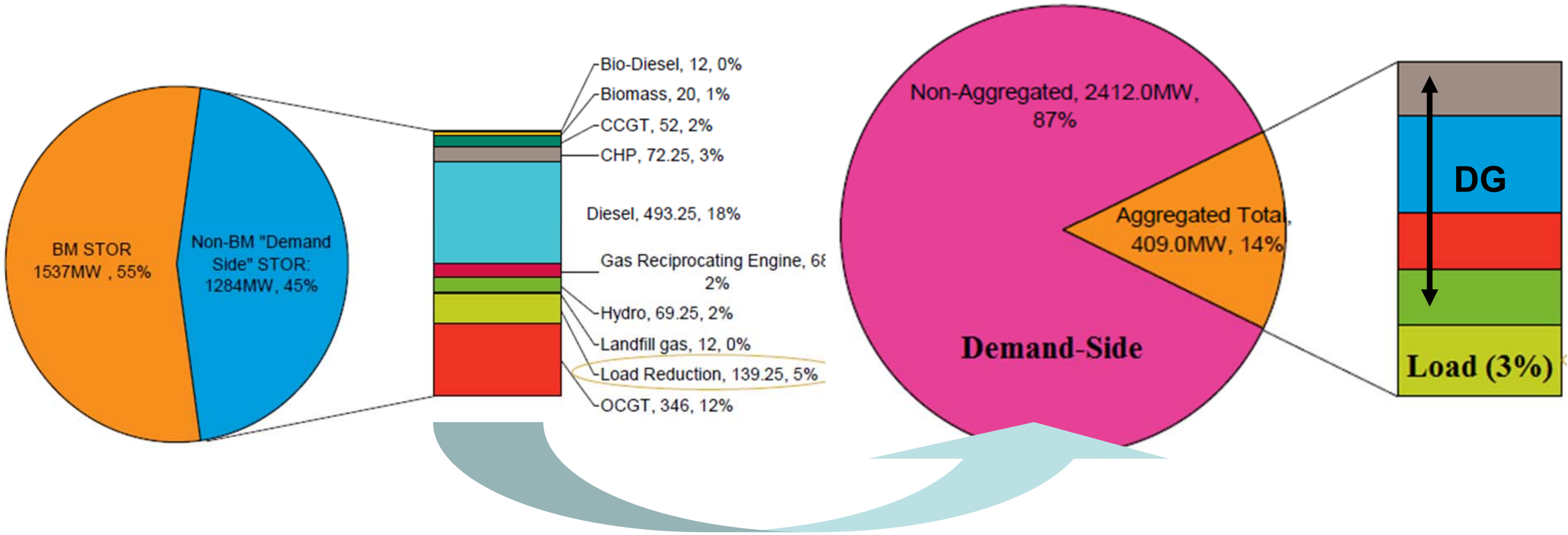
- **Benefits**
  - Availability of demand-side (1200 loads) vs supply-side (6 generators)
    - Load is reliable enough (even more that generators)
    - Load is a geographically distributed resource (“conventional” generation is not)
      - Figure source: Oak Ridge National Laboratory (USA)



- → Aggregation is needed (rules and procedures)

- **Catalizers:**
  - USA:
    - FERC Orders 719 (governs RTO & ISO allowing DR to participate in AS) and 745 (DR € compensation in markets)
      - DR and Supply can provide AS on an equal foot
    - DoE&FERC, National Action Plan (R&D):
      - "Develop or enhance DR estimation tools an methods"
      - "Incorporating DR in dispatch, AS and Resource Planning"
  - European Union/European countries of OCDE
    - Energy Efficiency Directive (2012/27/EU): art 15.8 enables the participation of DR in balancing and ancillary services.
    - EU Commission Staff Working Doc (11/2013): it is necessary making DR participation fairly in comparison with supply
    - Council of European Energy Regulators (CEER)
    - Agency for the Cooperation of Energy Regulators (ACER)
    - Eurelectrics (electricity industry)
    - …

- **Some example in the EU: The Short Term Operating Reserve (STOR) in UK**
  - UK is very active on DR
  - Aggregation providers have been experiencing a growing trend (16 in 2013).
    - Note: more than 60 aggregators play in PJM, 34 in NYISO (USA).
  - The problems:
    - Supply-Side wins in balancing markets
    - In the Demand-Side, the majority of resource is generation yet
      - Figure source: J. Torriti (Florence School of Regulation, 2013)
  - Conclusion: DR potential in AS services need to be explored



- **IIE-UPV & ETSII-UPCT proposal for demand models for AS services**

Our proposal (I)

- **Focussed on small/medium customers segments**
  - As mentioned, they are unexplored, except for some pilot tests (PGE, 2009)

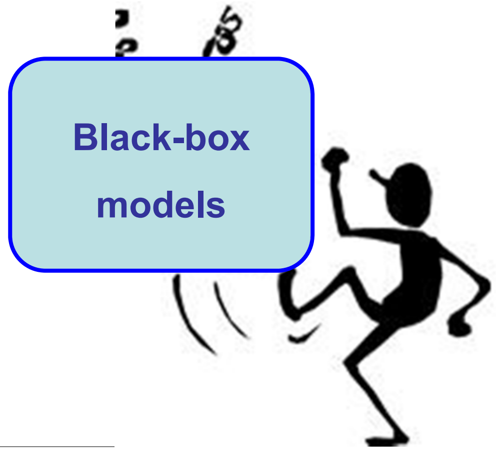
- **Properties of the Methodology:**
  - The model is “universal”, i.e. the same philosophy for all the possibilities of DR: Price, Events, Capacity and AS!
    - The same database for the parameters of the model
    - A similar “architecture”: elemental models & aggregation

Our proposal (I)

- **Properties of the Methodology:**
  - Robustness of the specific model for AS
    - The parameters are easy to be evaluated and do not change during different time periods (day, week, season,..)
  - **An example** of available models in the literature: Demand as Frequency Controlled Reserve (DFR),Denmark (2008) & **IEEE**
    - The model (for electric&water heaters) has important failures. T is the indoor temperature; P the power; w (0,1) the control mechanism

$$C\frac{dT}{dt} + G(T - T_a) + P_{disturbance} = w * P$$

    - Where is the solar radiation? Where are the internal (heat) gains?
    - In these models C and G can change because important physical phenomena are ignored… so they are not robust models.



Our proposal (I)

- **Properties of the Methodology (III):**
  - Fast response
  - "Easy" interpretation of the results

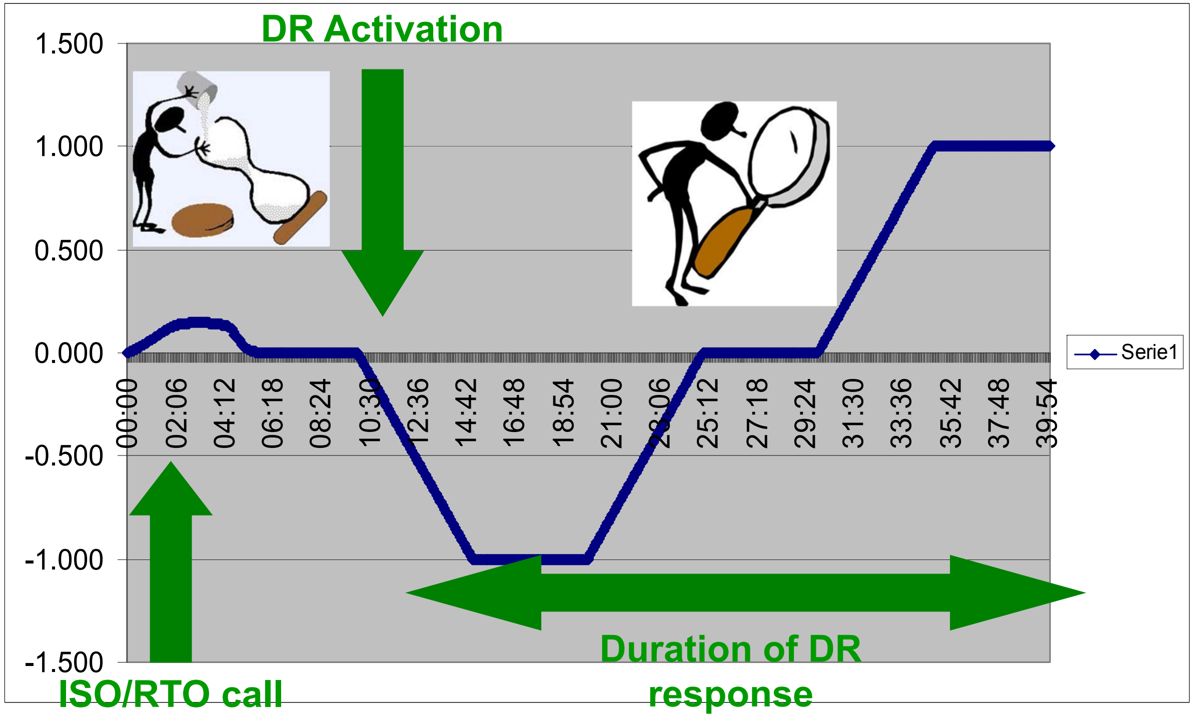
  - Aggregation is allowed
    - Elemental models
    - Monitoring (to analyze some "representative loads" only)
  - Possibility of feedback
    - Non intrusive load monitoring.
- **Our choice: PBLM (Physically-Based Load Modelling)**

Our proposal (II)

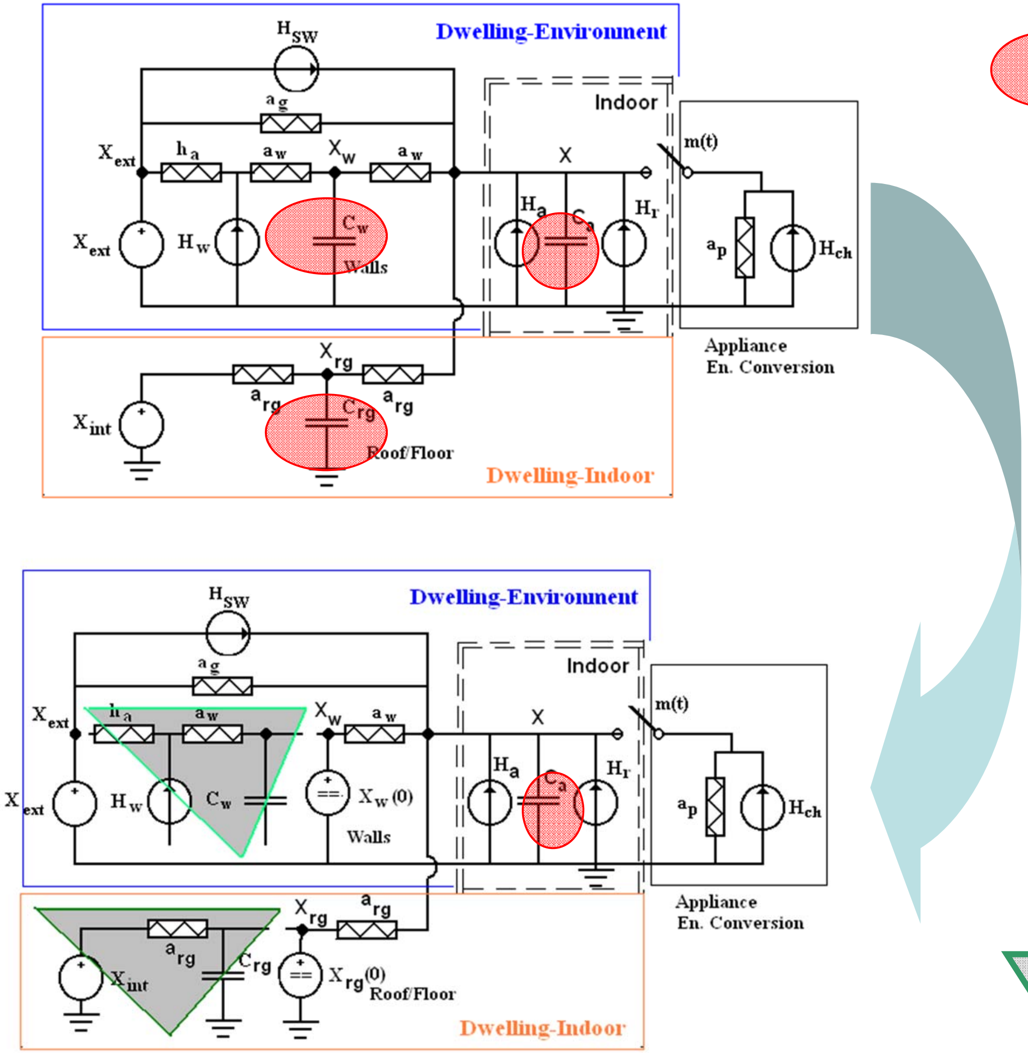
- **PBLM methodology (Schweppe and Ihara, 1981)**
  - Different approaches since 1981, but all have two phases:
    - First, we define an elemental model
    - Then, aggregate the elemental models.

Authors	Elemental model	Aggregation	Problems
Chong-Malhamé	First order	Stochastic (Fokker-Planck)	Parameters are simple enough
Callaway, 2009	First order. Thermal losses and gains	Stochastic (Fokker-Planck)	Solar radiation? Specific heat from other rooms? ► Parameters change!
Mathieu, Callaway, 2011	First order. Thermal losses and gains	Stochastic (Fokker-Planck)	Validation? AC annual demand KWh in California (size?)
Alvarez-Gabaldon 2004	Third order. Solar radiation, specific heat of roof, walls, floor	Monte Carlo/ Stochastic	Speed of response. Suitable for price DR, but not for AS.
A.G. Martins, 2013	Third order. Latent and sensible heat are considered	Monte Carlo	Speed of response. Suitable for price or event DR. Not for AS

- **In detail: ISO requirements for AS response**
  - Call by electronic media (e.g. eMarKeT in PJM)
  - Then, the activation of each resource in the very short term: seconds to minutes. The model must be fast enough
  - Finally: the resource must work during 10-60 min following a regulation signal (test signal: at the bottom). The model must be accurate enough during the time of response



- **First,** to increase the simulation speed: order reduction (from 3rd to 1st) and stochastic (Fokker-Planck) aggregation



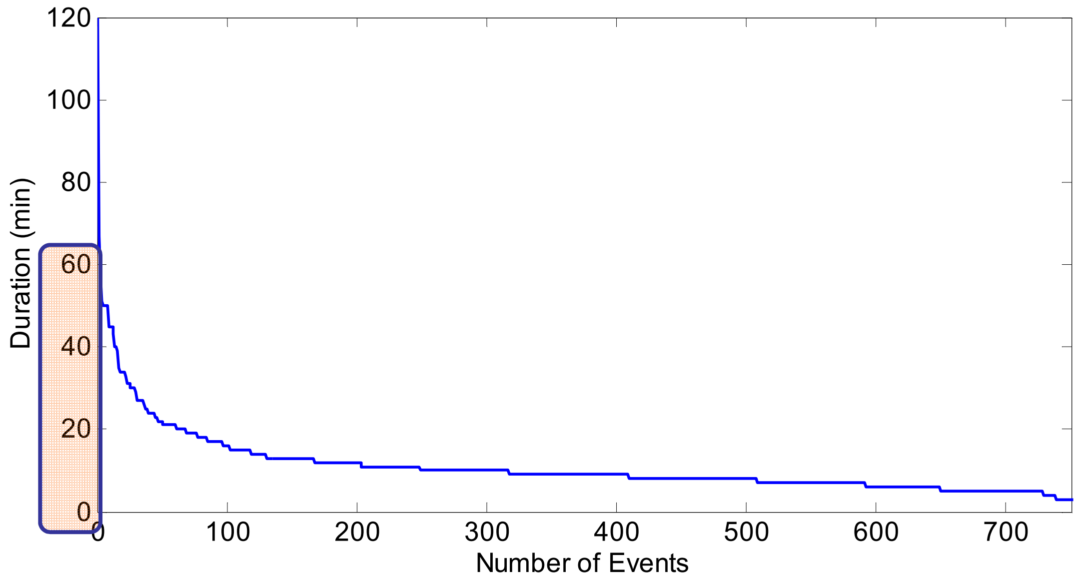
Specific heat: drives system order

Simplification: Inertia of walls, floor, roof… as a constant voltage heat source (the discharge is very low in short term, the necessary window for AS)

Remains: solar radiation, infiltrations…, and the main parameters of the model (the same can be used in DR for price and events)

Simplification: elements out of the model

- **Second: the duration of response (“model lifetime”)**
  - In PJM (USA) 98% of the events in synchronized reserve last <u>less than 40 minutes</u> and the average time per event is about <u>11 minutes.</u>
    - Figure source: PJM, Synchronized Reserve Markets (2002-12 data)



- **What is the basis for order reduction (i.e. ↑ speed)?**
  - Intuitively: the high inertia of roof, ground and walls
  - Mathematically: eigenvalues and eigenvectors
    - Eigenvalues: i.e. the inverse of time constants. Three different dynamics in the elemental system (fast response T1: 1-3h)
      - Data source: EU-DEEP project, www.eu_deep.

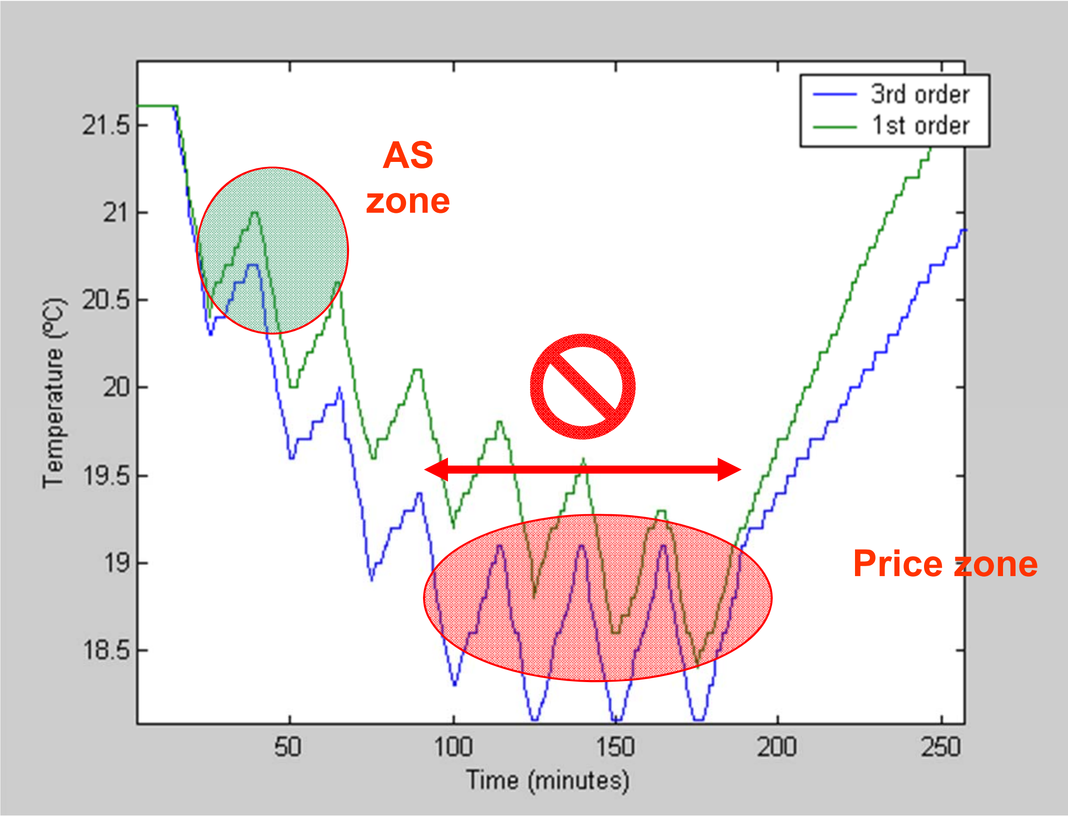
Average Load	T1 (hr)		T2 (hr)	T3 (hr)
Load 1	1,36		7,5	13,5
Load 2	0,95	AS	7,25	14,3
Load 3	1,15		8,9	12
Load 4	1,29		10,82	17,93

    - Eigenvector: the weight of each eigenvalue in the behaviour of the system (in our case X, the indoor temperature)

State variable	λ_{s1}	λ_{s2}	λ_{s3}
X_w	0.0486	0.9127	-0.6747
X_i	-0.9906	0.3237	0.4739
X_{cf}	0.1279	0.2494	0.5659

    - Conclusion: X is driven in short term (T1) by eigenvector λ1 (and the component of eigenvector associated to T1, 0.99 vs 0.32&0.47)

- **Simulation results fit quite well!**
  - First order model sums errors (period 1h-5h): due to the behavior (inertia) of “hard” heat capacities (they need to be considered for price DR or event DR): walls, roof, ceiling,…



- **Aggregation**
  - Drawing together a resource of interest for AS needs

- **Aggregation (duality with Load Power Flow):**
  - **OPTION A:** Accurate response: solve ~1000 elemental models (time!!! 2-3hr!!) (like an optimal power flow) and obtain the indoor temperature for each load: i.e. $X_i(t)$

$$\frac{dX_i(t)}{dt} = A_i X_i(t) + B_i(t) + H_{ch}(t) m_i(t) u(t); \quad i = 1,2,\ldots 1000$$

  - "Optimal power flow": a detailed calculus for each load (great precision but in medium term, with a hard simulation process)

- **Aggregation (duality with Load Power Flow):**
  - **OPTION B:** Solve one (several*) stochastic equation (s) that is (are) representative of the aggregation: less accuracy in results but higher computational speed (decoupled power flow)
    - (*) Thus, several aggregation segments are allowed. I.e. a similar load classification and clustering (source EU_DEEP)… for price DR!
    - We solve an "average" load, X(t) is the mean indoor temperature

$$\frac{d\overline{X}(t)}{dt} = \overline{A}\;\overline{X}\;(t) + \overline{B\;(t)} + \overline{H}_{ch}(t)\overline{m_{ch}}(t)u(t) + W(t)$$

    - W(t) is a Wiener process taking into account the increments on parameters of elemental models with respect to the average load being considered
    - "Decoupled power flow": losses precision but it is fast and appropriate for contingencies.

  - Computational time required: < 20 seconds/eq (hardware: HP xw8600 Work Station)

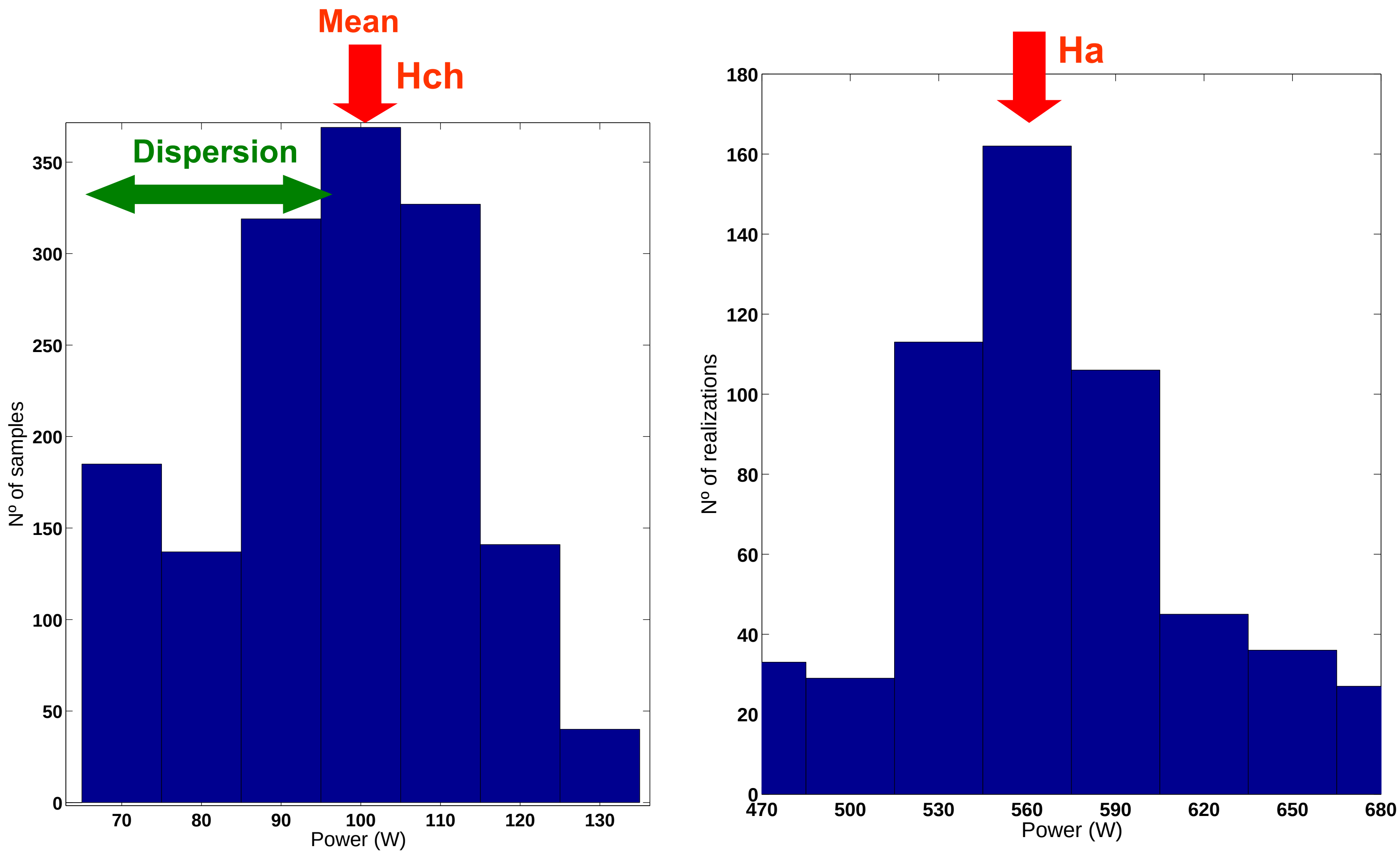
Example: Residential Load Aggregation (I)

- Elemental load: Heat Pumps, rated power 1kW
- Dwelling: 25 m^2
- Number of customers: 1000. Location: Murcia (Spain).
- Average load (aggregated): 750kW (75%)
  - Given 2h before by simulation of "third order" model and non-intrusive load monitoring in "selected" users (feedback)
- Band of regulation for DR: 750±250kW (Baseline ±Capability)
- Main Parameters: dwelling/environment/load
  - Room volume: 50m3; external walls 12.5 m2; glazed area 3 m2; internal wall 32.5 m2; Orientation: Southwest

Parameter (subinex)	Windows (g)	External Walls (w)	Indoor (a)	Ceiling and Floor (rf)
1/a ($W/(m^{2o}C)$)	5	1.35	2.25	1.99
C (kJ/ºC)	N.A.	2192	1358	12304
Ha (W)	-	-	200	-
H_{ch} (W)	-	.	1000 (COP 2.8)	-

Example: Residential Load Aggregation (II)

- In detail, the dispersion of two parameters: Ha (appliance power), Hch (internal load). Approximately normal distributions



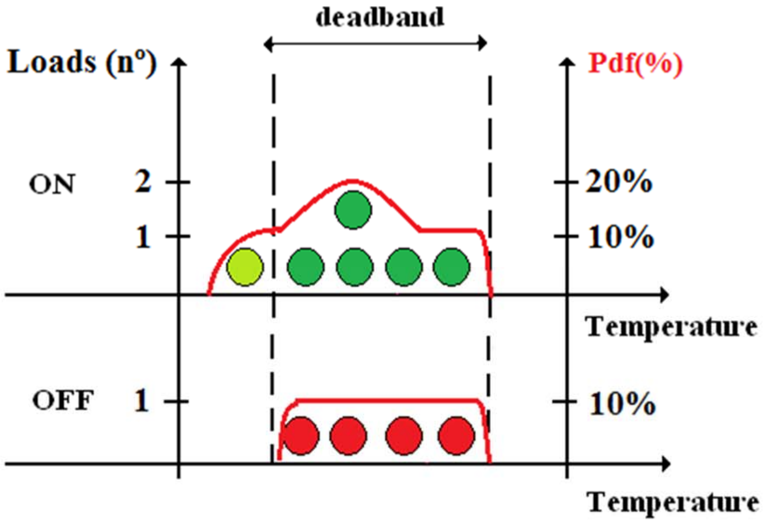
- **Fokker-Planck give probability density functions (Pdf) $f_k(X,t)$ for indoor temperature X(t)**
  - $f_k(X,t)$ for k=1 (ON) and k=0 (OFF) load states

$$f_k(x,t)dx = \Pr\left[x \le X(t) \le x + dx \bigcap m(t) = k\right]; k = 0,1$$

- **And allow to evaluate cumulative prob. functions $F_k(X,t)$**

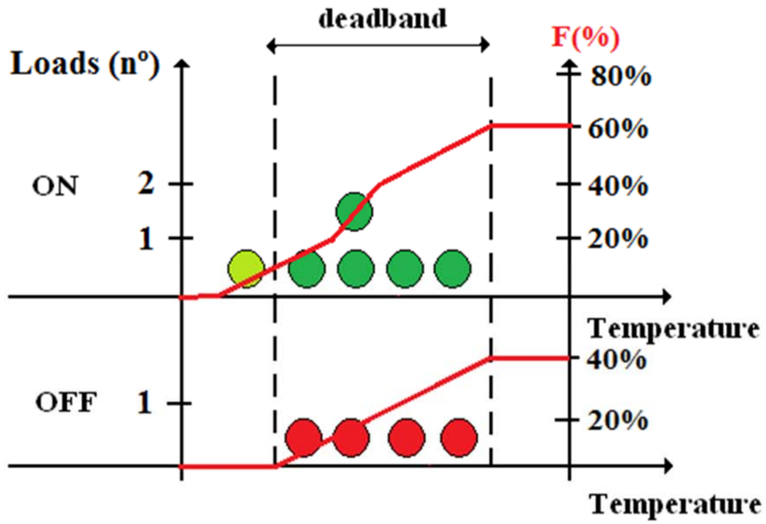
$$F_k(x,t) = \Pr\left[X(t) \le x \bigcap m(t) = k\right] = \int_{-\infty}^{x} f_k(\lambda,t)d\lambda; k = 0,1$$

$f_k(X,t)$



Where is the load?

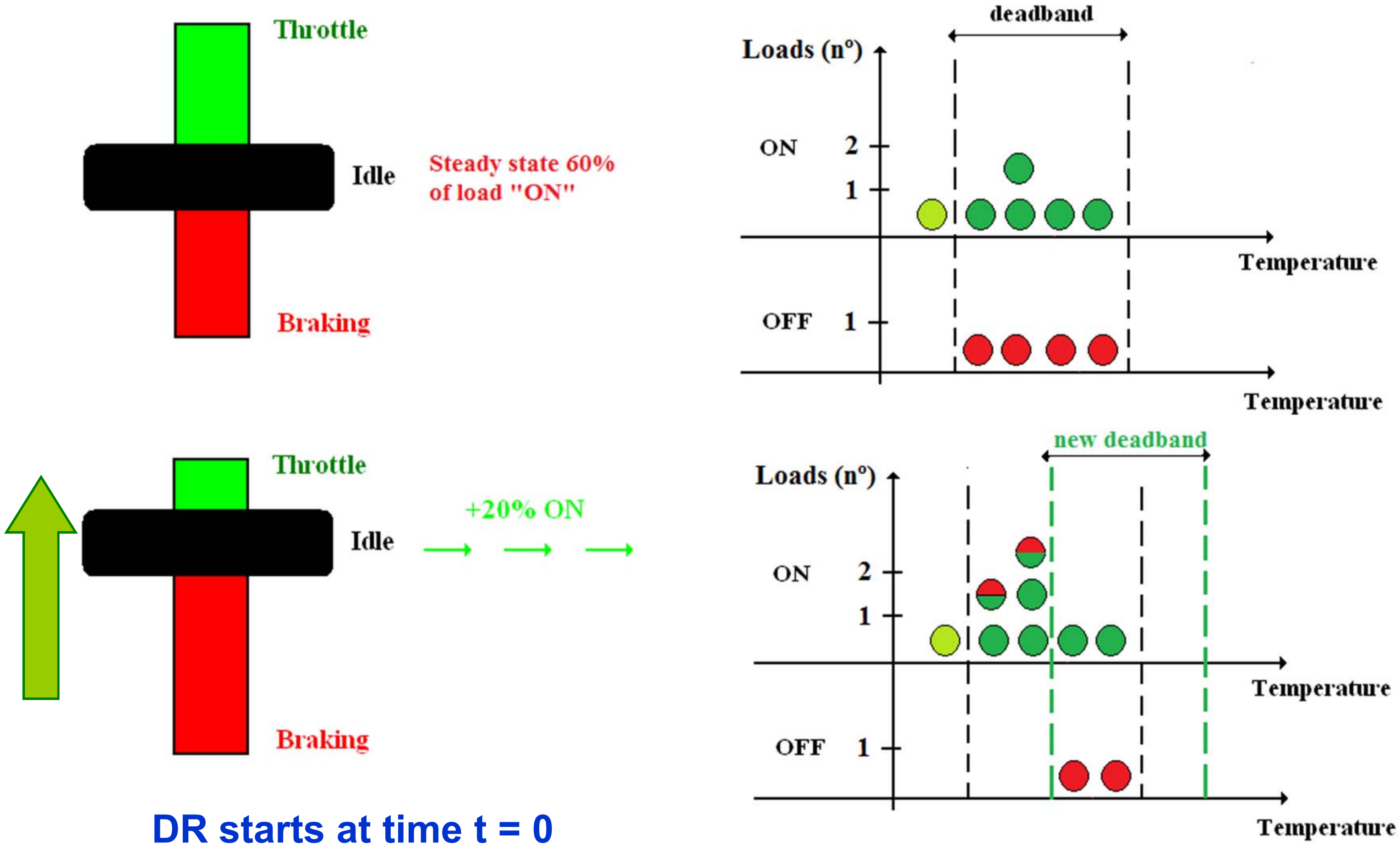
$F_k(X,t)$



How many loads under a temperature?

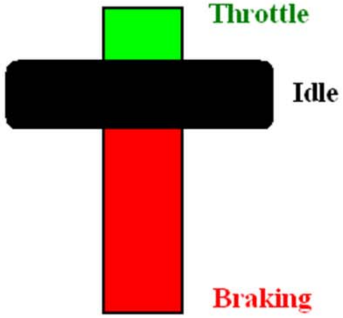
Our proposal (VII)

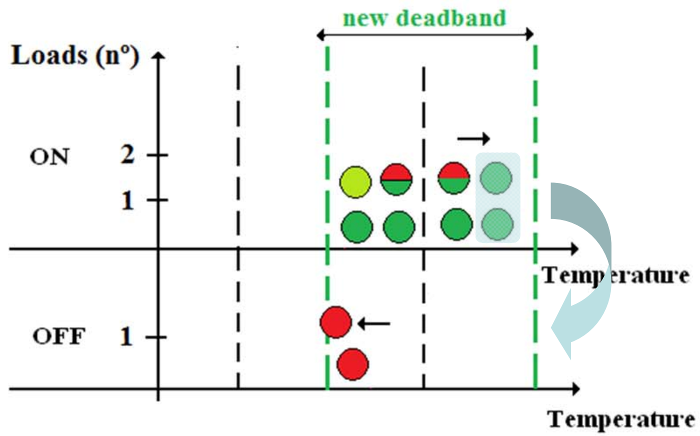
- **Idea: to tune the thermostat dead-band (up or down) to change the state of load demand (On ►Off / Off ► On)**
  - i.e. to correlate power vs. thermostat band temperature
- **If the aggregator needs a demand growth of 20% (60%→ 80%) a 20% of "OFF population" must change to ON**

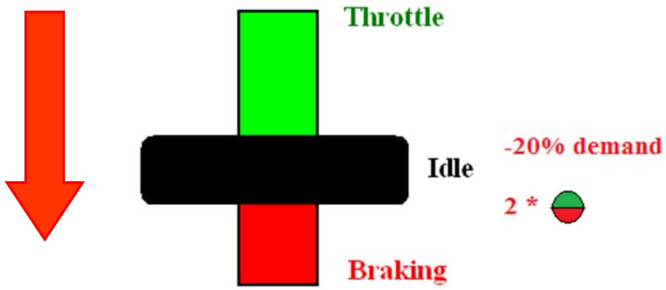


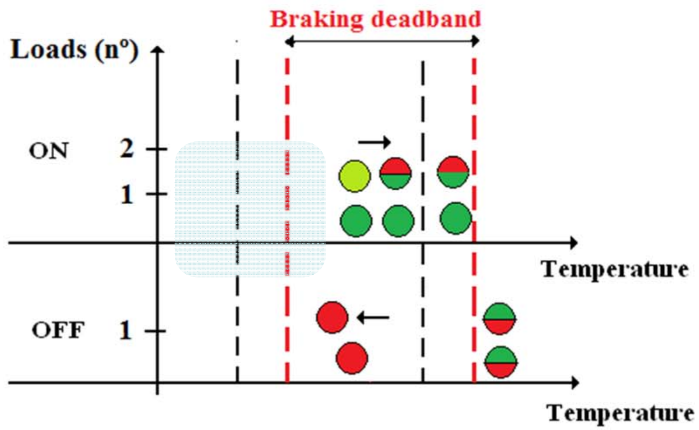
DR starts at time t = 0

- **10 minutes past, the aggregator needs to recover the initial demand,i.e. 60% (80%→ 60%), thus 20% of “ON population” must change to OFF**
  - A WRONG IDEA!: to get the original thermostat deadband
  - NOTE THAT: LOADS ARE NOW IN A **TRANSIENT STATE**!!!



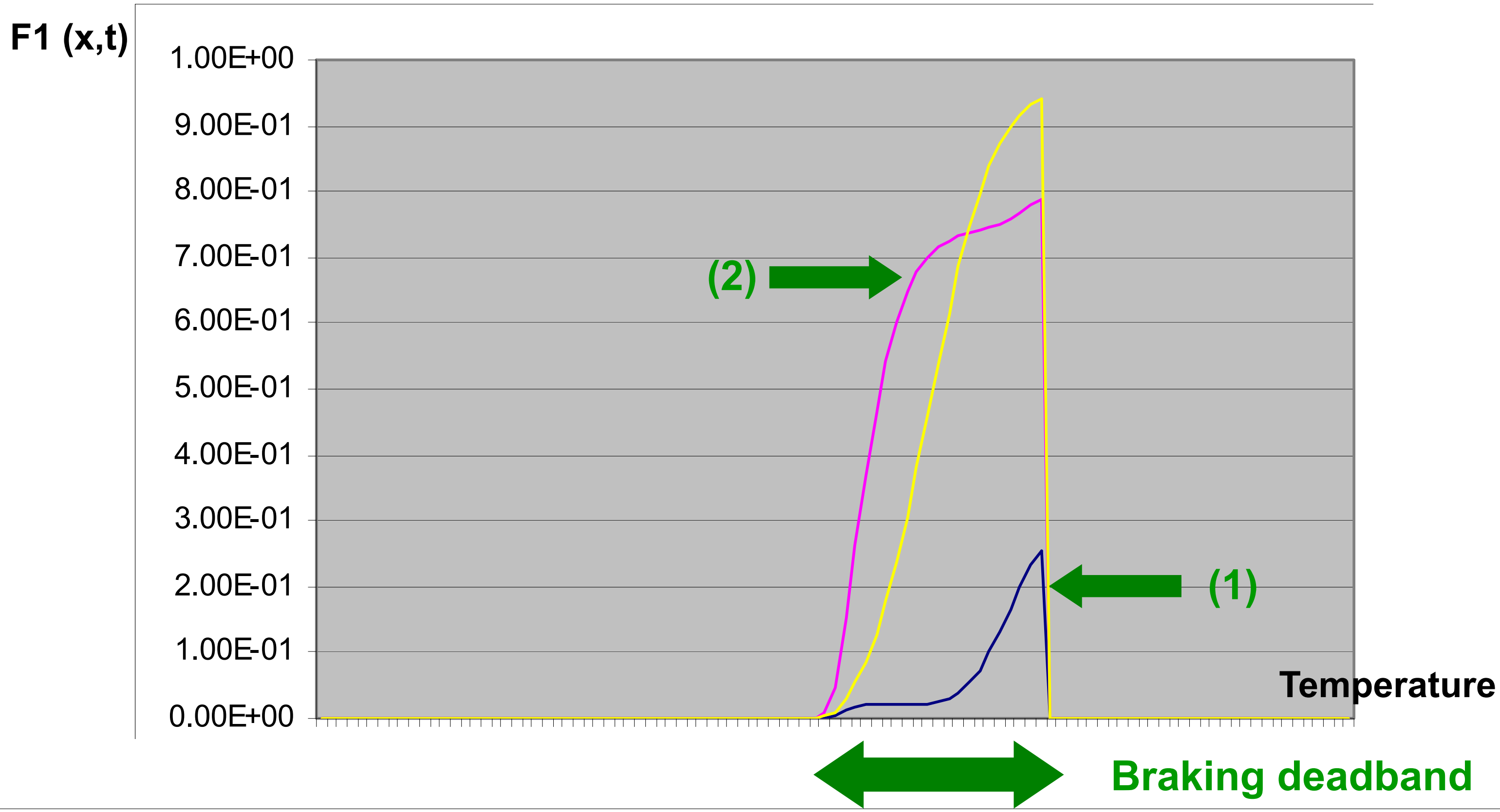






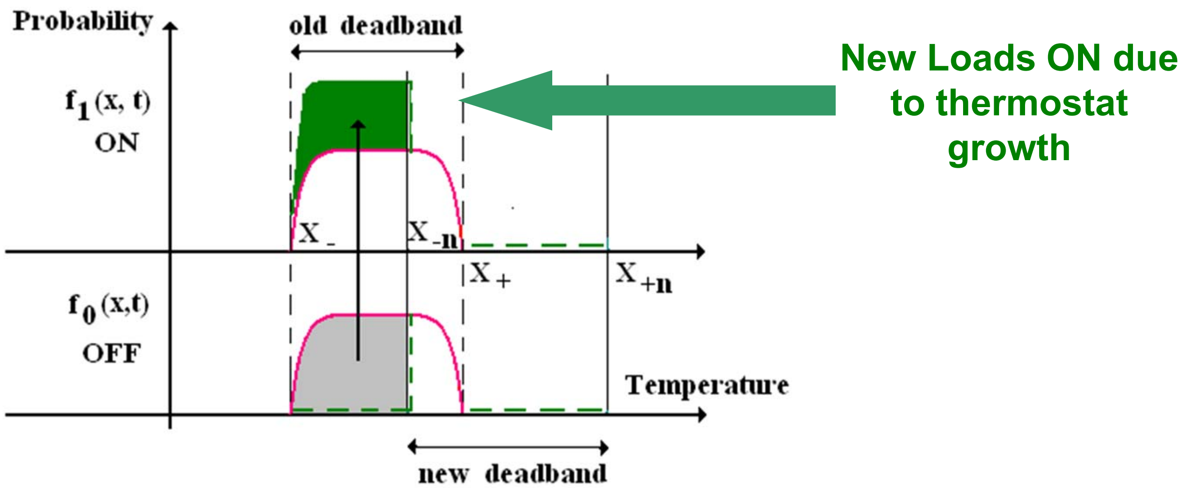
DR “brakes”, Time t = 10min

- **Example of transient response of prob functions**
  - F1(X,t), after braking, at
    - t=+5 (blue): (1) loads are in the upper zone of new "deadband"
    - t= +15 (magenta): (2) loads previously accumulated in OFF switch to ON, Load are near the bottom zone of new "deadband"
    - t=+25min (yellow): a time in apparent "steady state", i,e, the load is uniformly distributed in the deadband. VERY NICE!!!!



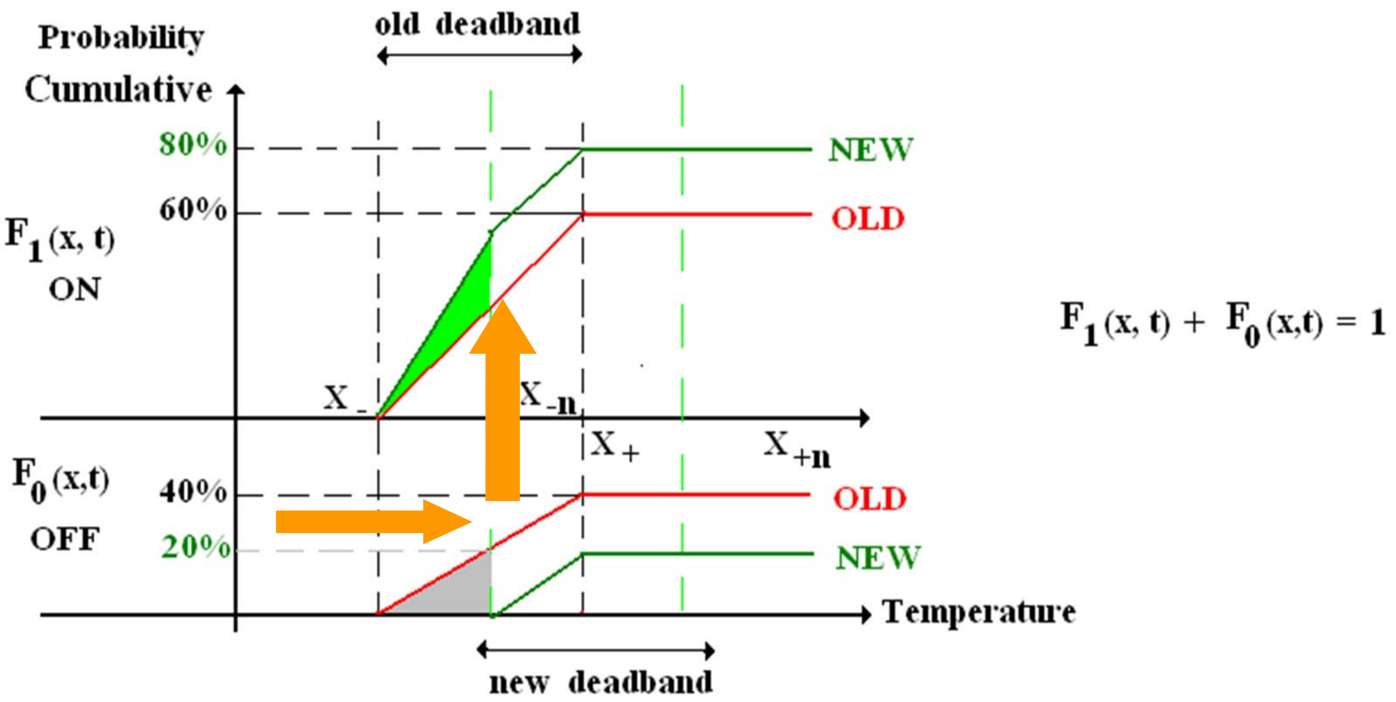
Our proposal (VIII)

- **Mathematically speaking: The task can be done by tuning the thermostat dead-band (up or down) according to the change of pdf functions induced (old Pdf, new Pdf),**
  - i.e. to correlate power vs. pdf temperature
  - When the thermostat is changing its values…



- **Problem (not critical from $): nowadays the thermostat hardware resolution is finite (0.1-0.5ºC). It has not been considered by Callaway in 2009 (according to paper by Perfumo, CSIRO-Australia, 2012)**

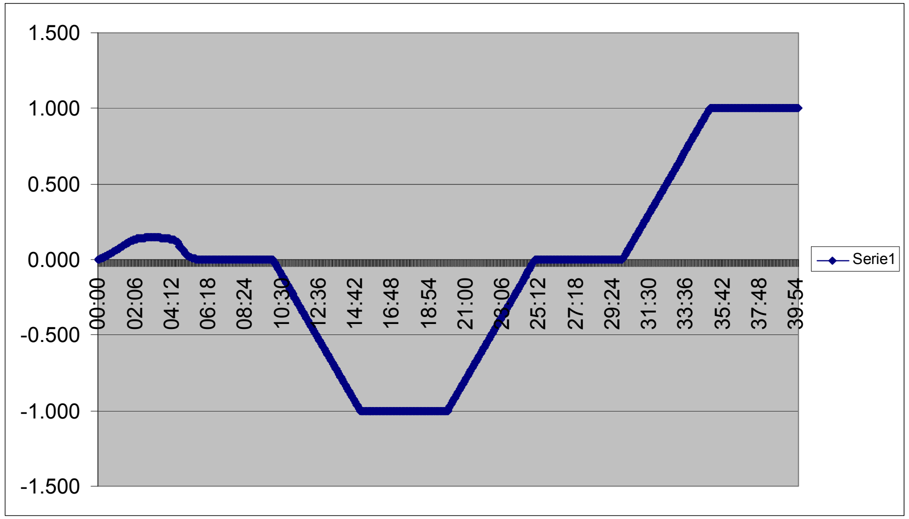
- **As seen before, in the practice it is usually better to work with cumulative probability functions F_1 and F_0**
  - E.g. 20% more of load “ON” is needed: the thermostat is tuned until deadband reaches 20% (OFF picture)



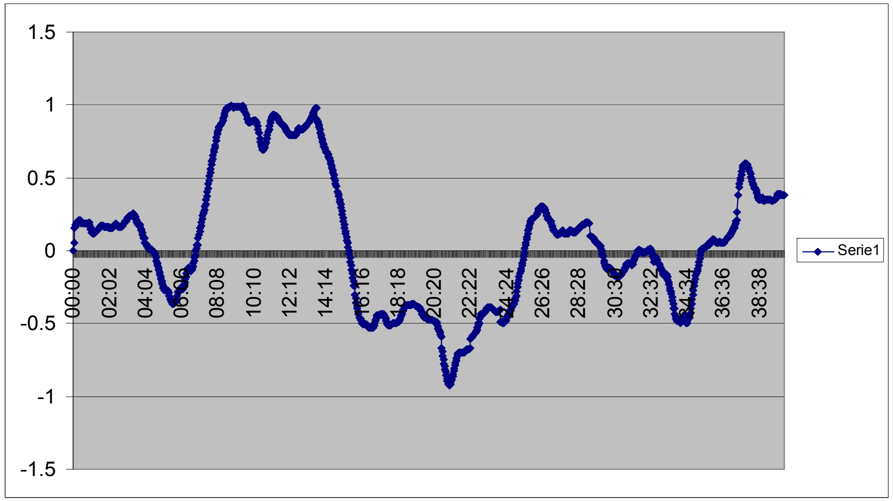
Probability (i.e. load) “flow” from OFF to ON

- **Test control (regulation) signals: e.g. PJM**
  - RegA test wave: traditional signal (40 min)

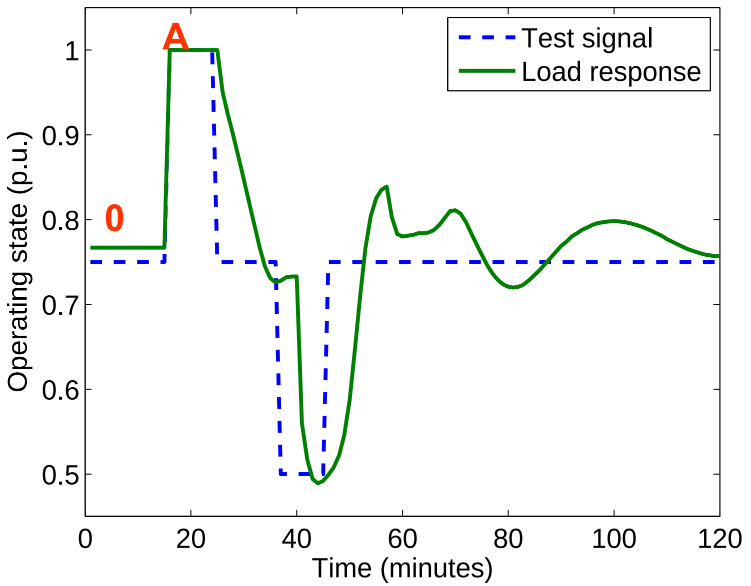
IIE-UPV Objective for 2014

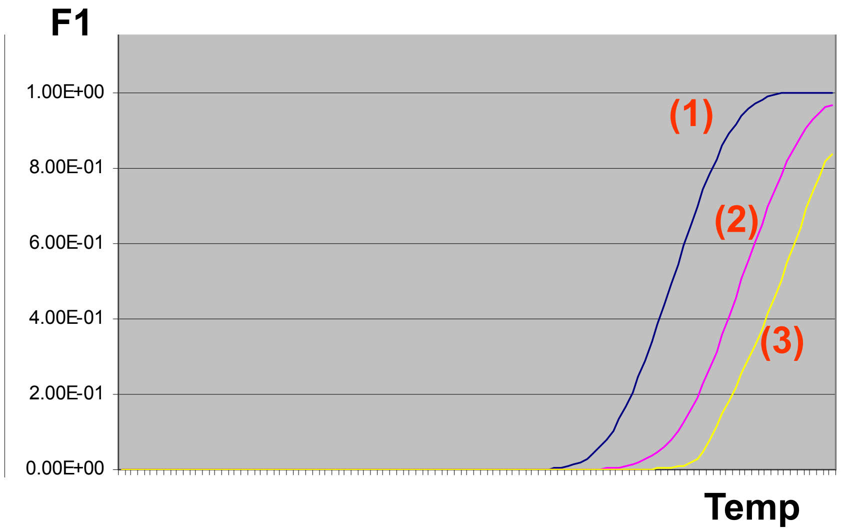


  - RegD test wave: dynamic signal (40 min)

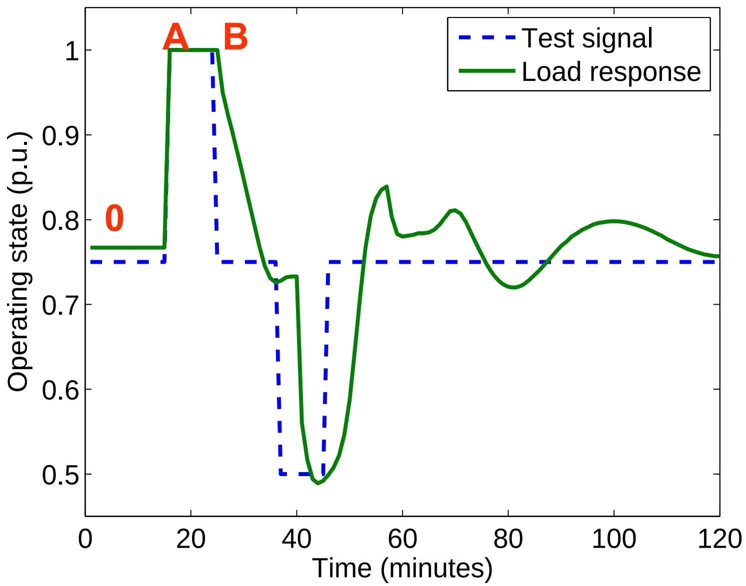


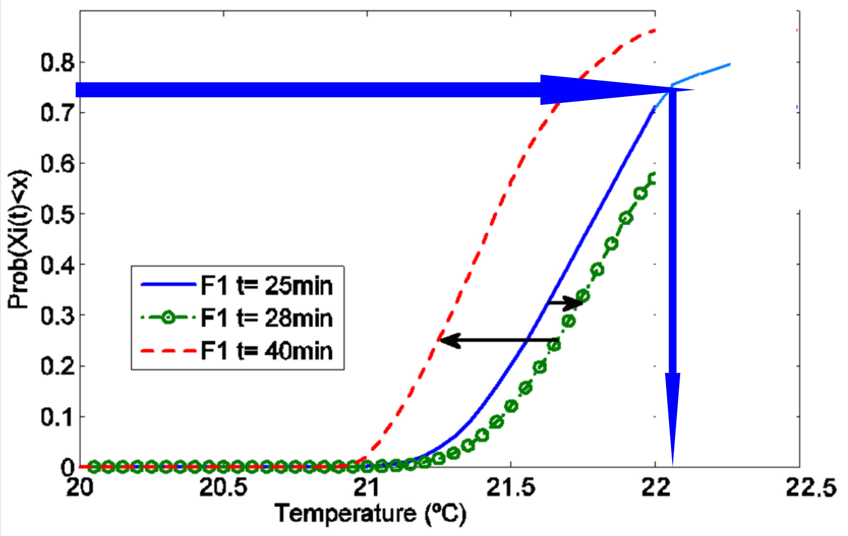
- **Example: control test signal (a pulse similar to RegA)**
  - First step in t=15min (A): we need all the load ON (“easy”: step up the thermostat, for example from 22ºC to 23.5ºC)
    - There is not a unique solution!!!→ fast simulation of various scenarios
    - (1): t + 5 minutes (100% ON)
    - (2): t + 15 minutes (96% ON)
    - (3): t + 25 minutes (85% ON)





- **Example: control test signal (a pulse similar to RegA)**
  - Second step in t=25min (B): recover the initial state (0.75 pu) How is it done?
    - 1) Simulate aggregated load from 15 to 40 min and analyze pdfs´
    - 2) Select pdf for **t≈25** min and take the desired value of aggregated power (0.75 pu). **Note that loads are in transient state**
      - Perhaps some minutes of delay can be necessary regarding pdfs
    - 3) Obtain the upper temperature of the dead-band: 22.2-22.3ºC





- **Test pattern for generator and ideal response (PJM, before 2013)**
  - This “explains” new Reg A trapezoidal signal

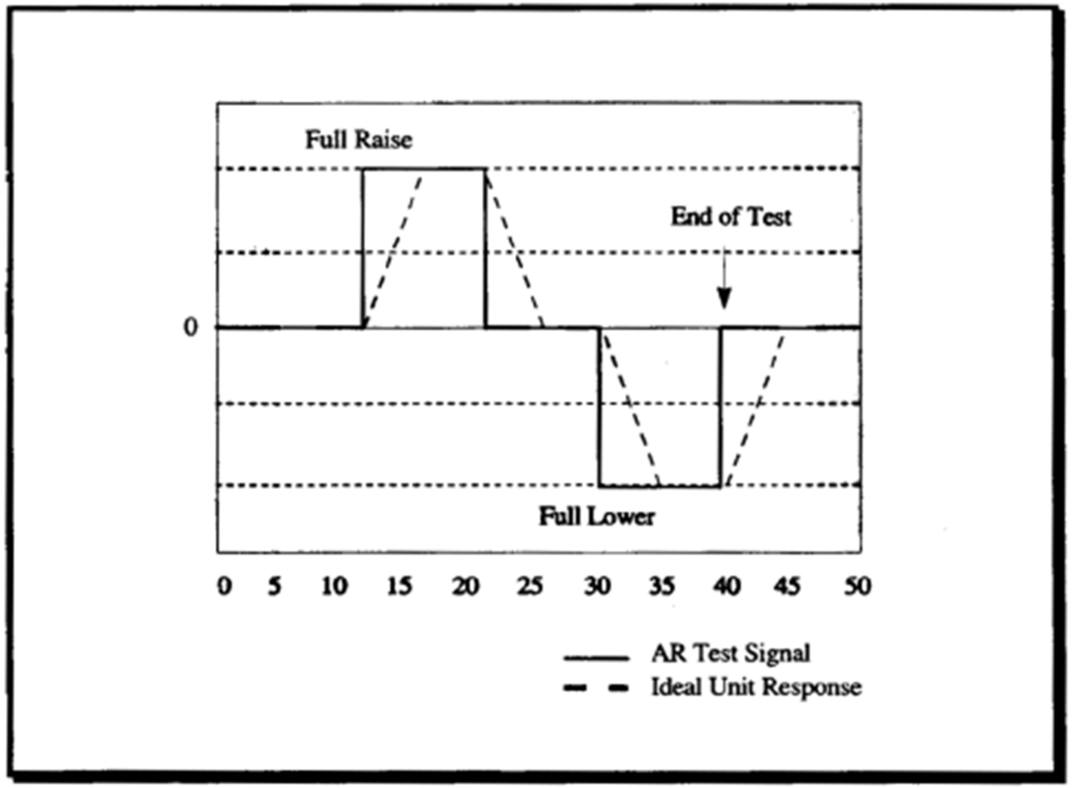
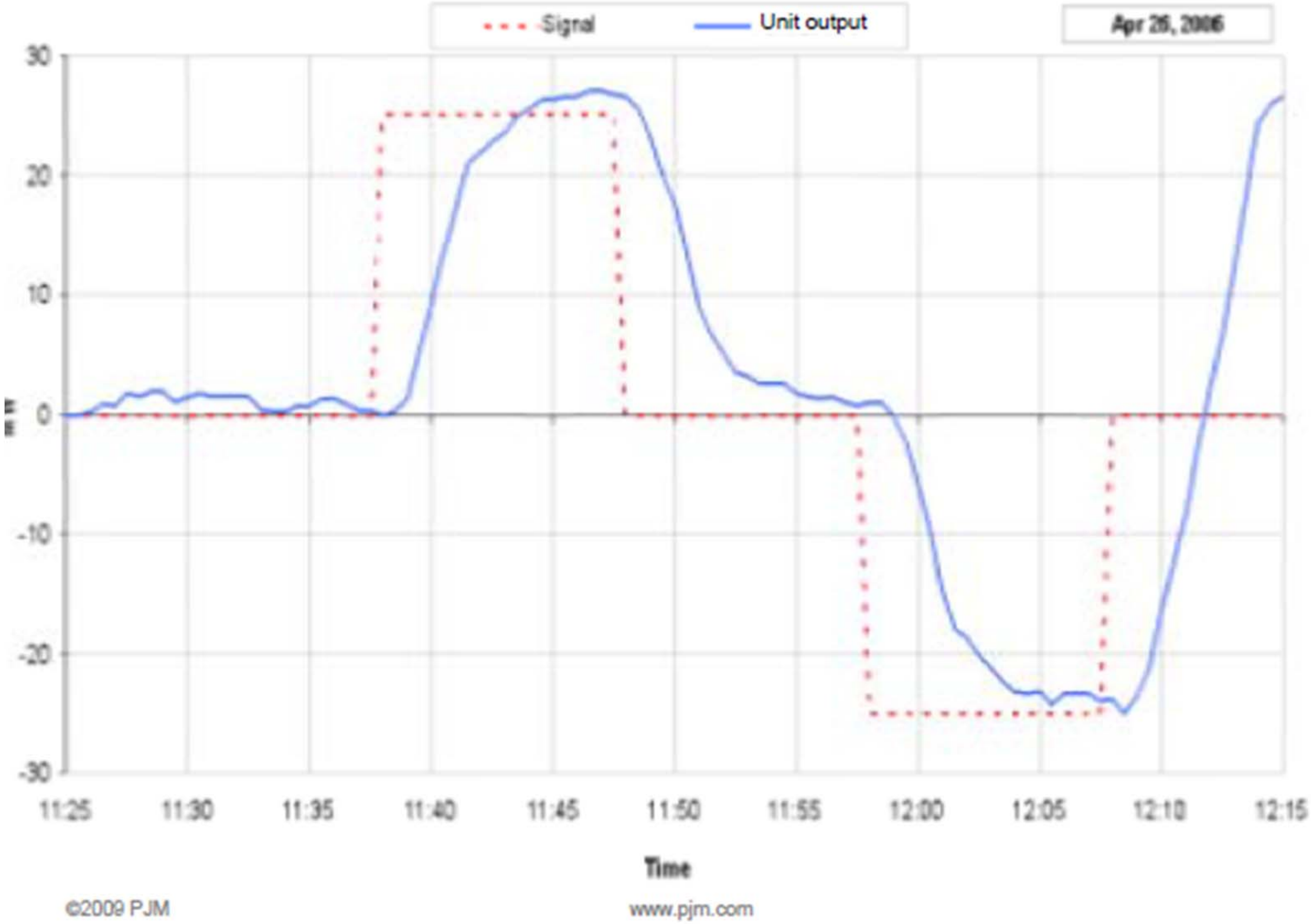
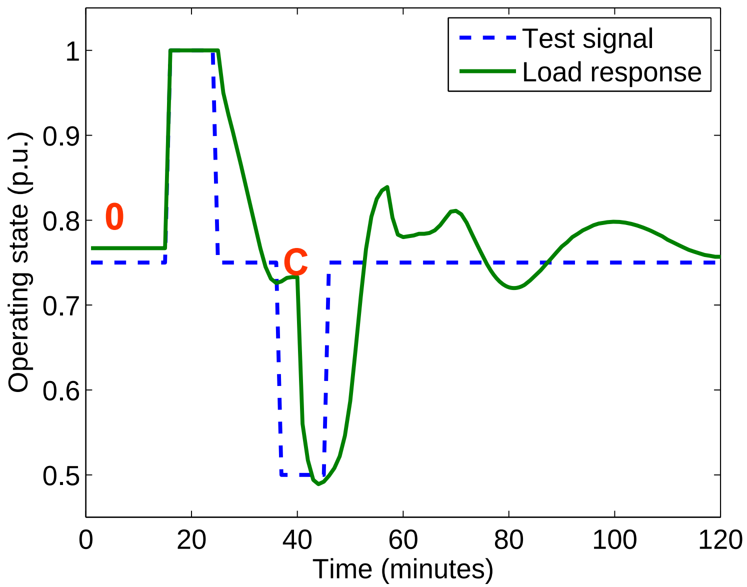


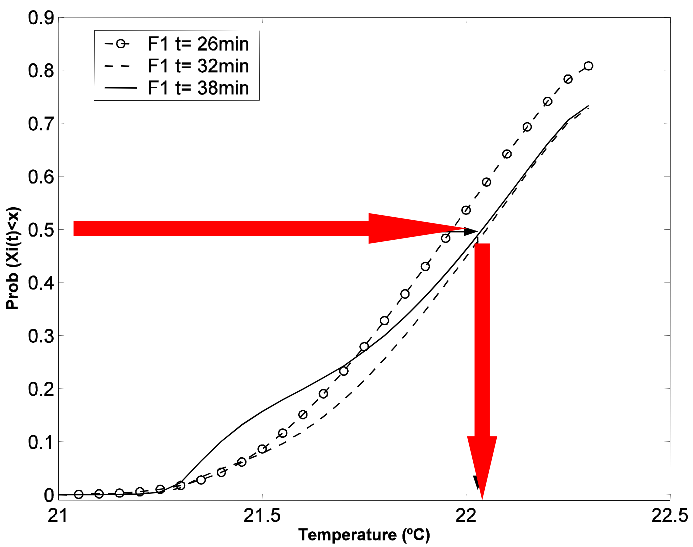
Exhibit 4.3: Regulation Test Pattern

- **Real response for a generation unit**
  - Figure source: Ancillary Services training (PJM, 2006)

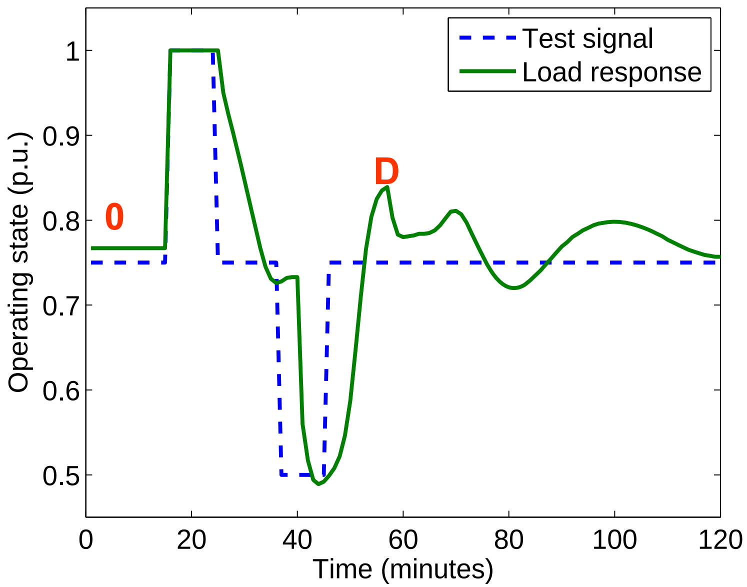


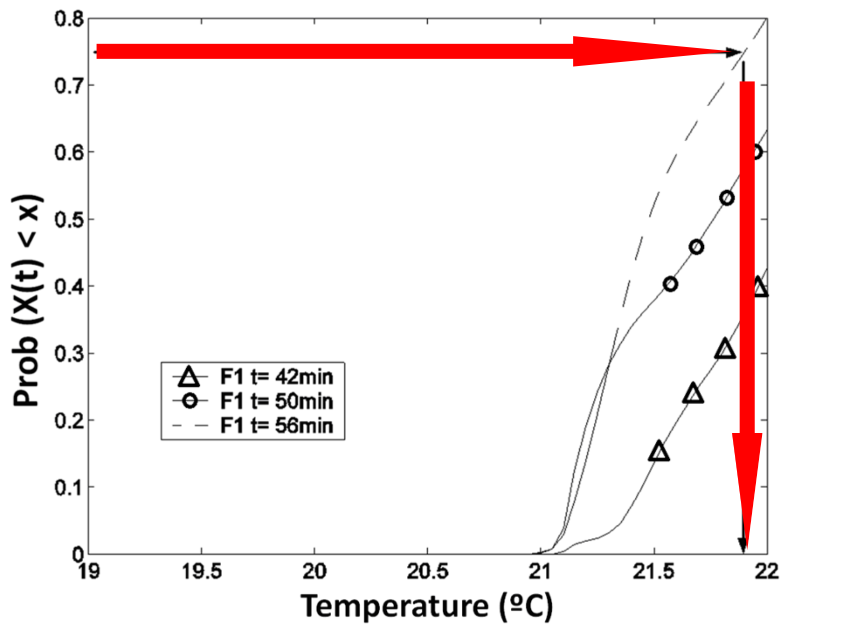
- **Example: Control test signal (PJM)**
  - Third step in t=35min (C): reduce (braking) aggregated demand to 0.5 pu) How this is done?
    - 1) Simulate load from 25 to 50 min and take pdfs´
    - 2) Select pdf for t=35 min and take the desired value of aggregated power (0.5 pu) in y axis
    - 3) Obtain temperature (the upper temperature of the dead-band) in x axis. Result ~ 22ºC
    - Remember that "initial" deadband ("0" state) is not a good value!



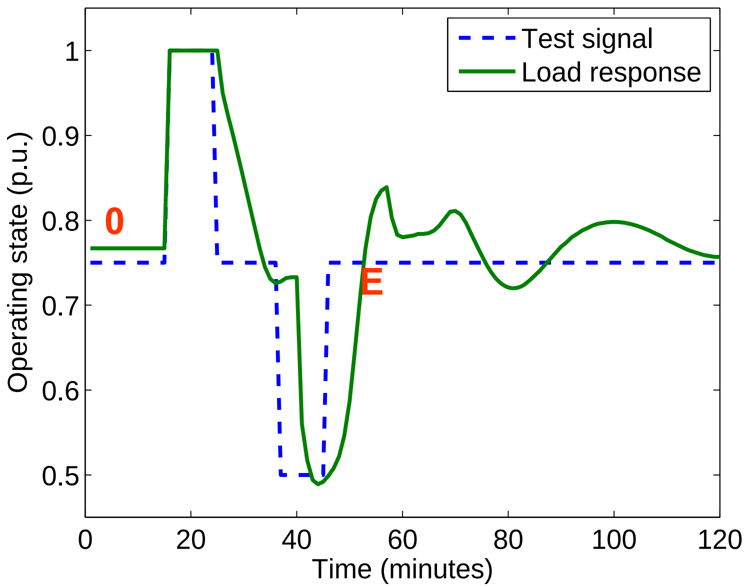


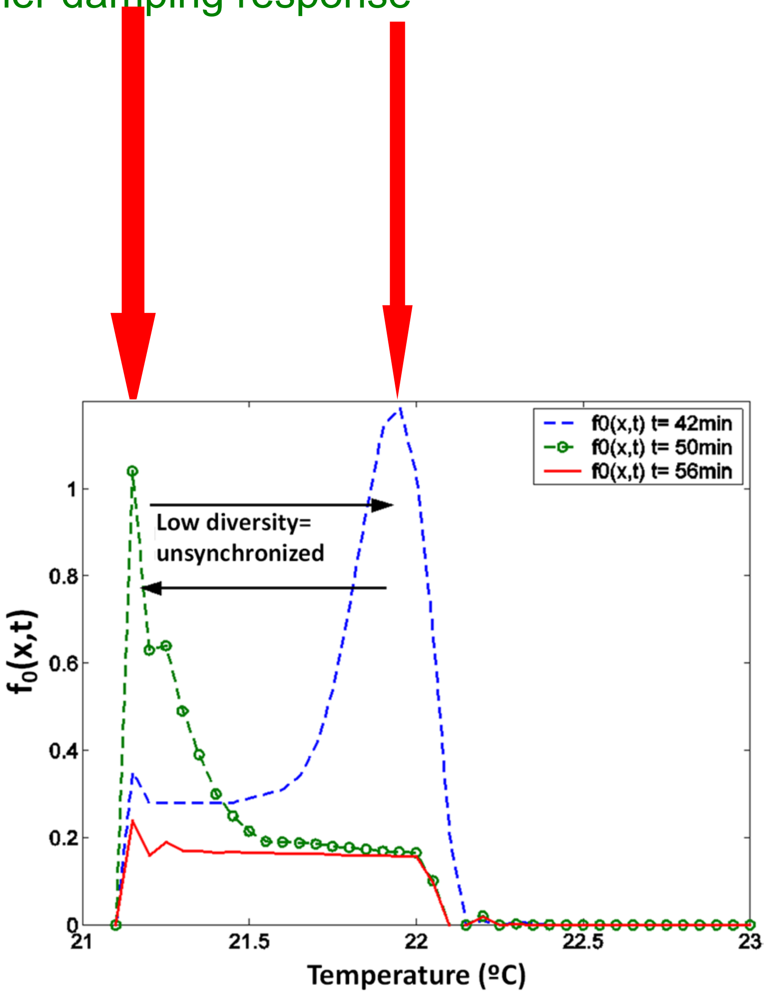
- **Example: Control test signal (PJM)**
  - Fourth step in t=55min (D): get (throttle) aggregated demand to 0.75 pu) How this is done?
    - 1) Simulate load from 25 to 50 min and take pdfs´
    - 2) Select pdf for t=35 min and take the desired value of aggregated power (0.5 pu) in y axis
    - 3) Obtain temperature (the upper temperature of the dead-band) in x axis. Result 21.8~ 22ºC
    - Remember that “initial” deadband (“0” state) is not a good idea!



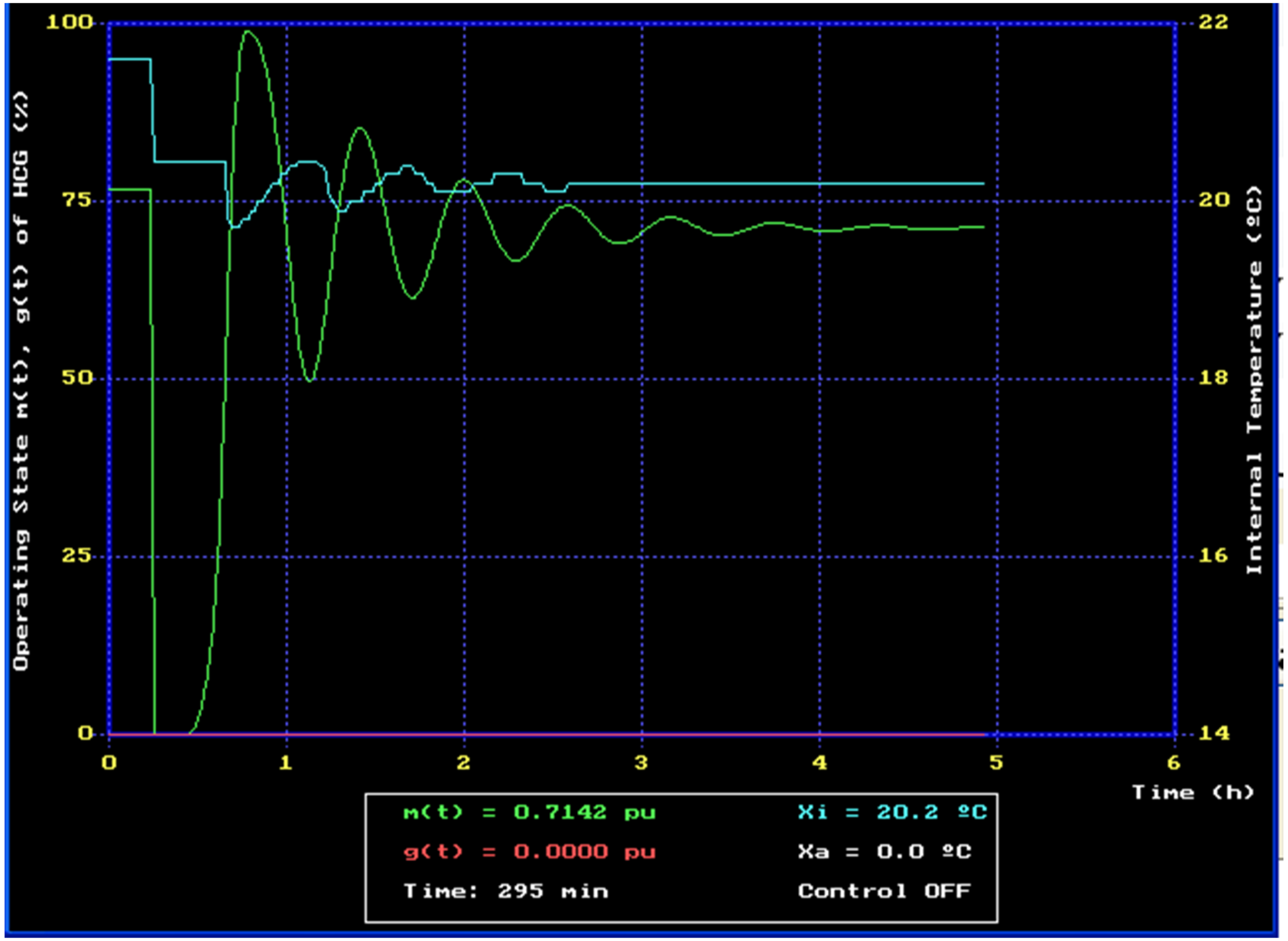


- **A bad example: Control test signal (PJM)**
  - Fourth step in t=50min (E): set up (throttle) aggregated demand to 0.75 pu) Why not?
    - Because pdf are oscillating too much, i.e. the load group is fully “unsynchronized” → a higher damping response

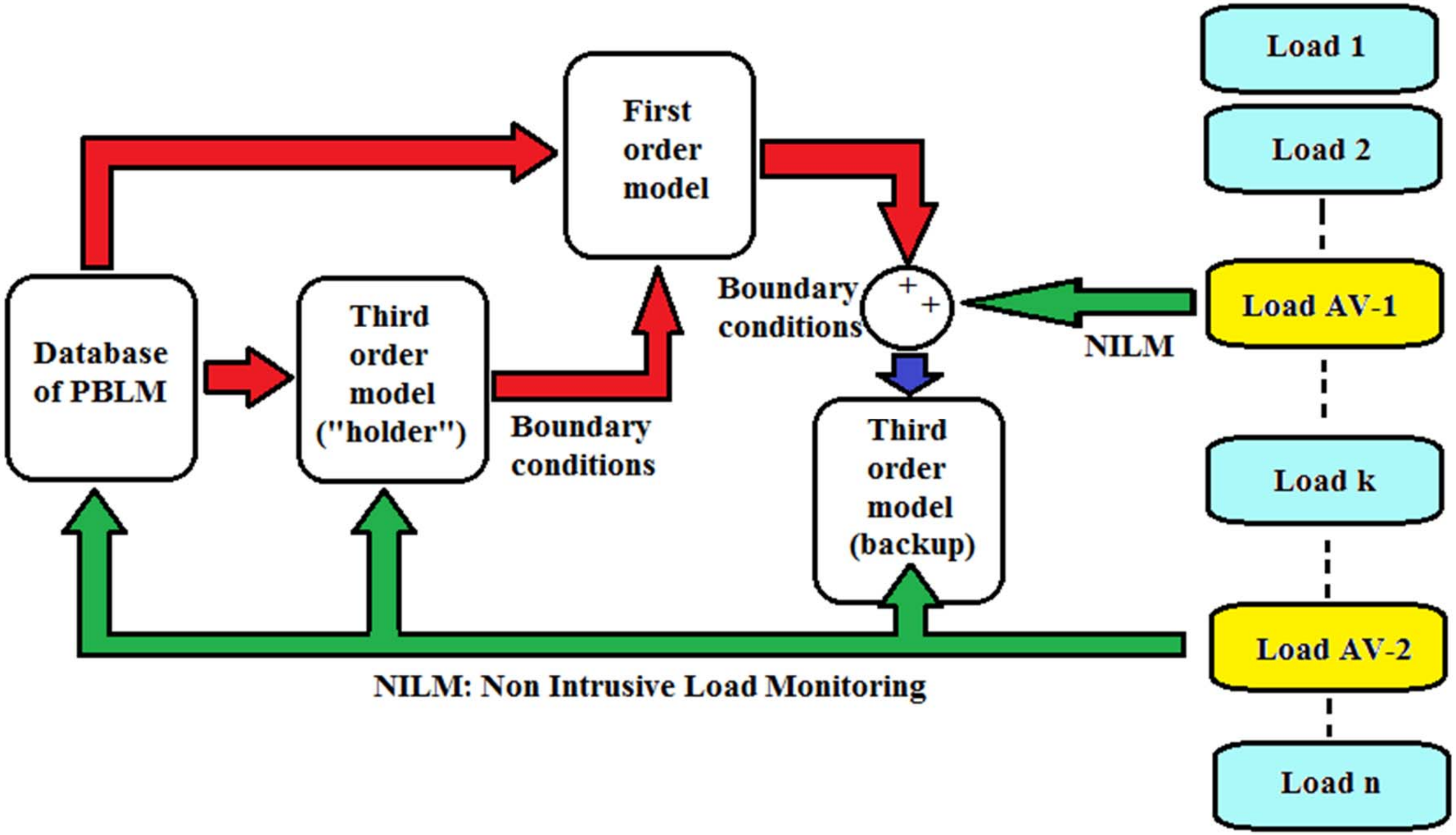




- **For example: non-admissible scenarios**
  - Load under regulation bands (leading of point C)
  - Overdamping



- **The proposed "architecture" for Energy and AS**
  - Third order: price or event response (warning 2h-4h)
  - First order: AS (warning < 10-30 min).
    - Feeds a third order "backup" in short term to evaluate states
  - NILM: monitoring, validation, to tune database,



Conclusions

- The interest for AS markets is continuously growing
- DR is almost unexplored for a lot of AS Services
  - Aggregation is even less used in AS markets than in energy mkt
- We propose a methodology to facilitate DR participation
  - To use the same “architecture” that can be used for energy markets (similar to power load flow approaches)
  - To improve the speed of response of the models
    - “Tuned” elemental models
    - Aggregation procedures are revisited
  - The results are easy to understand: the output is the same
- Some additional tools are needed
  - Assisted response to the aggregator (e.g. artificial neuronal networks to fit thermostat change)
  - To integrate NILM (Non Intrusive Load Mon.) with models
  - To develop procedures to find Average/Representative Loads in the aggregation (monitoring, feedback,…)
  - To develop “hybrid” models for backup: 1h-2h range

- **Thanks. Questions?**

Thank you. Questions?

The Old Spanish Navy Hospital (1750)
(ETSII headquarters, Cartagena)

Acknowledgements:

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"

www.demandresponse.eu (Research project ENE2013-48574-C2-2-P)