Modelling water user behaviour

From smart metered data to agent based modelling

(PART II)
The social dilemma of water conservation

- Conflict between private and public interests.

- Two possible angles of approach:
  - **structural**: apply strategies that intervene directly in the outcome of the dilemma, e.g. (install water meters and) use price policy by charging based on usage
  - **social-psychological**: intervene to alter the way people value and think about the resource
Agent based policy design loop

a) User profiling Model

Water demand management policies

b) Agent Based Modelling

Meteorological influences

Water users

Simulation of water conservation behaviour

consumption characteristics

Simulation outputs

incentives

Selection of water management policy

c) Advanced Metering Infrastructure (smart meters)

consumption data
An Agent Based Model is...

- a computational model composed of computational objects - agents - interacting within and with an environment, i.e. a virtual worlds represented by some mathematical structure (e.g. a grid or a network)

- Agents
  - have their own goals and behaviours
  - are autonomous, with a capability to adapt and modify their behaviours
  - are characterised by their own attributes and decision rules (agents are diverse and heterogenous)
A landscape of ABMs for water consumption

<table>
<thead>
<tr>
<th>Model</th>
<th>Danubia</th>
<th>Dawn</th>
<th>FIRMA Thames</th>
<th>FIRMABAR I &amp; II</th>
<th>Memetic</th>
<th>SmartH2O</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of study</td>
<td>Danube upper basin</td>
<td>Thessaloniki</td>
<td>South region of England</td>
<td>Barcelona &amp; Valladolid</td>
<td>-</td>
<td>Tegna &amp; Valencia</td>
</tr>
<tr>
<td>Diffusion of water saving technology</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Water pricing</td>
<td>-</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[Y]</td>
</tr>
<tr>
<td>Diffusion of water saving actions and attitudes</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Meteorological conditions</td>
<td>-</td>
<td>Y</td>
<td>Y</td>
<td>-</td>
<td>-</td>
<td>[Y]</td>
</tr>
<tr>
<td>Urban dynamics</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Y</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
DAWN


- aims at estimating the water consumption under different scenarios of pricing policies, and taking into account
  - social interaction,
  - the propagation of water conservation signals among individual consumers.
3 type of agents:
- water consumers (CA),
- supplier (WSA) and
- meteorologist (MA)

The society of CAs is distributed over a 2D grid.
Econometric model

1. Society of Water Consumer Agents (CA)
   ① Collection of individual consumptions
   ③ Total demand calculation
   ⑥ Price policy review

2. Metereologist agent (MA)
   2. Total results

3. Water-pricing policy

4. Influence diffusion

5. Estimation of individual consumption

6. Environmental Data

7. DAWN

Alessandro Facchini, IDSIA
1. Initialisation of econometric model and water-price policy
2. MA informs WSA about meteorological conditions
3. WSA informs CAs about meteo and asks to determine the water demand
4. each CA interacts with its neighbours
5. each CA estimates its demand...
6. and sends it back to WSA
7. WSA decides to revise (or not) its policy and starts new cycle (go to 2)
8. iteration is over: total results
Water demand is given by:

\[ C(i,t) = \alpha + \beta X(i,t) + \gamma Z(i) + \delta S(i,t) + v(i) + \epsilon(i,t) \text{ [m}^3\text{]} \]

where:

- \( X(i,t) \) is a vector of price variables
- \( Z(i) \) is a vector of community-specific variables
- \( S(i,t) \) is a vector of social variables (excluded in \( Z \))
- \( \alpha, \beta, \gamma \) and \( \delta \) are elasticities (to be estimated)
- \( v(i) \) is the unexpected water consumption regime
- \( \epsilon(i,t) \) is the error term
a social variable $S$ is determined by each CA$_i$ at time $t$ as

$$S(i,t) = f(sw_{i(1)} + \ldots + sw_{i(k)})$$

where:

- $sw_{i(j)}$ is the social weight that CA$_i$ receives from its neighbour $i(j)$
- $f$ is a diffraction function adjusting the sum of social weights
The case of Thessaloniki (metrop. area)

- Data on households and community variables collected by a field survey in 1356 households, and confronted with data covering period from Jan. 1994 until April 2000

<table>
<thead>
<tr>
<th>Variable</th>
<th>Elasticity</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal price</td>
<td>MP</td>
<td>-0.340</td>
</tr>
<tr>
<td>Marginal price squared</td>
<td>MP²</td>
<td>-0.308</td>
</tr>
<tr>
<td>Marginal price cubed</td>
<td>MP³</td>
<td>0.158</td>
</tr>
<tr>
<td>Temperature</td>
<td>TEM</td>
<td>0.100</td>
</tr>
<tr>
<td>Rainfall</td>
<td>RNF</td>
<td>-0.015</td>
</tr>
<tr>
<td>Well-informed consumers</td>
<td>WIC</td>
<td>-0.368</td>
</tr>
<tr>
<td>Family income</td>
<td>INC</td>
<td>0.351</td>
</tr>
<tr>
<td>Having many children</td>
<td>CHI</td>
<td>0.194</td>
</tr>
<tr>
<td>Car washing</td>
<td>CAR</td>
<td>0.055</td>
</tr>
<tr>
<td>Watering plants</td>
<td>W</td>
<td>0.128</td>
</tr>
<tr>
<td>Cleaning balconies</td>
<td>B</td>
<td>0.043</td>
</tr>
<tr>
<td>Cleaning pavements</td>
<td>P</td>
<td>0.032</td>
</tr>
<tr>
<td>Household residents</td>
<td>RES</td>
<td>0.026</td>
</tr>
</tbody>
</table>

*Table 1 in Athanasiadis et al. (2005). Variables and elasticities.*
Social interaction submodel

- Well-informed consumer variable (WIC) sets as average value for the whole society at $t_0$ and

- WIC increases by an average of 6% every 3 years following:

$$\left(\frac{0.06}{36}\right)(t-t_0)\text{WIC}(t_0) + \text{WIC}(t_0)$$
Social interaction submodel

- Clustering of CAs in four types based on questionnaire

<table>
<thead>
<tr>
<th>Consumer Type</th>
<th>Population (%)</th>
<th>Ability to Promote</th>
<th>Consumption Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Opinion leaders</td>
<td>10</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>B: Socially apathetic</td>
<td>20</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>C: Opinion seekers</td>
<td>30</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>D: Opinion receivers</td>
<td>40</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

*Table 2 in Athanasiadis et al. (2005).*
### Social interaction submodel

<table>
<thead>
<tr>
<th>Type of agent</th>
<th>Social weight</th>
<th>Diffraction function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> opinion leader / early adopter</td>
<td>$sw_A = 2 \cdot sw_C$</td>
<td>$f_A$ with low slope</td>
</tr>
<tr>
<td><strong>B</strong> socially apathetic</td>
<td>$sw_B = 0$</td>
<td>$f_B = 0$</td>
</tr>
<tr>
<td><strong>C</strong> opinion seeker</td>
<td>$sw_C = (0.06/36) \cdot WIC$</td>
<td>Slope $f_C$ double of slope $f_A$</td>
</tr>
<tr>
<td><strong>D</strong> opinion receiver</td>
<td>$sw_D = sw_C$</td>
<td>$f_D = f_A$</td>
</tr>
</tbody>
</table>
Example

opinion leader (A)
socially apathetic (B)
opinion seeker (C)
opinion receiver (D)

$WIC = 10$

“social pressure” on agent $i$:

$$2 \times (0.06/36) \times 10 + 0 + 0 + (0.06/36) \times 10 + (0.06/36) \times 10 = 2/30$$
Example

opinion leader (A)
socially apathetic (B)
opinion seeker (C)
opinion receiver (D)

"social pressure" on agent $i$: $\frac{2}{30}$

<table>
<thead>
<tr>
<th></th>
<th>diffraction function</th>
<th>social weight</th>
<th>impact on water demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$f_A(x)=2x$</td>
<td>$sw_A= \frac{1}{30}$</td>
<td>$\delta S_A(i,t) = -0.368 \times (2 \times \frac{2}{30}) = -0.05$</td>
</tr>
<tr>
<td>B</td>
<td>$f_B(x)=0$</td>
<td>$sw_B= 0$</td>
<td>$\delta S_B(i,t) = 0$</td>
</tr>
<tr>
<td>C</td>
<td>$f_C(x)=2f_A(x)=4x$</td>
<td>$sw_C= \frac{1}{60}$</td>
<td>$\delta S_C(i,t) = 2 \times \delta S_A(i,t) = -0.1$</td>
</tr>
<tr>
<td>D</td>
<td>$f_D(x)=f_A(x)=2x$</td>
<td>$sw_D= \frac{1}{60}$</td>
<td>$\delta S_D(i,t) = \delta S_A(i,t) = -0.05$</td>
</tr>
</tbody>
</table>
Simulation

- 100 CAs randomly distributed on a 12x12 square grid
- period simulation: 2004-2010
- time step: one month
### Simulation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water price</td>
<td>adjusted to real price</td>
<td>+5%</td>
<td>+7,5%</td>
<td>adjusted to real price</td>
<td>adjusted to real price</td>
</tr>
<tr>
<td>educational/information policy</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>medium scale</td>
<td>major scale</td>
</tr>
</tbody>
</table>

- the implementation of an education or information policy is encoded within the social diffusion model.
Results

Figure 12 in Athanasiadis et al. (2005). Per capita reduction in the evaluation of the five scenarios.

- aims at verifying the influence of urban dynamics (e.g. changes in territorial model) and socio-geographic effects, like technological and opinion dynamics, in domestic water demands
Environmental's layer

Agent's layer

Statistical model of water consumption
Consumption function
GIS - Socioeconomic and territorial georeferenced databases
Socioeconomic data
Spatial data

Agents

Water conservation behaviour
Technology adoption

Urban dynamic model

Behavioural diffusion Model
Young's Model
Technological diffusion Model
Bass model

Location and type of dwelling

Water conservation behaviour
Technology adoption

Behavioral diffusion Model

Technological diffusion Model

Young's Model
Bass model
Bass technology diffusion model

\[ aR = pA^* (inC + imitC^* \text{adopters/population}) \]
Young’s opinion diffusion model

Aims at capturing diffusion and social pressure


H. Peyton Young
(Johns Hopkins U.)
Young’s opinion diffusion model

- **Binary case**: each agent can either adopt behaviour $E$ or not (hence adopt behaviour $NE$)

- The choice of a behaviour is determined by a utility function $U$ that depends on:
  - the agent’s current behaviour
  - the behaviour of its social network
  - an exogenous parameter ($p_E$) that measures the social pressure towards behaviour $E$
Young’s opinion diffusion model

- Utility function:
  \[ U(A, E / E) = a \ V(A, E) + p_E \]
  \[ U(A, E / NE) = a' \ V(A, E) + p_E \]
  \[ U(A, NE / E) = b \ V(A, NE) \]
  \[ U(A, NE / NE) = b' \ V(A, NE) \]

- The probability of an agent to maintain its behaviour \( E \) is given by the formula:
  \[ Pr(A, E / E) = \frac{e^{\beta U(A, E/E)}}{e^{\beta U(A, E/E)} + e^{\beta U(A, NE/E)}} \]
Example

\[ a = b' = 0.7 \text{ and } a' = b = 0.3 \]
\[ p_E = 0.5 \]
\[ \beta = 0 \]

\[ V(A,E) = 3/5 \]
\[ V(A,NE) = 2/5 \]

\[ U(A, E / E) = a \cdot V(A, E) + p_E = 0.92 \]
\[ U(A, NE / E) = b \cdot V(A, NE) = 0.12 \]

\[ Pr(A, E / E) = 0.69 \]
\[ Pr(A, NE / E)) = 0.31 \]
\[ = 1 - Pr(A, E / E) \]
Example

\[ U(A, E / NE) = a''V(A, E) + p_E = 0.68 \]
\[ U(A, NE / NE) = b''V(A, NE) = 0.28 \]

\[ Pr(A, E / NE) = 0.6 \ (\lt Pr(A, E / E) ) \]
\[ Pr(A, NE / NE) = 0.4 \]
\[ = 1 - Pr(A, E / NE) \]

\[ a = b' = 0.7 \text{ and } a' = b = 0.3 \]
\[ p_E = 0.5 \]
\[ \beta = 0 \]
Urban dynamics model

• Assumption: agents prefer to live
  * among those that are similar to themselves and
  * in dwellings according to their present economic resources.

• The larger is this difference, the most likely an agent will try to move to another area

Model based on:

Results of simulations

- Simulations over 10 years, time step 3 month, with 12'500 agents
- Higher adoption rates are produced with higher values of $p_E$
- The impact of the immigration effect and the change of the territorial model can be reduced significantly to just 2 – 6% of increase in most of the diffusion scenarios
Purposes of the SmartH2O ABM

Modelling the aggregate water usage based on:
- the specific socio-psychographic attributes of the agents
- their current level of water usage
- other exogenous factors

and focusing on the diffusion of:
1. The adoption of the SmartH2O gamified platform and
2. A water-saving attitude within active platform users due to
   - social pressure and
   - the participation to gaming activities and challenges proposed by the portal
SmartH2O ABM structure

- Single-user Model
- Agents
  - consumption characteristics
  - water conservation behaviour
  - Behavioural diffusion Model
  - Portal diffusion Model
  - SIRS Model
- Water utility
  - incentives
- Environment
State variables and scale

- Two types of agents: Water Supplier and Households.
- Households agents are localised on the map of the geographic area of interest (environment)
- State variables of Households:
  - socio-psychographic attributes of users,
  - water usage patterns,
  - attitude towards responsible water use (E vs NE)
  - role in the portal diffusion model
- Time scale: daily
- Simulation period: one year
### Process overview

1. **Single user consumption model**
2. **Water-pricing policy**
3. **Metereological data**
4. **Influence diffusion**
5. **Estimation of individual consumption**
6. **Collection of individual consumptions**
7. **Total demand calculation**
8. **Water Supplier Agent**
9. **Price policy review**
10. **Total results**
Portal diffusion submodel

SIRS model
Portal diffusion submodel
Portal diffusion submodel
Young diffusion submodel: assumptions

- **susceptibles**: agents without behaviour E but with predisposition towards it
- **on the platform**: agents without behaviour E
- **recovered**: agents with behaviour E

\[\square = \text{agent without behaviour E but with predisposition towards it}\]
\[\triangle = \text{agent without behaviour E}\]
\[\triangle = \text{agent with behaviour E}\]
Young diffusion submodel: assumptions

- Susceptibles
- On the platform
- Recovered

= agent without behaviour E but with predisposition towards it

= agent without behaviour E

= agent with behaviour E

Alessandro Facchini, IDSIA
Young diffusion submodel: assumptions

- **susceptibles**
  - Blue triangle = agent *without* behaviour E but *with* predisposition towards it
  - White triangle with dotted outline = agent *without* behaviour E

- **on the platform**
  - Blue triangle = agent *with* behaviour E
  - White triangle = agent *without* behaviour E

- **recovered**
  - Blue triangle = agent *with* behaviour E
Young diffusion submodel: assumptions

\[\text{susceptibles} \rightarrow \text{on the platform} \rightarrow \text{recovered}\]

- \(\Delta\) = agent **without** behaviour E but **with** predisposition towards it
- \(\triangle\) = agent **without** behaviour E
- \(\Upsilon\) = agent **with** behaviour E

Alessandro Facchini, IDSIA
Young diffusion submodel: assumptions

- Susceptibles: agents without behaviour E but with predisposition towards it.
- On the platform: agents with behaviour E.
- Recovered: agents without behaviour E.

Diagram icons:
- Light blue triangle = agent **without** behaviour E but **with** predisposition towards it.
- Dark blue triangle = agent **with** behaviour E.
- White triangle = agent **without** behaviour E.
Young diffusion submodel: assumptions

- A SmartH2O portal user is a household agent whose variable `onThePlatform` is true.
- All agents who are not portal users are assumed to have behaviour NE by default.
- A non-portal user can have a predisposition for E, which is initialised once she becomes a portal user.
- A portal user can adopt either a water-saving (E) or a non-water-saving (NE) behaviour.
- The adoption of an E behaviour leads to a decrease in water usage in the player's household, achieved e.g. by shortening the shower time, or by adopting water saving technologies.
The choice of a behaviour is determined by the utility function $U$ that depends on:

- the agent’s current behaviour,
- the behaviour of its social network (on the platform),
- social pressure toward behaviour $E$ ($p_E$)
- role in the portal diffusion model
Applications to SmartH2O case study in Tegna

- Hourly measurements of 256 smart meters in Tegna (October 2014/February 2015 - now) and their psychographic attributes
- Parameters of Young’s model, as in Edwards et al., (2005) and Galan et al., (2009).
- Boolean parameter indicating a predisposition toward the adoption of behaviour $E$: 10.8% true (based on the results of a pricing survey conducted in Ticino among SES customers)
- Adoption of behaviour $E$ once on the platform leads to a reduction of 5% in water usage (WaterSmart)
Application to SmartH2O case study

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Factor A</th>
<th>Factor B</th>
<th>Factor C</th>
<th>Factor D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rateAdv.</td>
<td>contactR.</td>
<td>usePortalD.</td>
<td>timeImmunity</td>
</tr>
<tr>
<td>1</td>
<td>1/week</td>
<td>1/week</td>
<td>3 months</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1/week</td>
<td>1/week</td>
<td>1 month</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1/month</td>
<td>1/month</td>
<td>3 months</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1/month</td>
<td>1/month</td>
<td>1 month</td>
<td>3 weeks</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Robustness of the ABM model to the parameter $p_E$ (social pressure) for 4 different scenarios. Such scenarios are generated based on the analysis on the portal diffusion model.
Application to SmartH2O case study

*Figure 1.* Fraction of users using the SmartH2O portal as function of time in the four scenarios listed in Table 1 with $p_E=1$. 95% confidence interval (not reported) are always below 0.07.
Figure 2. Fraction of agents that are both portal and adopt behaviour E after 12 months, according to minimal and maximal values of $p_E$ (social pressure) and type of scenario.
## Application to SmartH2O case study

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Value of social pressure $p_E$</th>
<th>Reduction (%) on daily consumption, last six months</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.83 (± 0.57)</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>1.91 (± 0.51)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.09 (± 0.58)</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>2.32 (± 0.51)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2.50 (± 0.53)</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.90 (± 0.55)</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>0.98 (± 0.58)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.01 (± 0.52)</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>1.08 (± 0.54)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.12 (± 0.57)</td>
</tr>
</tbody>
</table>

*Table 2. Influence of emergence of behaviour $E$ among portal users on water consumption under different scenarios.*
Comments

- Bigger integration of water price policies
- “Feedback” of Young’s model to technological diffusion model (cf. FIRMA Valladolid)
- (Role of network structure in diffusion model)
Conclusions

- We have developed an ABM that models the adoption of a water awareness platform by a group of potential users.
- We have assumed that the awareness of self-consumption can lead to a change in behaviour depending on the user attitude.
- We plan to use the ABM model to evaluate the impact on water consumption behaviour of water awareness campaign.
- Model validation is in progress in the two main case studies of the SmartH2O project, in Switzerland and in Spain.