Endogenous transformation of exogenous effects in a system dynamics model of heating, ventilation and rebound

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Abstract

Energy efficiency measures do not fully translate into energy consumption reductions because occupants increase their dwellings' internal temperatures rather than only reducing energy bills. This effect, known as the rebound effect, has been empirically confirmed and is usually attributed to occupants' increase of thermal comfort. Based on system dynamics modelling, we offer a different and complementary explanation that shows how rebound may occur when occupants feel thermally comfortable throughout. The interaction of their desired behaviour with other practices, such as cooking, explains how shifts in their desired temperature may occur. We thus contribute to the understanding of domestic practices related to energy efficiency and rebound. In addition, our study shows how rebound occurs through the transformation of exogenous inputs through endogenous feedback mechanisms. While system dynamics emphasises continuous modelling and endogeneity, our study thus also motivates future research into the analysis of the endogenous transformation of time-varying inputs in system dynamics.

Keywords

System dynamics, rebound, internal temperature, heating, ventilation, energy efficiency, retrofit, endogeneity, time-varying inputs, heterogeneous models

Introduction

Climate change from carbon emissions and energy independence are important reasons to incentivise a reduction in energy demand, especially in the domestic housing sector which accounts for almost 30 percent of carbon emissions (Stubbs, 2008; DEFRA, 2001 cited in Johnston, Lowe, & Bell, 2005). In this sector, refurbishing the fabric of dwellings has the potential to reduce carbon emissions by about 60 percent (Innovation & Growth Team, 2010). However, evidence shows that once the fabric retrofits or other energy efficiency measures are implemented, they do not fully translate into energy consumption reductions. Occupants increase their homes' internal temperatures rather than only lowering consumption and reducing energy bills. This effect, known as the rebound effect, has been widely studied by economists and is usually partially attributed to occupants' increase of thermal comfort (Greening, Greene, & Difiglio, 2000; Sorrell, Dimitropoulos, & Sommerville, 2009). More recent explanations include how occupants have adapted to their new thermal environment using their habituated heating and cooling practices (Chiu, Lowe, Raslan, Altamirano-Medina, & Wingfield, 2014). While there is evidence to suggest that occupants do not necessarily increase their internal temperature consciously (Huebner, Hamilton, Chalabi, Shipworth, & Oreszczyn, 2015), the actual mechanism for adaptation is less well understood.

We propose a system dynamics model of occupants' decisions and socio-technical interaction with heating and ventilating their dwellings. Based on system dynamics modelling, we offer a different and complementary explanation to current literature that shifts the focus away from the idea that occupants increase their thermal comfort by higher temperatures. We do this by showing how higher internal temperature (HIT) may occur through adaptation. The purpose of this paper is thus to provide a structural-causal account of HIT in the domestic housing sector that explains the rebound effect via the interaction of endogenous mechanisms with outside effects of heat gains. We contribute to the understanding of occupant decision-making and domestic practices related to energy efficiency and rebound. In addition, our study shows how rebound occurs through the transformation of exogenous inputs through endogenous feedback mechanisms. The different dynamics arising from constant vs. pulsatile inputs warrant deeper analysis. While system dynamics modelling emphasises continuous modelling and endogeneity (Forrester, 1968a; Forrester, 1968c; Richardson, 2011), this study also shows that pulsatile exogenous inputs may be transformed very differently, motivating future research on the analysis of time-varying inputs with system dynamics.

A heating and ventilation model

In order to present the mechanisms contributing to rebound, we present a system dynamics model that draws on the qualitative evidence of a case study by Chiu et al. (2013; 2014). That study provided a socio-technical account of how occupants' behaviour interacts with the built system. The authors report that after low-carbon retrofit they found that some occupants resided in very warm conditions around 24°C, comfortable, but much warmer than expected. Although there existed other cases with different observed temperatures, the *reference mode* would thus represent equilibrium around 24°C.

Central to the model is the *internal temperature* stock which is affected by *heat gains* and *losses*. Figure 1 describes the balancing mechanism *B1* by which heat is lost through the wall. A certain fraction of the *gap between the internal and outside temperature* decreases per hour, depending on the *heat loss coefficient* (HLC) that characterises the dwelling's fabric' heat conductivity. The HLC is generally simplified as a constant that indicates the proportional heat loss through the fabric of a dwelling (BRE, 2014).

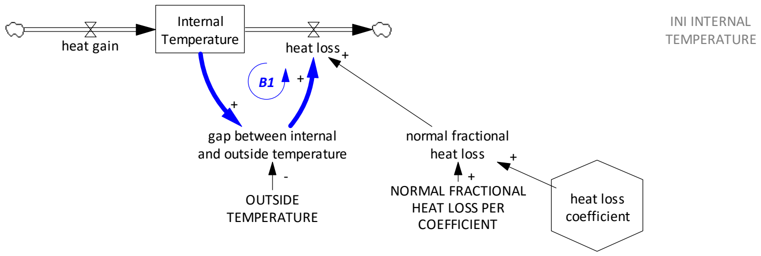

Figure 1: Temperature loss through wall

A primary heating system counteracts the heat loss by a balancing loop *B2* (see Figure 2). A *gap between the set point of a thermostat and the internal temperature* makes the *heating* "to switch on" and closes the gap. Whether this loop is active depends on the functioning of the primary heating system. The internal temperature would thus settle somewhere between the *thermostat set point* and the *outside temperature*, depending on the relative strengths of the two balancing loops. In addition, heat gains can occur by incident solar heat gains, i.e. the sun shining through the windows and thus warming the dwelling, and also by occupant behavioural heat gains through cooking, use of showers, etc. The model also includes two switches to run analyses with or without such effects occurring.

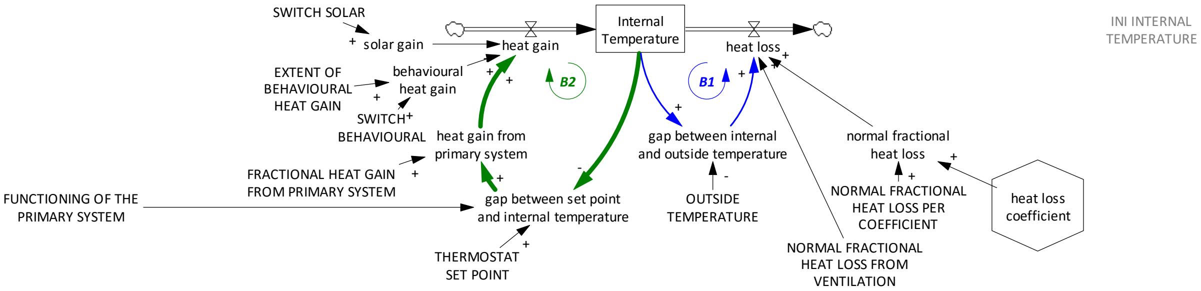

Figure 2: Temperature gain from primary heating

So far, the system does not include any human decision and intervention, but humans intervene if they feel either too cold or too warm. Figure 3 explains through balancing loop *B3* how building occupants would add secondary heating if they feel too cold, i.e. if there is a positive *gap between the desired and perceived internal temperature*. Here, desired internal temperature represents occupants' comfortable temperature. The secondary heating system can be an electric heater, but, as exemplified in the case study by Chiu et al. (2014), it can also represent surprisingly the use of a tumble-dryer for the purpose of warming the dwelling. It is assumed that building occupants perceive the *internal temperature* with an exponential smoothing delay of about two hours, depending on their clothing and metabolic rates. They also adapt their *desired temperature* to their *perceived internal temperature* with an exponential smoothing delay of a few days. This balancing feedback loop *B4* corresponds to the acclimatisation of their physiological thermoregulation system (Brager & de Dear, 1998, p. 86).

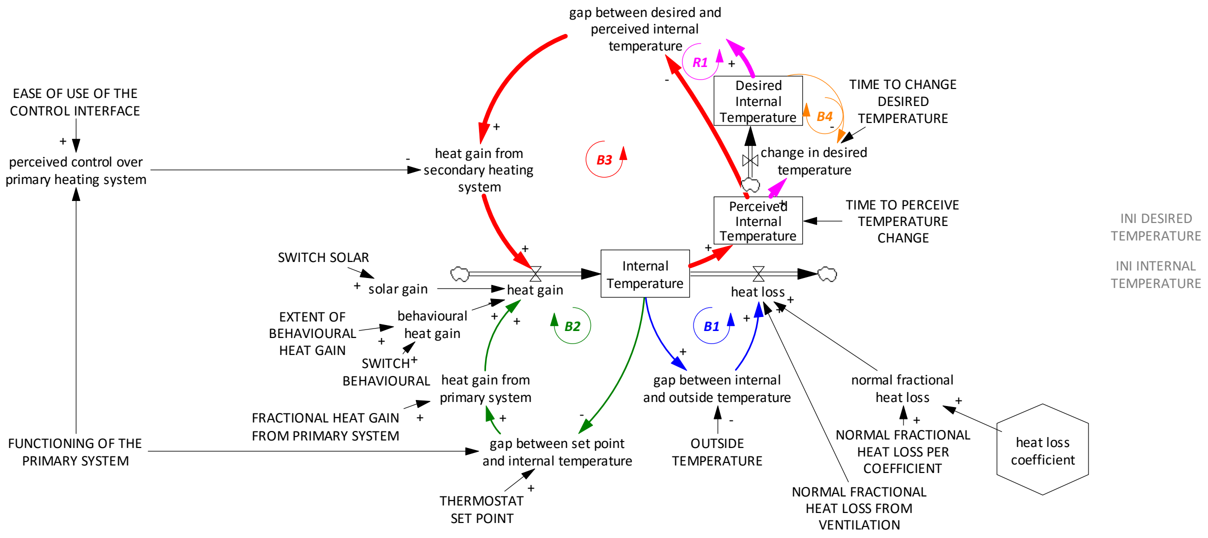

Figure 3: Secondary heating

It is further assumed that occupants cannot adapt their desired temperature indefinitely, but that their body physiology has an upper and lower boundary of adaptation and that occupants adapt more slowly the closer the desired temperature is to one of these boundaries (see balancing loops *B6* and *B7* in Figure 4).

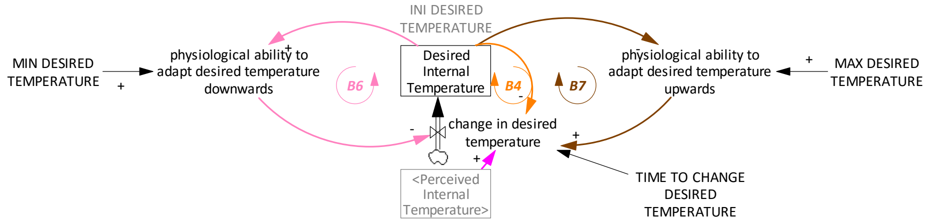

Figure 4: The body's limits of adaptability

Occupants may also affect the temperature by controlling the *extent to which their windows are open* (Guerra Santin, 2012), i.e. opening them more to cool down and closing them to be warmer, as shown in balancing loop *B5* in Figure 5.

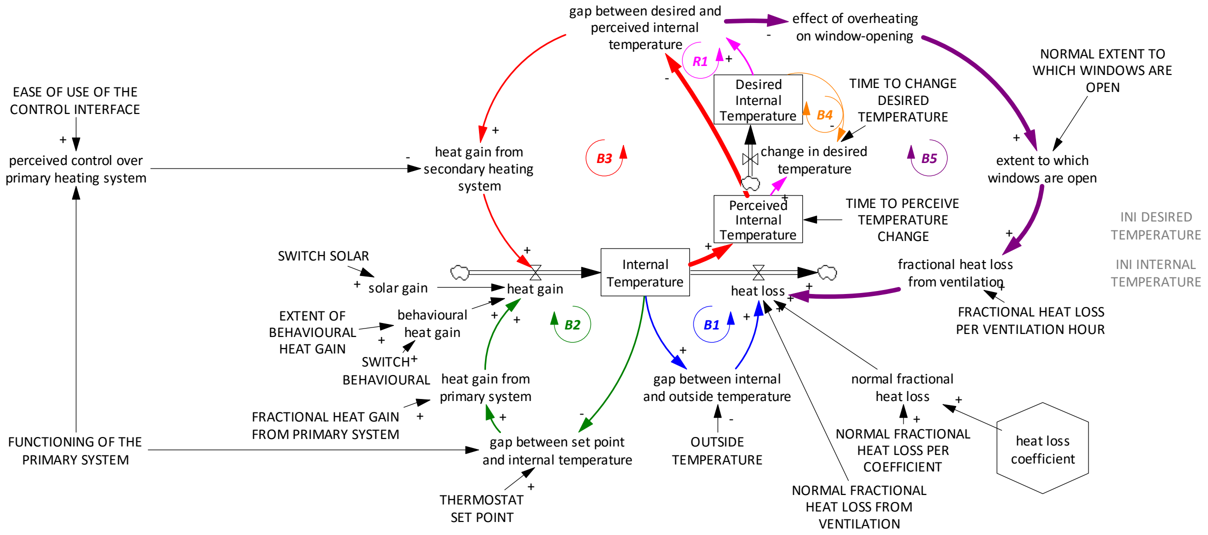

Figure 5: Window opening

In addition to the endogenous mechanisms, the model captures the *energy consumption* of the primary heating system as well as the secondary heating system for the purpose of comparison and analysis (see Figure 6).

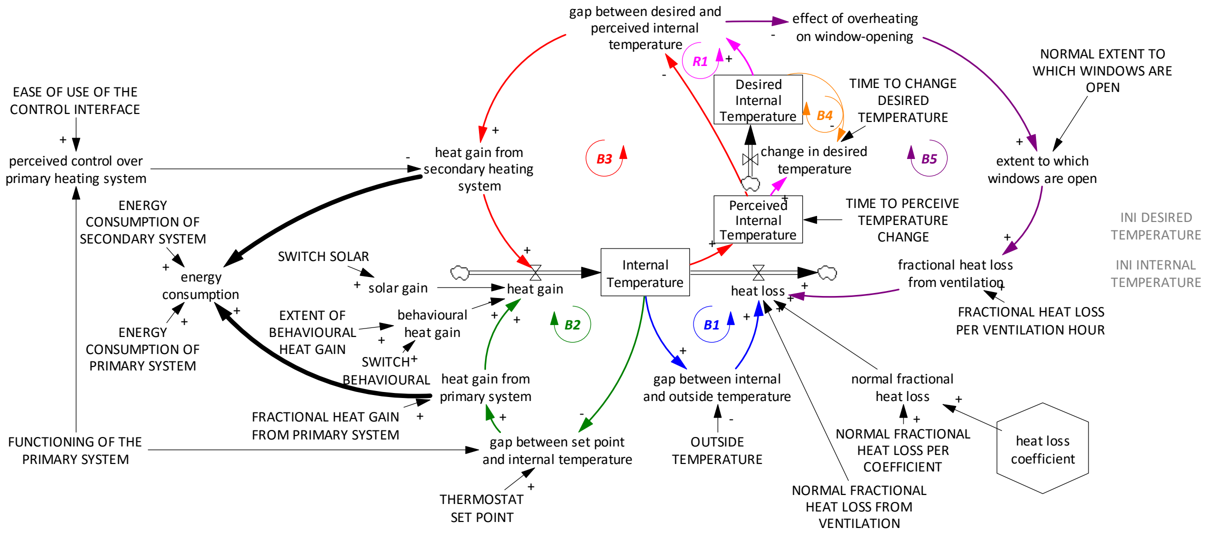

Figure 6: Energy consumption

Overall, Figure 7 shows that we can describe the model through its major feedback loops: two balancing loops (*B1* and *B2*) by which internal temperature adapts to outside temperature as well as the thermostat set point, two balancing mechanisms of secondary heating (*B3*) and window opening (*B5*) depending on comfort, and two reinforcing mechanisms (*R1* and *R2*) by which desired temperature follows actual conditions and requires more adaptation because of the shifting goal.

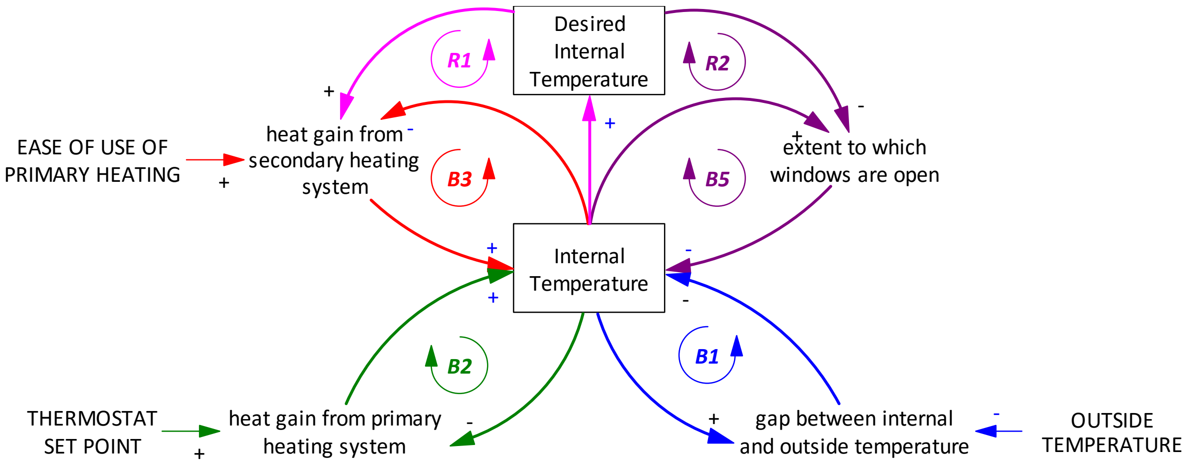

Figure 7: Heating and ventilating causal loop diagram

Validation of the model

The model was structurally and behaviourally validated and we also included some tests about the robustness of insights concerning some uncertainties in parameters and the nonlinear shape of relationships. The model is dimensionally consistent and shows reasonable behaviour under extreme conditions. It was run in Vensim, using Euler integration with a time step of 2^{-7}.

We focused on *structural validity* by concentrating on the major mechanisms that affect indoor temperature in relation to occupant adjustments to this temperature. We primarily based the structure on the case study by Chiu et al. (2013; 2014) who report heating and window-opening as the main mechanisms to control indoor temperature. In general these are strong mechanisms to control temperature; other not considered mechanisms are, for example, solar shading (Andersen, Toftum, Andersen, & Olesen, 2009). There is no correlational agreement in empirical studies on the effect of thermal comfort on window-opening, but Andersen et al. (2009) attribute this to an underlying adaptive feedback mechanism. We modelled this mechanism. However, we did not account for the delays occurring in window-closing that are considered responsible for the low statistical correlations. Our study thus corresponds to other studies focusing on the state of window opening, and not on people’s maybe different motivators and delay times for opening vs. closing windows (Fabi, Andersen, Corgnati, & Olesen, 2012). As it was irrelevant to Chiu et al.’s case study, we considered the possible adaptation of the thermostat set point to be outside the model boundary. We modelled desired temperature as an adaptive feedback mechanism, as was also identified by Brager and de Dear (1998), thus supporting the first-order exponential smoothing used in the model. The HLC is generally simplified as a constant that indicates the proportional heat loss through the outside shell of a dwelling (BRE, 2014). The proportionality warrants its modelling as a balancing mechanism.

We *parameterised* the model with regards to the HLC, a stronger primary and a weaker secondary heating system, adaptation times for perceived and desired temperature, and window-opening. We assumed that the greatest adaptability in desired temperatures occurs around 21°C. It matches the UK climate and clothing as well as some degree of activity in the dwelling. It concurs with other studies who report preferred indoor temperatures between 19 and 23°C (for overviews see Brager & de Dear, 1998; Mishra & Ramgopal, 2013). The comfort values could easily be adapted to represent different cultures, climate and humidity. Window-opening is affected by physical, environmental, contextual, psychological, physiological and social factors (Fabi et al., 2012), all of which we summarised by one inversely s-shaped nonlinear effect, indicating that occupants open (close) windows when they feel too warm (cold). We so far assumed that, relative to the normal extent to which windows are open, occupants open their windows up to ten times wider when they feel too warm than if they are comfortable and they reduce the opening by up to a factor of ten when they feel cold. Assuming that some windows may have trickle vents that are open in their normal state and can be shut when occupants feel too cold and that other windows may be fully opened when occupants feel too warm, this seemed a reasonable assumption, but could be investigated further.

The model replicates the *behaviour* of the cases reported in Chiu et al. (2013; 2014) that we chose as our reference mode. It is also able to replicate the behaviour of other cases reported in Chiu et al (2013; 2014) under different parameterisations representing the respective retrofit strategies for the dwellings in terms of the HLC and capacity of the heating system as well as the occupants' perceived ease of use of it. However, the model is intended not only to be tied to a specific case, but have generic applicability for understanding occupants' interaction with heating and ventilation systems of their homes.

The model behaviour was sensitive to the assumptions we made, not in relation to the overall patterns of behaviour which it replicates well, but to the question what degree of heat gain is necessary to increase the desired temperature and trigger rebound. We thus have confidence in the model's structure, but we would recommend to improve our assumptions of parameter values if the model is to be used for more exact analyses rather than for system explanation and understanding.

Behavioural analyses

In the base run, we investigated the reported situation prior to the retrofit with an assumed heat loss coefficient of 1.5 W m^{-2} K^{-1} to represent high heat loss through walls, windows, roofs and floors. We assume that before the retrofit the primary heating system was not yet in place and temperature was moderated via a system that works by handling a thermostatic radiator valve or other heating elements based on occupant comfort, thus operating like a secondary heating system. We excluded all external disturbances and investigated how the model behaves with external temperature set to 10°C and initial desired internal temperature set to 21°C. Figure 8 shows that, as expected, in the base run (red line 1) the model reaches equilibrium at a temperature somewhere between the external temperature and thermostat set point, here at a rather cold 17°C. In Table 1 we list the model parameters used and we show the full model and its equations in the appendix.

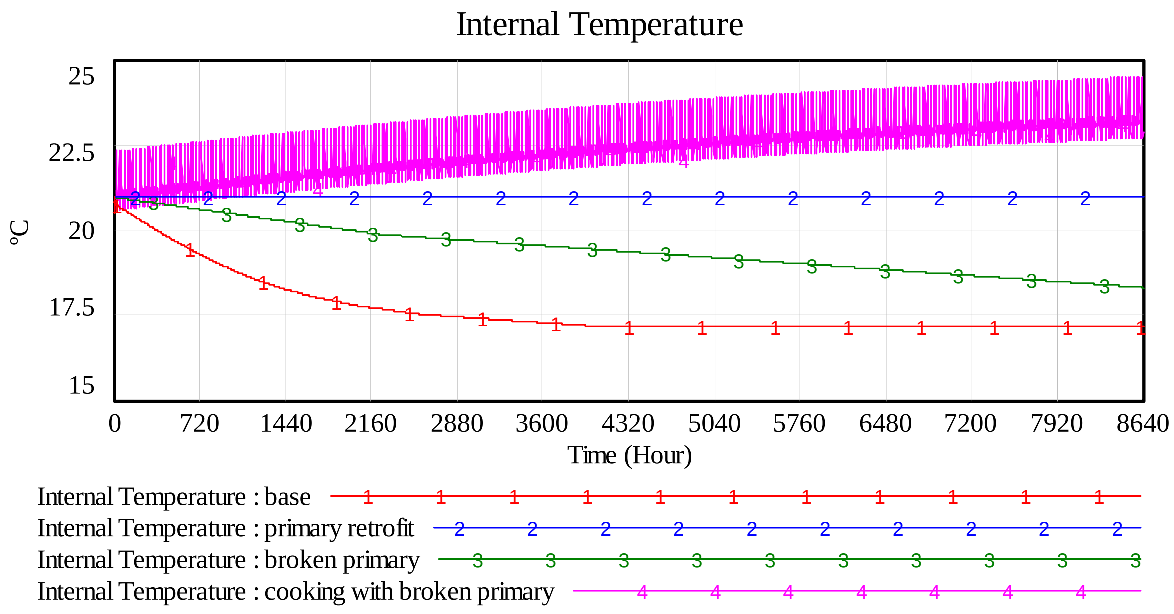

Figure 8: Model behaviour

In order to ascertain whether the model is able to replicate the behaviour observed, we simulated the situation post retrofit. We compare further simulation runs in Figure 8 (and Table 1). Blue line 2 shows the situation post retrofit with a low heat loss coefficient of 0.1 W m^{-2} K^{-1} and the primary system working. It results in equilibrium around 21°C. However, the new system failed in several dwellings; green line 3 shows the resulting decrease of internal temperature to ca. 18.5°C. We are still unable to simulate the observed temperature of about 24°C.

Assuming that occupants cook for an hour every day, we introduced a time-varying pulsatile input into the model via behaviourally-induced heat gains. In the post-retrofit scenario with a broken primary heating system we assume that cooking heats the house by 1.5°C over the course of an hour from 6 to 7 pm. Pink line 4 in Figure 8 now replicates well the temperatures that were observed and we will next analyse the reasons why.

Table 1: Parameters (0=non-functioning or switch off and 1=functioning or switch on)

	Base	Primary retrofit	Broken primary	Cooking with broken primary
heat loss coefficient (W m^{-2} K^{-1})	1.5	0.1	0.1	0.1
functioning of the primary system	0	1	0	0
behavioural switch	0	0	0	1

Further analyses revealed that the temperature increase does not result from the cooking heat gain per se, but that endogenous dynamics determine whether the additional heat will actually change the temperature. Average temperature hardly increases (1) when the heat increase from cooking is flat (i.e. distributed over the entire day) and (2) when the primary heating system is working. The rise in temperature up to 24°C thus does not only occur from the heat gain associated with cooking, but interestingly by how the pulsatile nature of cooking interacts with the model structure when the primary heating system is off.

The model structure is able to explain the behavioural differences. Therefore we compare the actual and desired internal temperature of the 'cooking with broken primary' simulation run, shown by pink line 4 in Figure 8 and the pink line 2 in Figure 9 that replicate the reference mode. The strong increase in temperature from cooking permanently shifts desired temperature (purple line 2 in Figure 9) upwards, thus shifting the goal that the system reaches asymptotically. This is captured by the reinforcing feedback loop *R1* that is responsible for the temperature shift and explains why some interviewees appear to be comfortable under fairly warm conditions. If cooking occurrence is flat, this reinforcing loop is never triggered so strongly.

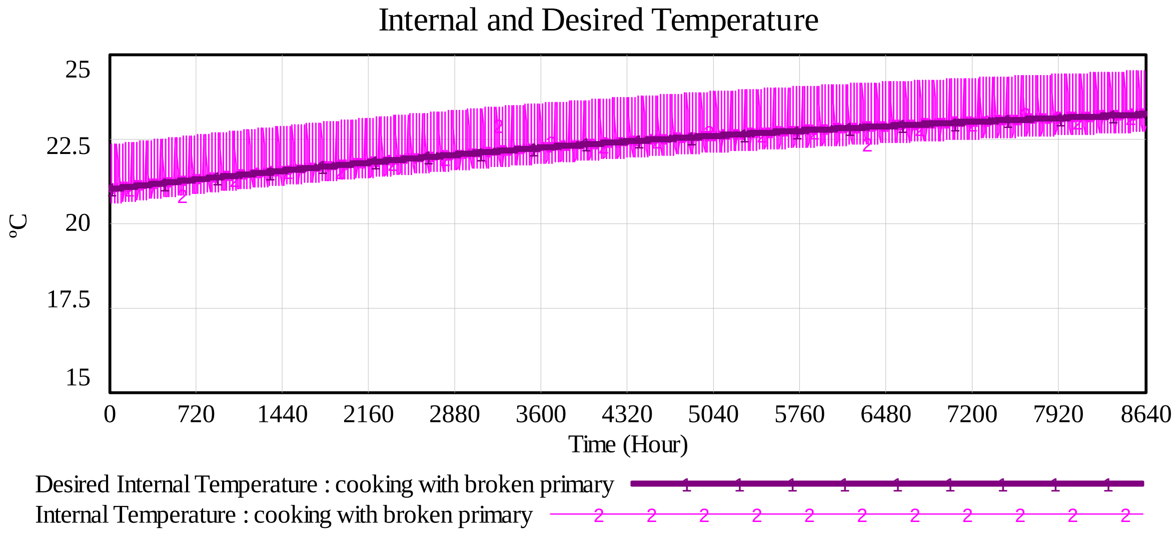

Figure 9: Actual and desired temperature (cooking with broken primary)

Discussion

The increase in occupants' desired temperature as caused by the non-homogeneous inputs from cooking represents an interesting phenomenon that offers a different explanation of the rebound effect than what can be found in the literature. It suggests that endogenous structure strongly transforms these pulsatile inputs which makes it worthwhile to investigate non-homogeneous system dynamics models.

Structurally, the issue bears similarity with the eroding goals archetype and Forrester's (1968b) market growth study. The sudden increase in the occupants' *perceived temperature* from cooking heat gains shifts the actual system state and pushes the desired temperature upwards. Thus we see a mechanism of shifting goals upwards. Each evening, cooking slightly increases the desired temperature so that until the next afternoon the system adapts to this raised goal.

As internal temperatures around 24°C consume more energy than around 21°C, we observe a rebound effect in the sense that the energy efficiency measures do not fully translate into energy savings. We can also conclude that the process of retrofitting resulted in higher internal temperatures (HIT), thus extending previous empirical results that found positive correlations between the dwelling's energy efficiency and internal temperature (Kelly et al., 2013). However, our model offers an alternative explanation by highlighting adaptation as a possible mechanism as a result of simulating a dwelling before and after retrofit rather than comparing across different energy efficiency levels at one point in time. In addition, it provides a structural account of the process of adaptation in which HIT could be explained by a shifting goal mechanism. This proposition contradict the idea that HIT occurs because occupants adapt to a constant desired temperature.

By representing the interactions among the technical heating systems, temperature and occupants' decision-making, this study also reveals socio-technical relationships between heating systems, their operation and occupant comfort. HIT occurs in the feedback mechanisms that have both human and technical elements.

Limitations, future research and conclusions

This study represents decision-making about heating and ventilation with the respective technical systems in dwellings. We represent occupants' decisions about heating and ventilating as an effect of perceived temperature and exclude the explicit representation of factors such as sticky air, perceived energy costs, different use of rooms or the interaction of window-opening with solar shading, which are known to interact with occupants' heating and ventilation behaviour. Further limitations include the lack of information on occupant behaviour, making it difficult to more exactly parameterise the model and define the nonlinear shape of the effect of feeling too cold or too warm on heating and ventilation. The presented analyses are also limited as we did not simulate differences in solar gains, in outside temperature, in the ease of use of the primary heating's control interface or in day-time vs. night-time desired temperature.

While system dynamics modelling emphasises continuous modelling and endogeneity (Forrester, 1968a; Forrester, 1968c; Richardson, 2011), this study also shows that exogenous inputs, such as incidental heat gains in this case, may be transformed very differently, motivating future research on the analysis of time-varying inputs with system dynamics. System dynamics objects in principle to a focus on discrete decisions and events and focuses instead on the continuous creation of a situation that arises from multiple pressures that emerge through the system structure (Forrester, 1968a; Forrester, 1968c; Forrester, 1971; Richardson, 2011). It is then no wonder that system dynamicists have avoided focusing on the effects of external disturbances or influences that are often represented by pulses or trends. Nevertheless, our study corresponds to other examples of market adaptation when it would be worthwhile analysing external disturbances with system dynamics (Milling & Zimmermann, 2010; Sastry, 1997; Zimmermann, 2011). Investigating how endogenous pressures shape the reaction to the more abrupt external effects is thus a worthwhile route that strengthens rather than counteracts the importance of endogenous structure.

Acknowledgments

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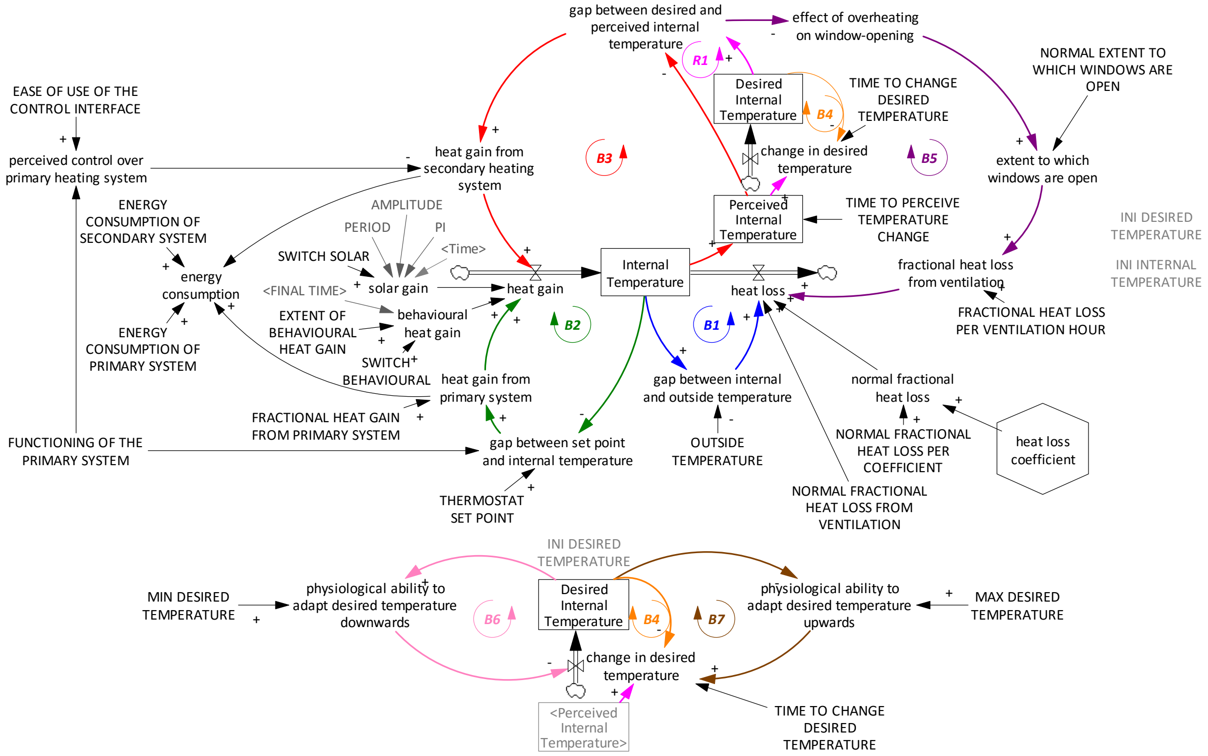
Appendix



AMPLITUDE = 0.1
Units: °C/Hour
Height of the cosinus oscillations. This needs to be a value between 0 and 0.5. It can also be an oscillation itself to represent seasons.

behavioural heat gain = PULSE TRAIN(18,1, 24, FINAL TIME) * EXTENT OF BEHAVIOURAL HEAT GAIN * SWITCH BEHAVIOURAL
Units: °C/Hour
Temperature change due to e.g. cooking, use of appliances, etc.

change in desired temperature = (Perceived Internal Temperature - Desired Internal Temperature) / TIME TO CHANGE DESIRED TEMPERATURE * physiological ability to adapt desired temperature downwards * physiological ability to adapt desired temperature upwards
Units: °C/Hour

This indicates how much the desired temperature changes. It is part of a smooth, moderated by the body's physiological ability to adapt further.

Desired Internal Temperature = INTEG (change in desired temperature, INI DESIRED TEMPERATURE)
Units: ºC
The temperature that inhabitants feel most comfortable at. Inhabitants adapt their desired temperature to the actual conditions they live in. This is modelled as a smooth of the perceived temperature.

EASE OF USE OF THE CONTROL INTERFACE = 1
Units: Dmnl
Dimensionless variable that indicates how easy it is for the occupants to operate the primary heating system. A value of 1 indicates that it is very easy; a value of 0 indicates that it is totally incomprehensible, rendering the inhabitants incapable of using the system. Values in between are possible.

"effect of overheating on window-opening" = WITH LOOKUP (gap between desired and perceived internal temperature, ([(-1,0)-(1,10)],(-1,10),(-0.5,10),(0,1),(0.5,0.1),(1,0.1)))
Units: Dmnl
Variation in the normal tendency to open windows depending on feeling too cold or too warm.

energy consumption = INTEG (ABS(heat gain from primary system) * ENERGY CONSUMPTION OF PRIMARY SYSTEM + heat gain from secondary heating system * ENERGY CONSUMPTION OF SECONDARY SYSTEM, 0)
Units: W
Total consumption of energy from primary heating system and secondary heating system.

ENERGY CONSUMPTION OF PRIMARY SYSTEM = 1000
Units: W/ºC
The energy consumption of the primary heating system.

ENERGY CONSUMPTION OF SECONDARY SYSTEM = 2000
Units: W/ºC
The energy consumption of the secondary heating system.

EXTENT OF BEHAVIOURAL HEAT GAIN = 1.5
Units: ºC/Hour
Extent of temperature change due to e.g. cooking, use of appliances, etc.

extent to which windows are open = "effect of overheating on window-opening" * NORMAL EXTENT TO WHICH WINDOWS ARE OPEN
Units: Dmnl
Fraction of time with open windows, depending on a normal propensity to open windows and the effect of feeling hot or cold.

FINAL TIME = 8640
Units: Hour
The final time for the simulation.

FRACTIONAL HEAT GAIN FROM PRIMARY SYSTEM = 0.5
Units: Dmnl/Hour
Fraction of the thermostat - actual temperature gap that the primary heating system closes per hour. To model this as a fractional instead of an absolute change is a simplification.

fractional heat loss from ventilation = extent to which windows are open * FRACTIONAL HEAT LOSS PER VENTILATION HOUR

Units: Dmnl/Hour
Fractional adaptation of the internal temperature to the outside temperature from open windows.

FRACTIONAL HEAT LOSS PER VENTILATION HOUR = 0.1
Units: Dmnl/Hour
Fractional adaptation of inside to outside temperature per hour when windows are open.

FUNCTIONING OF THE PRIMARY SYSTEM = 0
Units: Dmnl
Dimensionless variable that indicates whether the primary system is functioning (value 1) or not (value 0).

gap between desired and perceived internal temperature = Desired Internal Temperature - Perceived Internal Temperature
Units: ºC
The temperature difference between desired and perceived temperature. It indicates whether inhabitants feel too cold (positive gap) or too warm (negative gap).

gap between internal and outside temperature = Internal Temperature - OUTSIDE TEMPERATURE
Units: ºC
Temperature difference between inside and outside.

gap between set point and internal temperature = (THERMOSTAT SET POINT - Internal Temperature) * FUNCTIONING OF THE PRIMARY SYSTEM
Units: ºC
Temperature difference between the thermostat setting and the internal temperature.

heat gain = heat gain from primary system + heat gain from secondary heating system + solar gain + behavioural heat gain
Units: ºC/Hour
Rate of increase of the internal temperature.

heat gain from primary system = MAX(gap between set point and internal temperature * FRACTIONAL HEAT GAIN FROM PRIMARY SYSTEM, 0)
Units: ºC/Hour
Temperature change due to heating by the primary heating system.

heat gain from secondary heating system = WITH LOOKUP ((1 - perceived control over primary heating system) * gap between desired and perceived internal temperature, ([(-10,0)-(10,100)], (-1,0),(0,0),(1,2),(10,10)))
Units: ºC
Heat emitted from a secondary heating system such as an electrically operated radiator, a tumble dryer used for the purpose of heating, or else.

heat loss = gap between internal and outside temperature * (normal fractional heat loss + fractional heat loss from ventilation + NORMAL FRACTIONAL HEAT LOSS FROM VENTILATION)
Units: ºC/Hour
Rate of decrease in the internal temperature.

heat loss coefficient = 0.1
Units: W/(m2*k)
Coefficient representing the walls' energy efficiency.

INI DESIRED TEMPERATURE = 21
Units: ºC

Initial conditions for desired internal temperature.

INI INTERNAL TEMPERATURE = 21
Units: ºC

INITIAL TIME = 0
Units: Hour
The initial time for the simulation.

Internal Temperature = INTEG (heat gain - heat loss, INI INTERNAL TEMPERATURE)
Units: ºC
The air temperature in the house/flat/room.

MAX DESIRED TEMPERATURE = 25
Units: ºC
Maximum temperature to feel comfortable at.

MIN DESIRED TEMPERATURE = 17
Units: ºC
Minimum temperature to feel comfortable at.

NORMAL EXTENT TO WHICH WINDOWS ARE OPEN = 0.04
Units: Dmnl
Normal tendency to open windows, measured in the fraction of time the windows are open.

normal fractional heat loss = heat loss coefficient * NORMAL FRACTIONAL HEAT LOSS PER COEFFICIENT
Units: Dmnl/Hour
Fractional adaptation of inside to outside temperature through walls.

NORMAL FRACTIONAL HEAT LOSS FROM VENTILATION = 0.001
Units: Dmnl/Hour
Fractional adaptation of the inside temperature to the outside temperature due to the airflow of the ventilation system.

NORMAL FRACTIONAL HEAT LOSS PER COEFFICIENT = 0.025
Units: Dmnl/Hour/(W/m2/k)
Fractional adaptation of inside to outside temperature based on the heat loss coefficient.

OUTSIDE TEMPERATURE = 10
Units: ºC
Air temperature outside.

perceived control over primary heating system = EASE OF USE OF THE CONTROL INTERFACE * FUNCTIONING OF THE PRIMARY SYSTEM
Units: Dmnl
Dimensionless variable that indicates the inhabitants' ability to use and control the primary heating system. The more difficult it is to use and control the primary system, the more the occupants also use a secondary heating system.

Perceived Internal Temperature = SMOOTH(Internal Temperature, TIME TO PERCEIVE TEMPERATURE CHANGE)
Units: ºC

Temperature perceived by the dwelling's inhabitants. It differs from the actual temperature because the body does not heat up or cool down instantaneously, creating a lag in the perception of temperature. This is modelled as a smooth of the actual internal temperature.

PERIOD = 24
Units: Hours

physiological ability to adapt desired temperature downwards = WITH LOOKUP (Desired Internal Temperature - MIN DESIRED TEMPERATURE, ([(-1,0)-(9,1)],(-1,0),(0,0),(0.5,0.1),(1,0.3),(2,0.66),(3,0.8),(5,0.94),(7,0.98),(9,1)))
Units: Dmnl
The body's physiological ability to adapt further to a lower comfort temperature.

physiological ability to adapt desired temperature upwards = WITH LOOKUP (MAX DESIRED TEMPERATURE - Desired Internal Temperature, ([(-1,0)-(9,1)],(-1,0),(0,0),(0.5,0.1),(1,0.3),(2,0.66),(3,0.8),(5,0.94),(7,0.98),(9,1)))
Units: Dmnl
The body's physiological ability to adapt further to a higher comfort temperature.

PI = 3.14159
Units: Dmnl

SAVEPER = 1
Units: Hour [0,?]
The frequency with which output is stored.

solar gain = (AMPLITUDE - AMPLITUDE*COS(2*PI*Time/PERIOD)) * SWITCH SOLAR
Units: ºC/Hour
Temperature change due to solar gain.

SWITCH BEHAVIOURAL = 0
Units: Dmnl
Variable to enable or disable behavioural heat gains. Used in model analysis and testing.

SWITCH SOLAR = 0
Units: Dmnl
Variable to enable or disable solar heat gains. Used in model analysis and testing.

THERMOSTAT SET POINT = 21
Units: ºC
The temperature the primary heating system's thermostat is st to.

TIME STEP = 0.0078125
Units: Hour [0,?]
The time step for the simulation.

TIME TO CHANGE DESIRED TEMPERATURE = 72
Units: Hours
Time to adapt the desired temperature. Empirical research indicates that the adaptation delay is about 3 days.

TIME TO PERCEIVE TEMPERATURE CHANGE = 2
Units: Hours
Time to adapt the perceived temperature. The body does not heat up or cool down instantaneously, causing a lag in the perception of temperature.