Misconceptions regarding the self-attenuation of residential building energy retrofit policies? – Validation via disaggregation

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The reduction of heat energy consumption of buildings constitutes an important pillar in the greenhouse gas emission reduction strategies in Germany. This research investigates whether these strategies may suffer from a misconception of dynamic feedback. At first, a very simple model is introduced, as a hypothesis of oversimplified mental models in use. It is contrasted with a very simple dynamic model, which is then elaborated to more complex model versions by including more structural detail to test its validity. This seems to refute the initial hypothesis at first but with further disaggregation supports it again. However, model elaboration also surfaced that stock depletion may be partly circumvented by certain policies, but it is uncertain for how long. Since therefore simple mental models could lead to correct inferences about short-term system behavior, it may be difficult for actors to discover their misconception. This highlights the need to reduce this uncertainty.

Keywords: thermal home retrofit, residential building energy retrofit, energy transition, misconceptions of dynamics systems, public policy, Germany, validation by disaggregation

Introduction

Heating of buildings in Germany relies heavily on fossil fuels and is responsible for 40% of the German final energy demand and results in a third of Germany's greenhouse gas emissions (BMWI, BMU 2011). It also implies a dependence on fossil fuels from foreign countries, the political stability of which in some cases may appear doubtful. Since a large proportion (66%) of residential buildings in Germany have been raised before the first thermal protection ordinance (1978) and because of the low energy retrofitting activity, there is a high potential of energy-savings through energy retrofits in Germany: In 2009 more than two thirds of the building stock were old and had not been energetically retrofitted yet (BMVBS, IWU 2013). In addition, building retrofits are often considered to be a very cost-efficient way of greenhouse gas abatement, in fact incurring a negative cost i.e. at a long-term profit (see e.g. GHG-abatement cost curves for Germany in: McKinsey & Company 2007)

In consequence, the transition of the building stock to high-efficiency-low-carbon heating has been declared a key priority of the Energy Concept of the federal German government (BMWI, BMU 2011). The building sector is expected to yield a major proportion of the total envisioned greenhouse gas and energy consumption reductions: The Energy Concept of the German government aims at reducing the final heating energy demand by 20% until 2020 (2008-basis) and to reduce the primary energy demand for heating of buildings by 80% by 2050 (BMWI, BMU 2011). The remaining primary energy demand is to be supplied by renewable energy, so that a carbon-neutral building stock is reached (BMWI, BMU 2011). It is furthermore stated that reaching these goals would require increasing the *retrofitting quota*[1] (the fraction of the total building stock retrofitted each year) from currently 0.8% - 1% to 1.6% - 2%·a^{-1} (BMWI, BMU 2011; BMVBS, IWU 2013).

Problem definition

The Energy Concept is based upon a research report that analyzes different energy scenarios (Schlesinger et al. 2010). The reference scenario in Figure 1 assumes 'business as usual' (BAU) i.e. continuation of the policy path of 2010 and shows decreasing retrofitting quotas. So even without knowing the precise structure of the model used (it is not open for public scrutiny), one can still deduce that the system may have self-attenuating properties. SD-modelers may immediately suspect a first-order delay, i.e. that this self-attenuation may be caused by some sort of stock depletion.

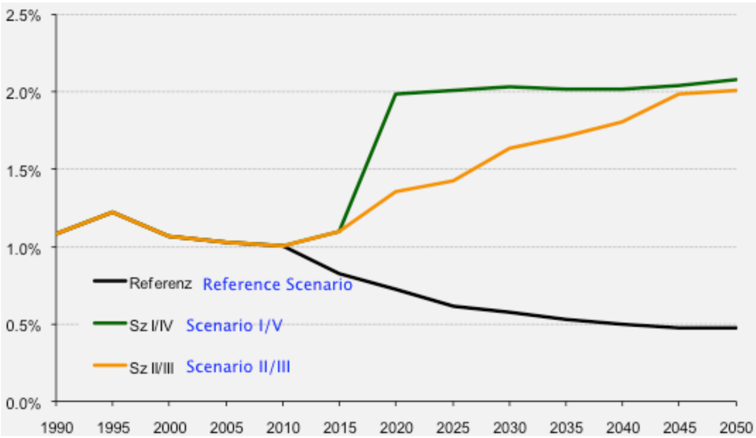


Figure 1: Scenario projections of the fractional retrofitting quota from the study that was the basis of the German Energy Concept (Schlesinger et al. 2010, translations added in blue). The yellow and green scenarios constitute reference modes for this study.

The policy scenarios do not seem to observe self-attenuation at all, which raises suspicion that the policy scenarios and therefore potentially the German Energy concept may ignore some important feedback properties of the system, for example stock depletion.

Simply by being based on historical data, the reference scenario depicted in Figure 1 likely implicitly takes into account properties of buildings, (e.g. age-cohort) and possibly even considers characteristics of the building owners (e.g. self-user, landlord, financial situation) to some degree. It is important to understand that the other two scenarios, which led to the 2%·a^{-1} goal for the retrofitting quotas do not consider such aspects. They are instead only normative *goal-scenarios* using the predefined desired outcomes in terms of energy use reduction and carbon neutrality mentioned above and only answering the question as to how a certain indicator (the retrofitting quota) would need to develop to reach these goals (Schlesinger et al. 2010; Kemmler, pers. comm.).

However, in order to reach the primary energy demand reduction and carbon neutrality goals within the specified time horizon it is likely insufficient to merely know how indicators of policy success should develop. For policy design it would likely be helpful if feasibility considerations including obstacles/resistance caused by stock depletion could be anticipated to get a more realistic estimation of the policy effort/policy intensity necessary to reach goals in time. So if the policy scenarios in Figure 1 have lead to misconceptions of dynamic feedback (ignoring stock depletion) in the German Energy Concept, this may be important to clarify.

[1] In Germany, what is termed *retrofitting quota* here is usually termed *retrofitting rate (German: Sanierungsrate")*. The term *retrofitting quota* is used here for this indicator that always uses the total buildings stock as its basis, in order to avoid confusion with the flows, which are normally termed *rates* in System Dynamics lingo and also to avoid confusion with fractional rates.

The main hypotheses here are:

a) The political discussion (and to some degree also the scientific discussion) is permeated by the implicit assumption that the indicator *retrofit quota* reacts proportionally to policy changes and stays at the same level as long as the same policy is in place.
b) Retrofitting behavior is actually exhibiting self-attenuation caused by the depletion of renovation potential and that therefore the self-attenuation should become even stronger if policies increase retrofitting rates

Outline and methods

The focus of this paper is on validating hypothesis b. The important question in this respect is whether adding more structural detail to a dynamic model representing hypothesis b could lead to such behavior as the yellow and green scenarios (reference mode behavior pattern) and thereby refute b.

Hence, the argumentation below first introduces a model of building energy retrofits that is supposed to represent the oversimplified mental models in use. This model is then contrasted with a simple dynamic model that takes account the self-attenuation that retrofitting quotas may experience that have been raised by policies and that is due to the depletion of renovation potential. For this comparison purpose the dynamic model is first held at the same level of simplicity/generality.

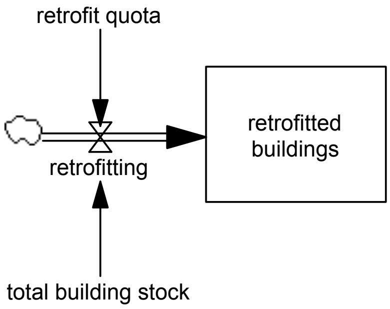
Afterwards more and more structural detail is successively introduced into the dynamic model to test whether the hypothesis of the self-attenuation is only an artifact of over-simplification of the first model, and whether it may be overcompensated by other mechanisms. In this process additional structures are introduced and the model is disaggregated. This process allows for relaxing some ad-hoc assumptions and using other more plausible, less ad-hoc assumptions instead. This validation via disaggregation represents a boundary adequacy test (Barlas 1996). What is termed *policy* in the models are actually merely intervention points where real policies may influence the retrofit behavior. While this cannot be sufficient to design effective policies, it allows for examining if there is a risk for underestimating the policy intensity necessary to reach and / or maintain elevated retrofitting quotas.

Models

The model diagrams shown below have been focused on the essential model components. Structures are needed only for initialization and indicator calculation have been left out but are included in the supporting online material and the included model files.

Figure 2 shows two contrasting simple mental models of building retrofit: much of the discussion including the German Energy concept seems to be permeated with the non-dynamic mental model: The *retrofit quota* (fraction of the total building stock renovated per year) is conceived as a constant fundamental system parameter, i.e. an expression of properties of the residential buildings and its owners that can be influenced by policies though. Consequently, if the total building stock does not change, neither should the *retrofitting* rate, unless policies change.

Non-dynamic mental model of retrofit:



Simple dynamic retrofit model:

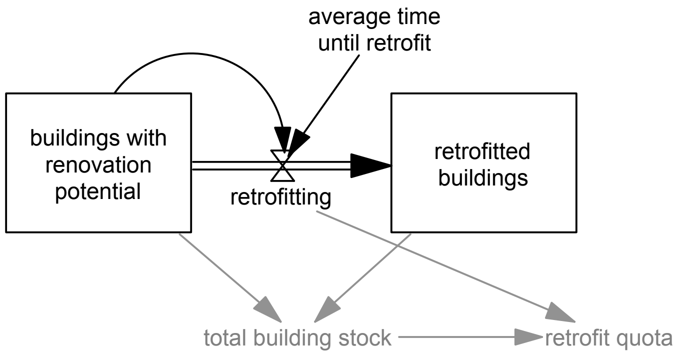


Figure 2: Two contrasting simple mental models of building retrofit

The simple dynamic retrofit model devides the total building stock into two stocks: The *retrofitting* flow depletes the stock of *buildings with renovation potential* and fills up the stock of *retrofitted buildings*. The reason for this differentiation is that renovation potential is known to be an important driver for retrofits, because retrofits are mostly carried out as part of necessary renovations. There are several reasons for this: Firstly, part of the retrofit cost would have accrued anyway in a hypothetical case of a renovation without retrofit. This 'anyhow-cost' is therefore attributed to the renovation, whereas only the retrofitting-related additional cost ('difference-cost'), is attributed to the retrofit. In case of a retrofit without renovation need, the *full cost* is attributed to the retrofit (Discher et al. 2010). Another financial way to look at this is that a house owner (especially commercial ones) may be reluctant to scrap part of the building before the regular end of its lifetime because that would mean distributing its investment cost over a shorter period i.e. increasing investment frequency. While owner-occupiers may think less in terms of return on investment than landlords, they may still postpone the hassle associated with retrofitting construction (dirt, noise, reduced comfort etc.) until the time for unavoidable renovations comes along. Also, from a practical perspective, there are many synergies in combining renovations with retrofits, e.g. scaffolding being installed for plaster repairs and can also be used for installing wall insulation or removal; roof tiles for replacement making it easy to also install insulation.

The reason why the dynamic model shown above is kept at such an oversimplified level in terms of conceptual detail is that it facilitates contrasting it with non-dynamic one that is hypothesized to be a representation of a mental model that seems to be prevalent in some of the political discourse. This contrast shows some core misconceptions:

- The non-dynamic mental model assumes that the *retrofitting* activity is influenced by the whole building stock, the dynamic mental model assumes that it is influenced by the *buildings with renovation potential* only but not by those buildings that have already been retrofitted.
- The non-dynamic mental model assumes that *retrofit quota* is a fundamental system parameter, which subsumes building properties and all other factors influencing house owners in their reno-

vation decisions. In the simple dynamic model, the *average time until retrofit* takes the position of the fundamental system parameter, whereas the *retrofit quota* is only an indicator that may dynamically change. Thus any policies that successfully incentivize house owners to renovate their buildings earlier than they would have otherwise, should increase retrofit activity and thus also the *retrofit quota*. If the stock of *buildings with renovation potential* decreases as a result, so should the *retrofit quota*.

Model 3: Retrofit cycle

The simple dynamic model above has the limitation that it assumes that buildings can only be renovated once. In reality, buildings accumulate renovation potential again some time after a renovation: Modernized heat generators fail, roofs become leaky, façade insulation may deteriorate in its insulating properties the or plaster covering it may come off the building etc. Besides this *technical* aging there is also *subjective aging* (e.g. new technical developments, fashion trends, energy cost, legal changes, consideration of real estate value conservation etc.) that may cause renovations long before technical deterioration (see: Bahr, Lennerts 2010).
To alleviate this shortcoming, Model 3 includes the notion of a renovation cycle. It assumes that after a retrofit a building stays in good condition for a number of years (*average time in good condition*) during which their owners see absolutely no need to renovate them again. After this time, buildings have gained renovation potential again but may still not be renovated immediately but rather may wait for their renovation for a number of more years (*average time until retrofit*). There may be several reasons for such waiting behavior: some owners may need to first accumulate sufficient funds, may not find the time to inform themselves or organize the retrofit or they may simply wait until they must renovate to keep the real estate value from decreasing dramatically.

Note that both processes (*leaving good condition*) and retrofit are implemented as higher order material delays. The reason is that a sudden disturbance of the system should see its delayed response concentrated around the delay time, which is only the case for higher order delays. Retrofit experts describe for example that Eastern Germany experienced strong disturbance of renovation rates caused by the German reunification: within a few years almost all coal-based heat generators were replaced with oil- or natural gas-based ones (Bickel, pers. comm.). Of course one would expect that we see a second, somewhat smoothed wave of heat generator exchange around their average lifetime, which is starting to show now (Bickel, pers. comm.). This is the behavior that a higher order delay can reproduce, whereas a first order delay would have most heat generators being replaced right after they were built in, which does correspond to reality.

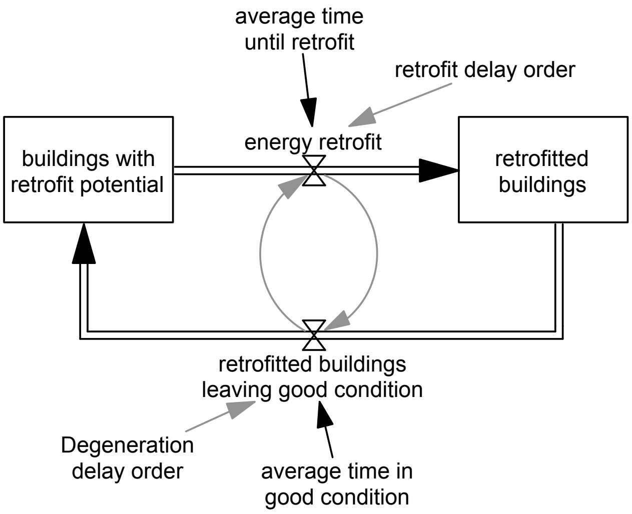


Figure 3: Model 3 – Retrofit cycle model. Note that the flows are all subject to higher order material delays, (hence the arrows from flow to flow). [2]

Model 4: Renovation-Retrofit-cycle

One limitation of the previous dynamic models is that in reality not all opportunities for retrofits opened up by renovations are currently actually utilized (Diefenbach et al. 2010), i.e. some renovations are carried out in such a way that they do not result in any energy savings even though they could. This is important as it principally means that there is room for increasing the *retrofit* rate and consequently the *retrofitting quota* without increased stock depletion, i.e. there may be room for policies that avoid self-attenuation. The amount of room for such kind of improvement is subject to uncertainty (Diefenbach et al. 2010):

- At the low uncertainty boundary only façade plaster repairs, attic conversions and roof tile replacements of heated attics (i.e. no insulation of the of the topmost floor against the attic) are considered retrofit opportunities.
- At the high uncertainty boundary, all roof tile replacements (including non-heated attics) and also any façade paint jobs are considered retrofit opportunities.

[2] Using Vensims built-in *DelayN* function results in connector arrows pointing form flow to flow because each flow is a delayed version of the other. What is not visible of course, is that the flows seen in the model actually depend on the last stocks in the aging chains hidden in the respective *DelayN*-functions. The stocks depicted here are merely used to keep track of the total amount of buildings that are in transit in the hidden aging chains.

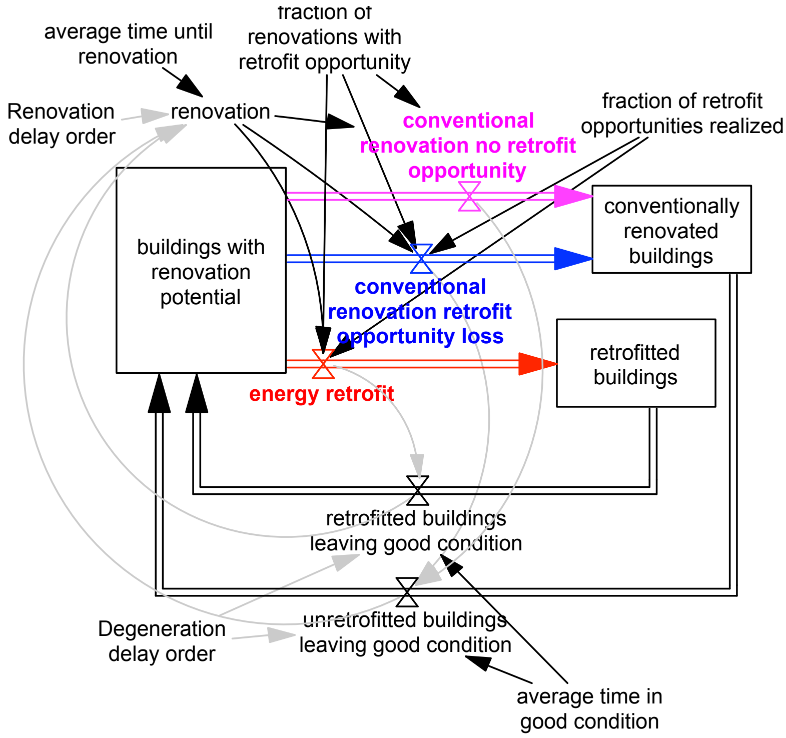


Figure 4: Model 4 – Renovation-retrofit cycle model differentiating energy retrofits from conventional renovations without energy savings.

Model 4 allows for investigating the influence of this uncertainty on the retrofitting performance through a simple sensitivity analysis based on the a.m. upper and lower bounds of uncertainty that are expressed by the *fraction of conventional renovations with retrofit opportunity*. It determines how much of the conventional *renovation* is going through the flows *conventional renovation no retrofit opportunity* and *conventional renovation retrofit opportunity loss*. The latter flow holds potential for policies to increase the *energy retrofit* flow. Both BAU and policy simulation runs are carried out under these differing conditions of uncertainty. The degree to which this potential is realized is determined by the *fraction of retrofit opportunities realized*. This variable can be used to carry out policy experiments (increasing this fraction). These policy runs are subjected to a sensitivity analysis varying the *fraction of conventional renovations with retrofit opportunity* to assess the influence of the uncertainty with respect to how much room for improvement the energy retrofit flow has without increasing the *renovation* rate.

Model 4 includes a number of intervention points for policies influencing the system:

a) decreasing the *average time until renovation*
b) decreasing the *average time in good condition*
c) increasing the *fraction of retrofit opportunities realized*

The first of these can be thought of as getting people to stop waiting with a pending renovation, such as ordinances, (financial) incentives (grants, tax discounts, cheap credits), information campaigns etc.

Policies that make people realize the need to renovate earlier are of the kind (b) noted above. For example, people (unless they are real estate experts) may only notice the appearance of renovation potential with quite some delay, when it becomes clearly visible. Policies aiming at convincing people that replacing a building component would lead to new desirable functions, increase 'subjective' aging and therefore also fall in this category. New functions could e.g. be programmable heating system, fuel switch, enhanced feeling of room heat comfort through insulation etc. Thirdly, policies that mandate the exchange of buildings parts before they become dysfunctional also belong into this category (in Germany for example heat generators above a certain age).

Policies of the sort (c) aim at making people utilize more opportunities to carry out renovations as retrofits (e.g. applying insulation when the outer walls need repair any way) instead of merely restoring the function of the building components without saving energy.

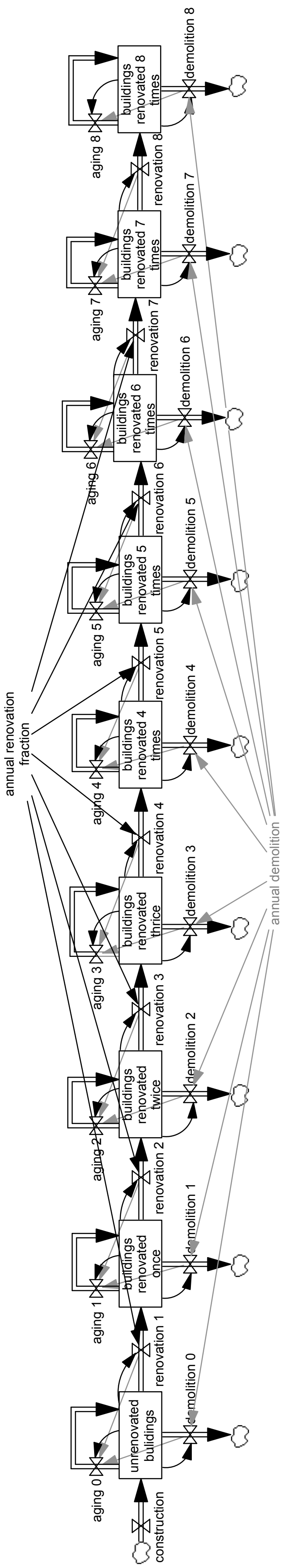


Figure 5: Model 5 – Two-dimensional aging chain with subsequent renovations from left to right and age after renovation going into the depth of the diagram (see Figure 5 for this dimension).

Model 5: 2D renovation aging chain

The models above have certain limitations:

Firstly, in reality it is difficult to pinpoint the transition from being in good condition to having renovation potential. Renovation potential is not dichotomous; rather it is more realistic to assume that buildings accumulate more and more renovation potential with time after the last renovation. There are probably even a few buildings that get renovated very soon after the last renovation (e.g. if the renovation was not carried out properly). From that perspective it seems somewhat arbitrary which flow during the aging process marks the transition from good condition to renovation potential. Secondly, construction & demolition rates are not included. In fact they cannot be included using Vensim's built-in higher order delay function *DELAYN* as it does not support 'leakage' from the invisible stocks.

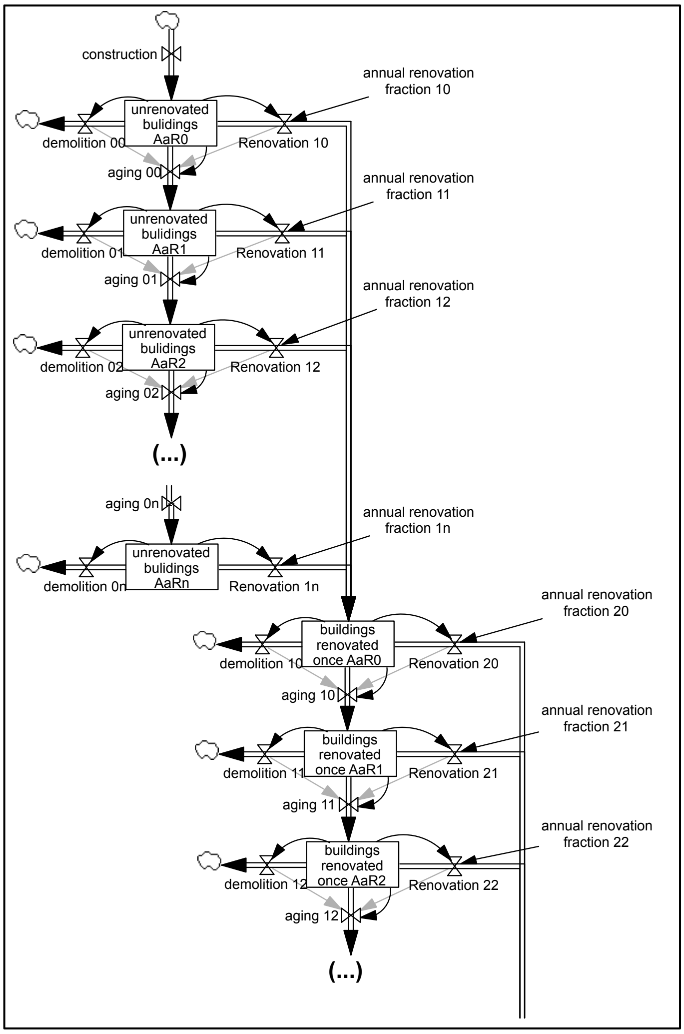


Figure 6: Conceptual side view of the stacks of stocks in the subscripted structure in Model 5

Model 5 alleviates these shortcomings by only assuming the obvious that buildings that have seen a longer time since the last renovation have on average higher renovation rates than those that have been renovated only recently.

To achieve that, Model 5 conceptualizes renovation as a progression along an aging chain with two dimensions: the first dimension is the *age after the last renovation*. Each stock in the picture is actually a stack of stocks that form an aging chain that is hidden in an array (using the subscript function in Vensim). The reader may think of looking at this stack from the top going into the depth of Figure 5. The same structure is shown from the side in Figure 6 to make the concept clearer. Any building is progressing one level deeper into the stack (*aging i*) each year (=*age cohort duration*). In order to make the *aging i* flows visible in this two-dimensional view of Figure 5, they are placed to the top of the stocks. The second dimension is progression towards the side via the *renovation i* flows (Figure 6). All stocks in each stack have renovation out-flows attached, but they all flow into the top-most stock of the next stack only (because the subscript of the stack it is not absolute age but *age after the last renovation*). In addition there are *demolition i* outflows for each stock as well. Naturally the lowest of the stocks in each stack do not have an aging outflow but only a renovation and a demolition outflow. Similar to the renovation flows, the *construction* inflow of new buildings enters only the topmost stock of the first stack of *unrenovated buildings*.

Please also note that Model 5 does not incorporate the notion of differentiating retrofits from renovations that could be retrofits and/or policies aimed at decreasing non-retrofit renovations (as Model 4 does). This has been left out here, not because it would not matter (in reality it is of great concern of course), but it is not expected not affect Model 5 much differently than it the previous models. Furthermore, since each stock would divide an incoming flow (renovation or retrofit) into two outgoing flows (renovation and retrofit), the structure would quickly branch out a lot and would therefore mainly increase visual clutter without yielding much additional insight. Hence, Model 5 can be thought of as only analyzing additional insights that result from analyzing renovation potential along a more continuous spectrum. It does not differentiate conventional renovations and retrofits but includes them both.

It is not surprising that research has shown that older buildings exhibit higher renovation activity (Diefenbach et al. 2010). The model therefore assumes that buildings accumulate renovation potential with time unless renovated: The *annual fraction of buildings renovated* increases with the subscript *age after renovation* i.e. with increasing depth of the stack.

For simplicity's sake, the *annual fraction of buildings renovated* is assumed to be the same for all subsequent renovation stages. This assumption also implies that a renovation brings a building back to the quality it had when it was first constructed since it is assumed to gain renovation potential at the same rate as a new building.

As demolition is an alternative option to renovation that reacts to the same fact that a building has accumulated renovation potential, it is reasonable to model the *annual demolition fraction* in a manner very similar to the *annual fraction of buildings renovated*. To keep things simple, the *demolitions to renovations ratio* simply assumes that the *annual demolition fraction* is certain fraction of the *annual fraction of buildings renovated*, but happening in addition to the latter

The aging chain was cut off after the stack of *buildings renovated 8 times* as this was found to be sufficient to examine the effects of self-attenuation of increased renovation rates.

Model Analysis & Discussion

Simple non-dynamic and dynamic retrofit models

Parameterization and Simulation Setup:

Due to their conceptual nature, the model assumes a total number of buildings of 100 to make fractions easier to oversee respective fractions while keeping correct account of units. Furthermore precise initializations are not known for all stocks due to lack of data availability any way. In order to keep things comparable to the static model, the policy setup for the simple dynamic model (Figure 6) involves a ramp-down of the *average time until retrofit* by a fraction (-57.5%) that corresponds in size to the ramp-up of the retrofit quota in the static case.

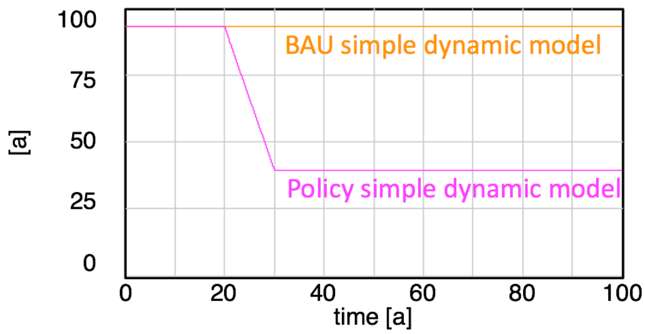


***Figure 6: Policy setup: Ramp-down of* average time until retrofit**

Simulation Results, Analysis and Discussion:

As can be seen in Figure 7, the static retrofit model qualitatively reproduces the green and yellow scenarios from Figure 1 (reference modes). So if decision makers use this mental model it would explain why they expect that increasing the renovation quota to $2\% \cdot a^{-1}$ would allow for retrofitting the whole building stock from within 40 years (2010 to 2050) while under BAU-conditions this transition is suggested to take almost 100 years (red and blue, respectively). The runs from the simple dynamic model depicted in Figure 8 suggest however, that this diffusion may take much longer due to the depletion of the stocks of *buildings with renovation potential* that results in decreasing retrofitting quotas (Figure 8).

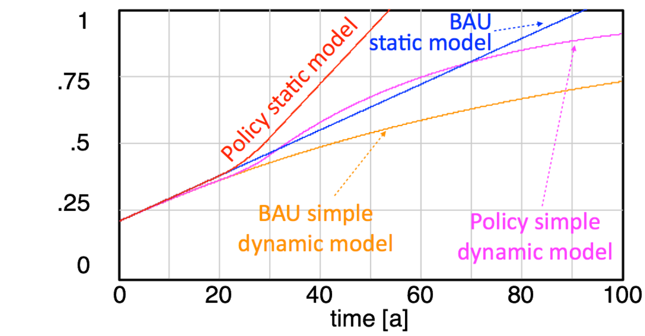


Figure 7: Total fraction retrofitted. (BAU: business as usual)

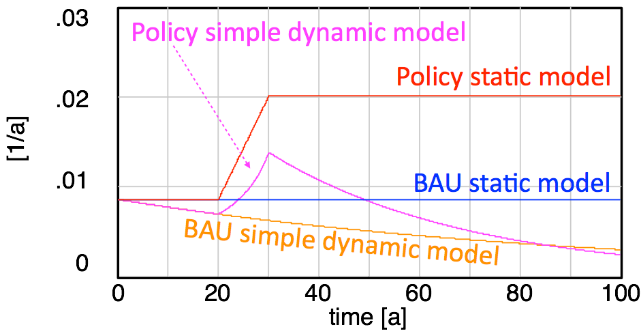


Figure 8: Retrofit quota. (BAU: business as usual)

Model 3: Retrofit cycle

Parameterization and Simulation Setup:

The total amount of buildings was set to 100 buildings to avoid the need to calculate fractions, the initial value of *retrofitted buildings* is known to be at 21 % (BMVBS, IWU 2013). The initial *average time until retrofit* was set so that the initial energy retrofit quota is at 0.85%·a^{-1} (Diefenbach et al. 2010). The *initial average time in good condition* was determined so that the model is initially in flow equilibrium based on the initial values of the stocks and the *average time until retrofit*. Note that in reality the system is unlikely in equilibrium. However, initial equilibrium makes it much easier to observe the influence of policy instruments.

As there is no data available that would allow for calculating the delay orders, they were assumed to be 15 for the *leaving good condition* flow and to 7 for the *retrofit* flow. The reasoning for the choice is that it can be assumed that the former flows are governed largely by processes of physical deterioration and that many building components experience a long time without any failure (hence higher delay orders as the response is relatively tightly centered around the adjustment time), whereas the latter flows are mainly governed by decisions that can vary a lot depending on individual conditions of house owners and therefore have a higher spread around the adjustment time.

The policy setup was identical to the previous model in order to compare model results.

Simulation Results, Analysis and Discussion:

When looking at Figure 9 the comparison of the development of the retrofit quota in the retrofit cycle model with the static model and the simple dynamic model it can be seen that while there still is some self-attenuation in the renovation cycle case it is considerably less than for the simple dynamic model. The replenishment from the *leaving good condition* flow leads the stocks to stabilize at a new level on the long run (see Figure 10), which also means that the retrofit quota will stabilize at a level lower than the aimed for 2%·a^{-1}.

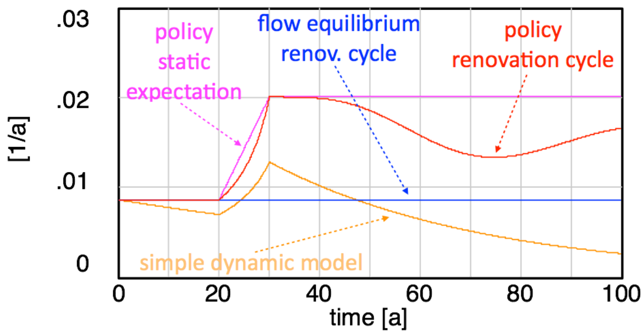


Figure 9: Renovation quota of the renovation cycle model with and without policy and static model and simple dynamic model for comparison.

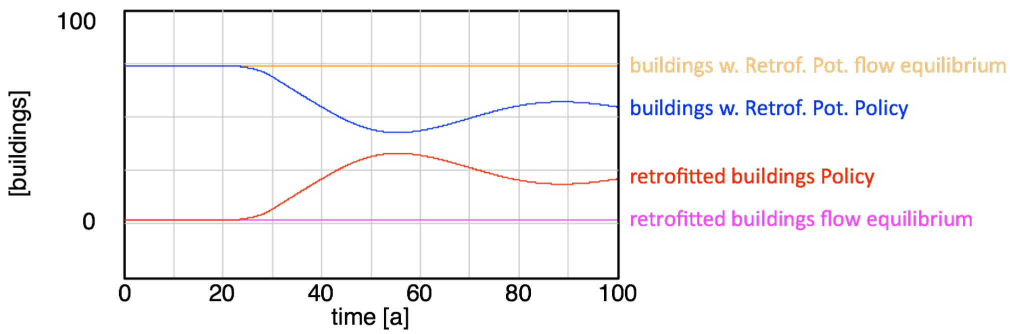


Figure 10: Stock development of the renovation cycle model with and without policy.

In Figure 11, the difference in the developments of the total fraction retrofitted in the static case vs. the retrofit cycle shows that the whole building stock will already have been renovated once before self attenuation becomes noticeable (*total fraction retrofitted* = 1 ca. in year 55).

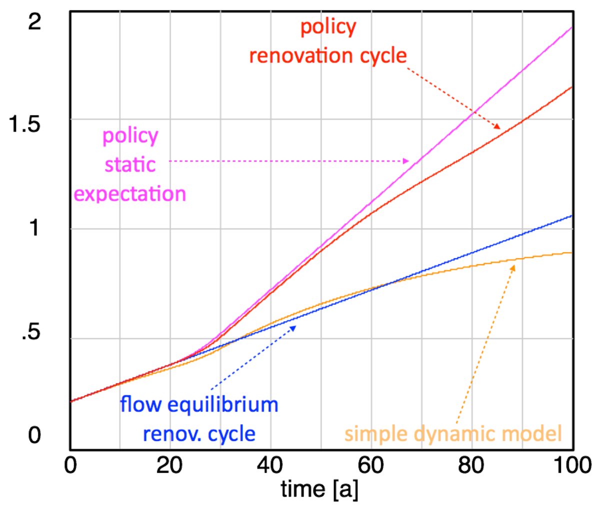


Figure 11: Total fraction retrofitted of the renovation cycle model with and without policy and static model and simple dynamic model for comparison.

This would mean that while self-attenuation is a system property it may not play out as a hindering factor in terms of retrofitting speed before the policy targets are reached. So one may ask if the static mental model wasn't so bad after all? On the other hand this also means that this system property may not be noticed by the actors for a long time because it is initially largely dormant.

Model 4: Renovation-Retrofit-cycle

Parameterization and Simulation Setup:

The model was first put into equilibrium by setting the stock of *retrofitted buildings* initially to 21 % (BMVBS, IWU 2013) of the total building stock again based on available data and adjusting the values of the stocks of *unretrofitted renovated buildings, buildings with renovation potential* and (*initial*) *average time in good condition* (see equations in supporting materials for details). Importantly, the proportion of *buildings with retrofit potential* is smaller than in the retrofit cycle case (now 53%, was 79%), because part of the total buildings is now in the stock of *conventionally retrofitted buildings* (26%). Again it should be noted that these fractions probably not correspond to reality because the assumption of flow equilibrium is not realistic but was made here to more easily observe policy effects.

The policy involves increasing the *fraction of retrofit opportunities realized* to 1 within 10 years starting in year 20.

As previously mentioned, a sensitivity analysis is carried out that repeats the policy runs under different assumptions with respect to which types of renovations can be considered retrofit opportunities. Due to data availability, it uses just the upper and lower boundaries of this uncertainty. The two uncertainty scenarios involve the following parameter settings:

- Low uncertainty boundary case: *fraction of renovations with retrofit opportunity = 0.5; initial fraction of retrofit opportunities realized* is 0.89
- High uncertainty boundary case: *fraction of renovations with retrofit opportunity = 1, initial fraction of retrofit opportunities realized* is 0.45

These values were calculated using 2009 data from Diefenbach (2010) who calculate aggregated renovation/retrofit quotas for whole buildings as the weighted sum of the renovation/retrofit quotas of different building components. Please refer to the supporting online material for details on the calculation.

Simulation Results, Analysis and Discussion:

It can be seen in Figure 12 that ramping up the *fraction of retrofit opportunities realized* to 100%, i.e. eliminating retrofit opportunity loss, leads to similar ramp-up of the retrofit quota that does not show any sign of self-attenuation. The reason is, as can be seen in Figure 13 that in the high opportunity case initially all conventional renovations have retrofit opportunity while in the low opportunity case this fraction is very low and most conventional renovations could not be turned into retrofits. So depending on these initial conditions the amount of diversion the policy can facilitate from the from the conventional renovations to retrofits may differ widely. In consequence, as Figure 14 shows, the goal could be reached in time in case the highest opportunity for converting conventional renovations to retrofits became reality. This may however not be very realistic and the development may likely unfold between these two extremes, which means that this ‘conversion’-policy alone, as useful as it may be to avoid self-attenuation, will likely not be sufficient to reach policy goals in time.

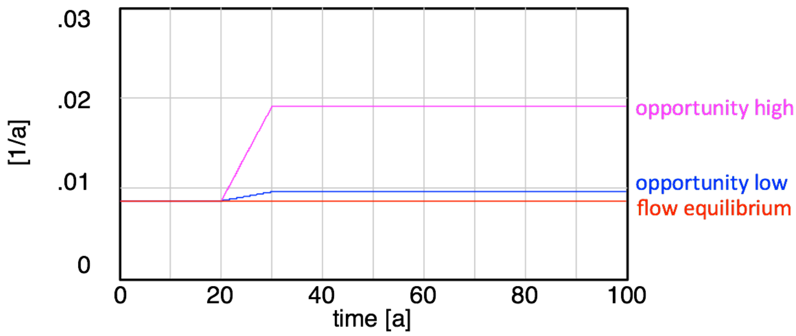


Figure 12: Retrofit quota development as a result of a policy scenario of ramping up the* fraction of retrofit opportunities realized *to 100% within 10 years starting year 20, depending on Upper and lower boundary of the uncertainty range of the opportunity to turn conventional renovations into retrofits

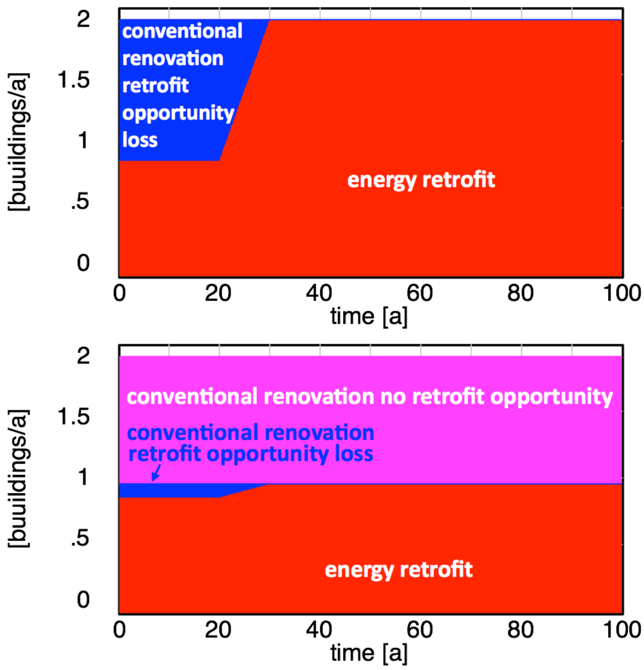


Figure 13: Stacked flow rates: Policy scenario of ramping up the* fraction of retrofit opportunities realized *to 100% within 10 years starting year 20. Upper and lower graph: Upper and lower boundary of the uncertainty range of the opportunity to turn conventional renovations into retrofits.

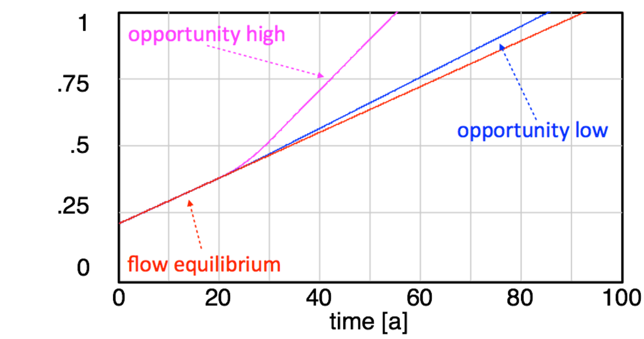


Figure 14: Behavior of the total fraction retrofitted depending on the scenario of high/low opportunity to turn conventional renovations into retrofits

Model 5: 2D renovation aging chain

Parameterization and Simulation Setup:

The subscript *age after renovation* was implemented with a depth of 101 stocks for each stack (from of 0 to 100 years). This could easily be increased to more years if actual lifetimes of building(-parts) made this necessary.

This distribution of the *annual renovation fraction* as a function of the subscript *age after renovation*, i.e. with increasing depth of the stack is subject to uncertainty. I have assumed several distributions of the variable as shown in Figure 16. Please note that all three distributions have in common that they are monotonically increasing as this seemed reasonable. Note also that none of these distributions have been calibrated to real data (as such data was not available).

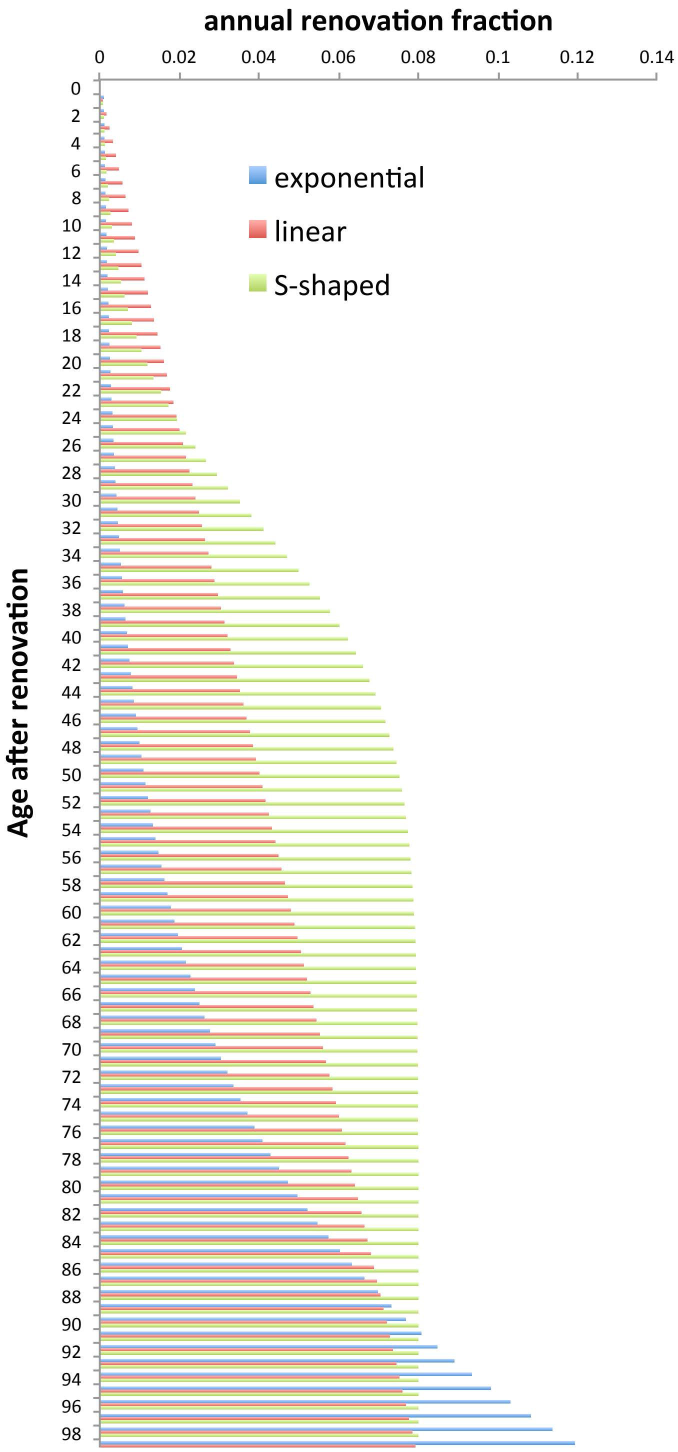


Figure 15: Different distributions for the **annual fraction of buildings renovated *as a function of* age after renovation**

In order to see the effects of a policy more clearly, the stocks were not initialized using realistic amounts/fractions of buildings but instead they were initialized to put the model into a flow-equilibrium. This was achieved using a constant construction rate of 1 building·a^{-1} and then simulating the model for a time horizon that was sufficient to establish flow-equilibrium (here 1000 years) and then using the final stock values for initialization of the model for BAU and policy runs. This is easiest achieved by letting the simulation start at -1000 years and observing if flow equilibrium is reached (rates and stocks) but considering only the simulation time from 0 to 100 years for BAU and policy scenarios. In order to reach flow equilibrium it is also necessary to check that the lowest stocks in the stacks and the last stack do not continuously accumulate buildings, as such a behavior would indicate that the depth of stacks and/or the length of the aging chain is insufficient. This setup is not realistic as in reality buildings do accumulate, but necessary for flow equilibrium. In order to achieve this, the *demolitions to renovations ratio* was set to 20%, which assumes that if 100 buildings are renovated per year, 20 are being demolished per year (so the total of demolition and renovation would be at 120 buildings·a^{-1}). This is clearly not realistic, but makes flow equilibrium possible. Even though somewhat lower demolition rates allow for flow equilibrium as well, the accumulation in the lowest stock poses other problems: In this case the lowest stock would need to be defined as a sort of rest-category (i.e. >99 instead of 100). For such a case, the *annual renovation fraction* could not be derived from the above-mentioned distribution but would need to be some sort of estimation of the average for all buildings >99 years of age, which is not trivial to derive.

In the policy experiments, the *annual renovation fractions* are ramped up by 57.5% within 10 years time starting at time 20. This implies that the policy affects the renovation rate of different ages after renovation differently in absolute terms: buildings that were renovated recently and therefore have low renovation rates are also affected little by the policy in absolute terms whereas buildings that have accumulated a lot of renovation potential expressed by higher renovation rates experience much larger increases of renovation rates in absolute terms. This appears realistic in the sense that renovation policies are likely targeted more at buildings that are old and thus have high renovation potential.

In order to compare simulation results with the previous models in terms of renovation potential this property has first to be extracted from the model. This can be achieved by aggregating buildings of younger and older age cohorts, as the renovation potential increases with the distribution of the renovation rates over the *age after renovation*. For this purpose, the depth of the stack was divided into three categories: Buildings with renovation age 0a - 45a, 50a - 99a, 100a. The latter category was only included to check whether significant accumulations take place in the lowest stock, i.e. to check if the stack is sufficiently deep and/or the demolition rate is sufficiently high (see further above). In Model 5, renovation potential is therefore defined a quality that emerges out of the model contrasting previous models where it was represented by dedicated structures (separate stocks).

Simulation Results, Analysis and Discussion:

Looking at the aggregation level of the renovation quota (across all renovation stages and all ages of renovation) it can be seen in Figure 16 that self-attenuation remains a clearly visible property of this more disaggregated system in spite of using less ad-hoc assumptions. Similarly, the tendency for oscillations observed previously in the renovation cycle models, is present in this more disaggregated system as well.

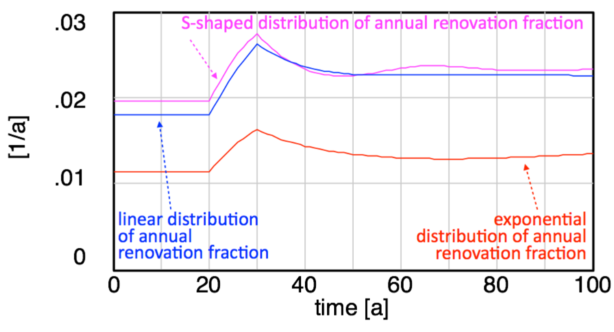


Figure 16: Renovation quota development (2D-aging chain Model 5)

Figure 17 shows that increased renovation results in a shift of buildings towards the upper half of the stack i.e. towards lower renovation potential. As buildings with lower age after renovation have lower renovation rates, self-attenuation is the natural result given this shift. This means that even though renovation potential is a property that emerges out of the system rather than having been hard-wired into it, the consequence of self-attenuation is still qualitatively the same.

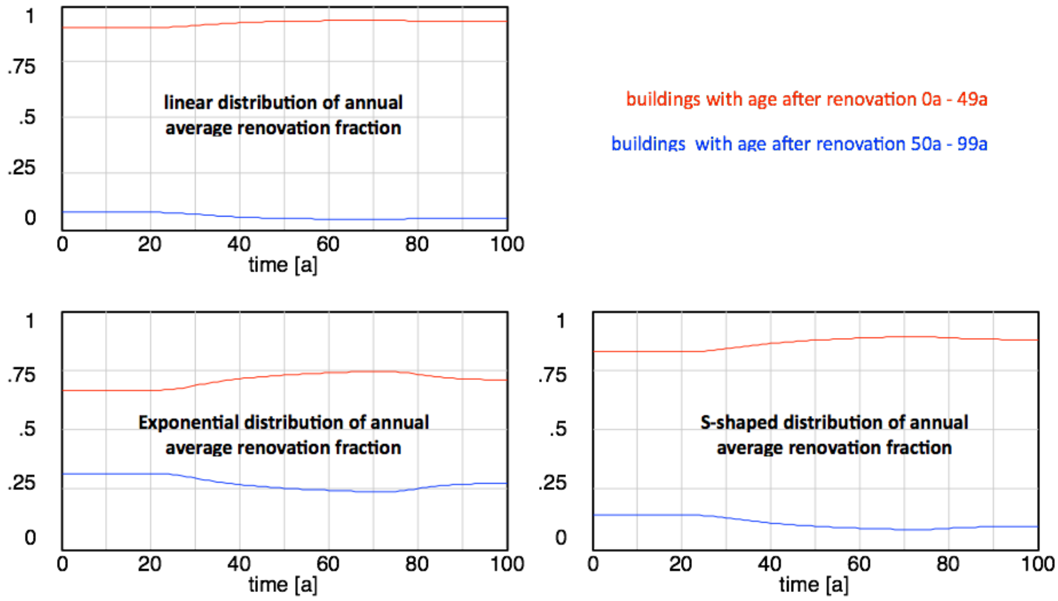


Figure 17: Upper and lower half of the stacks aggregated over all renovation states (note that lowest stock is not taken into consideration in these graphs)

The shift towards lower ages after renovation in this model is caused by the following mechanisms:

- The stocks further down in the stack (higher *age after renovation*) have higher absolute increases of renovation rates due to higher *annual renovation fractions*, leading to faster stock decline than for low ages after renovation further up in the stack
- increased sideways drainage flows lead to fewer buildings being able to trickle down the stack via aging because they are being renovated (moved out of the stack) before they get to higher *ages after renovation*
- the top-most stock of each stack receives an inflow-wave from all the sideways drainage flows from the previous stack (except the stack of unrenovated buildings of course), which increases the buildings with low ages after renovation

It is important to note that this sensitivity analysis contains only cases that are monotonically increasing as this seemed reasonable for increasing *age after renovation*. Under this assumption the presence of self-attenuation does not seem to be sensitive to different functional forms of the distribution of the *annual fraction of buildings renovated* over the *age after renovation*.

Conclusions

In the elaborations above, I have attempted to validate a dynamic counter-hypothesis to the hypothesized oversimplified prevalent mental model, both of which together constitute a hypothesis of misconceptions of dynamic feedback. I have used multiple boundary adequacy tests, to examine if these additional structures could yield a reference mode that is produced by the oversimplified mental model.

On the one hand, the dynamic counter-hypothesis of self-attenuation of retrofit quotas caused by depletion of retrofit potential could in principle be sustained for more disaggregated models that relaxed ad-hoc assumptions and used only assumptions that make immediate sense. This speaks in favor of the hypothesis that the political and partly also the scientific discourse appears to use oversimplified mental models that do not take proper account of this self-attenuation.

Interestingly on the other hand, boundary adequacy tests surfaced that more elaborate versions of the dynamic counter-hypothesis model could at least under some conditions, produce similar behavior as the supposedly oversimplified mental model: Firstly, it was discovered that there is some limited potential for increasing retrofit quotas and still avoid self-attenuation. That is because part of the renovations that in principle could provide an opportunity for retrofits are currently not carried out as such, i.e. do not lead to energy efficiency improvements. Secondly, self-attenuation due to increased retrofit rates may not play out to an observable degree within the policy time frame (the next few decades).

The somewhat unexpected finding that more elaborate versions of the dynamic counter-hypothesis model could at least under some conditions, produce similar behavior as the supposedly oversimplified mental model highlights the necessity for boundary adequacy testing. However, this finding still does not falsify the dynamic counter-hypothesis completely as the prevalent simple mental model only leads to correct inferences about system behavior within a limited parameter space the size of which is subject to considerable uncertainty. As a consequence the system may for some time behave as expected from the oversimplified mental model and then later, when the potential for retrofit quota increases that avoid self-attenuation is depleted, start experiencing self-attenuation. Importantly, this may make it difficult for actors to discover the limitation in their mental models that ignores the effects of the depletion of renovation potential. In addition, it makes it difficult for scientists or decision makers to differentiate actors that are simply not aware of the self-attenuating tendencies of the system at all from actors that are aware of self-attenuation but disregard it because they hope to increase the fraction of renovation carried out as retrofits (or more generally retrofit depth).

What this means for policy making depends on which intervention points are used by current and planned policies: to what degree do policies increase retrofit and/or renovation speed or increase the fraction of renovations carried out as retrofits? If policies mainly increased retrofit speed, this could lead to increased efforts being (partly) compensated by a depletion of renovation potential for which actors may be blind due to oversimplified mental models. If policies mainly increased the fraction of renovation carried out as retrofits and the unused potential for doing so was sufficiently high, self-attenuation may not matter and the mental models may be sufficient (for a while). If however this unused potential was rather small, self-attenuation would have a notable influence on the system behavior caused by policies increasing retrofitting rates. As a consequence, the policy effort necessary to reach and maintain elevated retrofitting quotas would be underestimated based on oversimplified mental models. In the face of importance of the unused retrofit potential for system behavior and policy options, it appears wise to attempt to reduce the connected uncertainty. I

It is furthermore important to note that the indicator *retrofit quota* seems to have fostered the misconceptions of the dynamic nature of retrofit systems. The indicator was probably invented because the total building stock is known and retrofit activity (building components per year) could at least be measured to some degree by surveys. Hence, the indicator was likely invented as a proxy simply based on data availability. Retrofit quotas not only ignore self-attenuation but also the depth of retrofit, i.e. actual energy savings and consequently are not adequate to assess greenhouse gas mitigation. Future retrofit models that are developed with the purpose of aiding decision makers in finding meaningful policies should therefore include this retrofit depth and use actual energy and greenhouse gas emission savings as indicators.

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