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HAZHIR OK, so for today, we can actually do a quick recap on SEIRb. So as we discussed, I think we covered pretty much everything. There were a couple of items that when I decided, OK, maybe I should build a solution-ish model to share with you, I noted that we didn't discuss it as closely, so I wanted to bring up those couple of items. And then we can switch to our main work.

So last week, Alexander asked the question about, how do we handle the waning of immunity due to natural versus vaccine-based immunity? And the challenge is that if you have somebody who had gotten vaccinated and then later they got the disease, they have both natural immunity and vaccine-driven immunity. And you need to decide how do you route them.

Do you send them back to the group that is susceptible but vaccinated-- that is, keep their vaccine immunity, but wane their natural immunity? Or send them to the group that is susceptible and completely unprotected-- that is wane both of them at the same time? Or even send them to the group of recovered but without vaccine immunity-- that is wane the vaccine immunity, but not the natural immunity?

And then later, the natural immunity waning happens. And we didn't really discuss it. And I gave a quick answer that wasn't quite going through the details of it. So I wanted to highlight how to deal with that situation, because it's a fairly common situation, actually, when you have these multiple stages and different movements across different multiple stages-- that is, for example, you can both go right and down, if you are thinking of the two dimensions.

So here is the model I put together. And here, we are really talking about what is happening on the right-hand side from people who are vaccinated and recovered. And then what happens to them, basically? So one possibility for them is to wane their natural immunity and go into the vaccinated susceptible population. Another possibility for them is to wane their vaccine immunity and go up into recovered population without vaccine protection.

And we also discussed a possibility of these people waning both types of immunity and going to unvaccinated susceptible population. And the critical idea here to keep in mind is that we usually don't want to have two different state transitions happening at the same time. So the long jump from recovered vaccinated all the way to susceptible and unvaccinated has these double jumps. That is, you're capturing two different state transitions at the same time.

And it is hard to do that internally consistently. So as a good heuristic, avoid doing that, and do one jump. And then when you do one jump, it is very easy. Basically, both jumps can happen with their own independent rates.

Now, there are some underlying assumptions when you make that type of movement. That is, you're saying the two types of immunity are independent of each other. One can wane with its own rate and the other can wane with its own rate, and the two don't impact each other. That is an assumption.

Now, if you want to relax that assumption, you really have to model how they are interdependent. That is, when you get vaccine immunity and then you get the disease, you go into a different type of a state that changes your rate of immunity loss. So that becomes a little bit more complex but doable.

Here, we are keeping the simple assumption that the two sources of immunity are independent of each other. And then it becomes the simple formulation that we have here. It's actually very straightforward, very parallel with what is happening in the rest of the method. That is, you have the vaccine waning, which is with the vaccine efficacy duration.

So this is the same time constant with which we are waning the immunity of Vaccinated S going back into Unvaccinated S. So the same time constant works for both of them. And similarly, we have the waning of natural immunity, so vaccinated waning of natural immunity, that happens with the natural immunity period, which is the same parameter used to wane the immunity for the recovered population.

Natural immunity period is also operating here. So this keeps things fairly simple, fairly clean. And the things are internally consistent. And you can actually now do the calculations, for example, how long a typical person entering the Vaccinated R state will remain in this state, which is the harmonic average of the two time constants.

You can calculate what's the probability that they go up versus they go down. You can do all of the kind of equilibrium-type of analysis you may be interested in once you lay this out. So that's number one. And in fact, theoretically, you could have the waning of vaccine immunity during the period you are vaccinated and infected. You could actually go up into unvaccinated and infected stock because your immunity from vaccine is waning during that short period.

In fact, that is probably a little bit more correct in terms of the machinery of the model. But because this is a very short period and you could kind of assume that during the time you are getting sick, actually, waning of immunity stops because your immune system is responding very heavily and so on, I think it is also OK not to include that flow variable in this model.

So that's kind of a choice that we are making. It's not something we are missing. So that's number one. Any questions on that conversation on this part of the model?

So then one more very minor thing, but something that is important for accounting. We talked about the current fraction of population that is willing to vaccinate. We said that's an important concept we need for calculating the vaccination rate. So the way we formulated vaccination rate up here is that we said, we need to have the unvaccinated fraction that is willing to vaccinate.

That unvaccinated fraction that is willing to vaccinate comes from the current fraction that is willing to vaccinate of the total population versus vaccinated fraction. And vaccinated fraction is all of the vaccinated people divided by all of the people and current fraction willing to vaccinate. Normally, you may think of it as a fixed number. It's just a fraction of population that is willing to vaccinate.

But if you think about these dynamics, if you had a disease where vaccine was very protective and the disease was very deadly, people who are unwilling to vaccinate are likely to get the disease very frequently and die at a much higher rate. In which case, the fraction of people who are willing to vaccinate is dynamically changing. That is, over time that fraction is increasing. So you need to capture that dynamic explicitly.

So that's another wrinkle that we didn't really talk about. But for an internally consistent clean model, we need to capture that. Now to capture that, you need to accumulate the vaccinated dead. You need to basically see how many people who aren't unvaccinated that are dead and then calculate what fraction of the population remains that is willing to get vaccinated.

And total population is accounting for those deaths. So the unvaccinated that is dead is removed from the total population. So those two, I think, are kind of two small pieces from last week that we didn't close the loop on.

We also didn't discuss the equilibrium conditions explicitly. And the equilibrium conditions, I think a couple of you-- so I think you submitted one and Jason submitted one, so that was nice. I think those who submitted it for the situation that we had the waning of natural immunity but not vaccination and no behavioral response.

So without those, it is a fairly straightforward setup. You can solve it for the case where we do have behavioral response, as well, depending on the formulation you use for behavioral response. So in the paper that I shared through email, there is a section that actually I go through solving of that equilibrium condition with behavioral response.

So take a look at that. That might be kind of helpful for thinking through the case with behavioral response, which is the more realistic one. And then the vaccination and waning of vaccination, it is a linear model, so I think it is solvable, but it becomes a messier problem.

So it's something you can actually try defining the problem cleanly for ChatGPT and see if it can solve the equilibrium condition for you. You should be able to at least define the problem very clearly for it to work. So that was kind of the couple of items I had on the SEIRb. Any questions on SEIRb before we move to our coflows of energy efficiency?

OK, so the main part of work today is to look at the models for energy coflows. And so basically, the coflow structure is probably something that most of you had seen. But some of you, it might have been new for you. So that would be a little bit more of the work to just learn the basics of the coflows. And then we were asking for something that was a little bit more than just plain vanilla coflow.

A coflow structure for tracking energy efficiency requires capturing vintage effects, capturing retrofits-- that is, changing of the energy efficiency that has limits-- and new technology that may be introduced and change the limits to efficiency gains so it can make it more feasible to introduce effective, meaningful retrofits.

And ultimately, we are looking for formulations that are robust for capturing the overall energy consumption given various types of interventions in terms of investing in retrofits, investing in efficiency energy technology introduction, and changes in the rates of building coming into the pipeline. So that was the problem definition.

So let's now go and see the submissions we have. So a good piece of feedback that you guys provided last time was maybe focusing on one aspect and going through multiple models is easier cognitively rather than going through multiple models very quickly and discuss different aspects on all those models. So let's try that idea today.

So I'll open multiple models that have been submitted. We can do a quick look at each aspect or how people are capturing those and see how it goes. So we'll learn as we go, in terms of how effective it is. So I'm opening the available models. So we have the vintage flows. So these are the buildings, Ali?

AUDIENCE: Yes.

HAZHIR OK. So the vintage is the buildings. And then you have buildings under construction. That's OK but not really
RAHMANDAD: central to our problem. We could just skip that.

So we have new buildings coming in. And these buildings have average lifetime. And then the vintages, probably you are dividing it to different stages. And you have three stages. But how is it--

AUDIENCE: I think you have to move it back.

HAZHIR So why is that this last removal time is not dependent? Oh, is it dependent on the average lifetime? OK. So it's
RAHMANDAD: just a 1/3 of that.

AUDIENCE: Yeah, the right group.

HAZHIR OK. So that's just the stock and flow of buildings. Fairly straightforward. Average residence time in each, I
RAHMANDAD: assume, is 1/3 third of the total or something like that, yes. So for each of these flows, it is that stock divided by the average lifetime divided by 3, assuming we have three vintages. And that's fine.

Then, you have this retrofitted on the top, which I don't know what it is. So let me see what you have below here. And then you have energy consumption of vintage. So what is the energy consumption of vintage? So what's the definition of that variable for you?

AUDIENCE: So we could have gone with two conceptualizations-- either considering the efficiency of each building and then multiply it by something that gives us the energy consumption or the other way around. So we can assume a baseline energy consumption. And the technology on the bottom is going to reduce energy consumption in that case.

HAZHIR OK, so this is basically energy consumption of all of the buildings together. So this is kilowatt hours per year.
RAHMANDAD:

AUDIENCE: Exactly.

HAZHIR OK. And it is basically initialized to be the vintage multiplied by the initial energy consumption. So all of that is
RAHMANDAD: good. Now, how does retrofitting work in this setup?

AUDIENCE: Retrofitting? Well, I made a very simplistic assumption, just it happens to the oldest buildings.

HAZHIR Ah, so that's an important assumption you're making, that retrofits happen to the last vintage not to other ones.

RAHMANDAD: So let's track what is happening with your last vintage in this case. So in the last vintage, you have retrofitted buildings versus not retrofitted buildings. So you are basically separating buildings by whether they are retrofitted or not.

So that's one way to do it, but it's probably not the easiest way. There is probably an easier way to do it. And what you're doing here is that you are taking away the energy consumption of the vintage based on retrofitting rate. So as you retrofit, you're taking away how much?

AUDIENCE: All of the averages.

HAZHIR All of the average consumption that those retrofitted buildings have.

RAHMANDAD:

AUDIENCE: This is our thought process.

HAZHIR Yes?

RAHMANDAD:

AUDIENCE: If there is natural demolition rate, so it's like a regular coflow that you see.

HAZHIR Yes.

RAHMANDAD:

AUDIENCE: But then we were thinking that if you are retrofitting some of these buildings, so a fraction of them will get retrofitted, so in addition to the natural outflow of the energy consumption, something additionally should be subtracted from the energy consumption to account for the decline of the stock of energy consumption for the buildings.

HAZHIR Yes. So this is important when we are doing coflows. The first thing is that for the main flow, which is in this case,

RAHMANDAD: buildings, every stock that you have, you usually need to have equivalent stock for the coflow. Otherwise it becomes very hard to keep track of things. It is very easy to make mistakes.

Not impossible to do it right, but I don't recommend it at the beginning. So in this case, we have a violation of that heuristic. That is, we have the vintage tree versus retrofitted tree. These are different groups of buildings. But the coflow here, this energy consumption of vintage is basically capturing the energy consumption for both of these groups.

AUDIENCE: There's another stock offering if you go further on in this model.

HAZHIR Ah, OK. Sorry. So this is because I didn't look closely. Thank you. So this energy consumption of retrofitting tree

RAHMANDAD: is exactly what you are trying to do. Now, it's much easier to keep it here within the same stock and flow chain. And then when you are reducing energy consumption from a group, you are doing the retrofitting on it.

So I think the confusion for you or the challenge here is that at one time, you're taking them out, you are removing all of the retrofitted, all of the energy consumption that goes with them, and then you go up there and create this other stock that is having the retrofitted value for--

AUDIENCE: New energy consumption.

HAZHIR New energy consumption, yes. So this actually should work. That is, it shouldn't be wrong. It probably does what you want to do. Basically, you're taking this group, the action of retrofitting reduces their energy consumption per building. So it does what you want to do.

It is not the simplest kind of formulation for this case. We'll see how others have done it. But let's see if the basic logic here is working for other parts. So once you are in this stock, then when you leave, you are taking out the retrofitted average, which is what you should be doing. So that's good. And the average time--

AUDIENCE: That is also a very simplistic assumption. So maybe I should have used another average.

HAZHIR So then there is the question of retrofitting rate, where it is coming from. And you are using the investment process to drive that decision. And as long as you are using the investment process, an independent process to retrofit things, to move items between Vintage 3 and Retrofitted 3, you are OK. You don't need to worry about the demolition rate or the average lifetime thing, assuming that the lifetime doesn't change because of retrofitting.

And you can actually change that assumption as well. That would be OK as well. But with that assumption, I think this would work fine. Now, let me take a look at the equations you have here. So removal rate for Vintage 3 is Vintage 3 divided by this total. And then this--

AUDIENCE: I took the idea from, like this here, we had death and recovery.

HAZHIR Yes. So in a way, you're saying at the end of their life of the buildings, you may be doing one of the two things. **RAHMANDAD:** Either you demolish it or you retrofit it. That's what you are modeling, the way you're modeling. Is that what you wanted to do? OK. So again, that's an assumption. If you make that assumption, that's how the world works, that's OK.

We need to be clear about that assumption. So here you're calculating total removal rate. A fraction of it gets demolished. 1 minus that fraction goes retrofitted or vice versa. And that retrofit rate, then these buildings have a new life, which is how long they will stay in this third stage or in fourth stage. Now, it is really a fourth stage, not a third stage.

And you're assuming that residence time is the same as the last stage demolition rate. So these are the assumptions that go into Ali's model. That is, the retrofit is kind of giving it a new life or 1/3 of a new life with a new level of consumption of energy that comes from whatever that initial retrofit technology is. So with those assumptions, this model is doing it correctly, at least for this third stage.

Now, for the previous stages, you haven't added it. And that adds a few complexities because then you are creating different lives for retrofitted versus not retrofitted buildings. And those different lives, you have to track them separately, so it creates kind of a stock and flow change for those other stages that may feel a little bit intimidating. Now there is the New Building Energy Consumption.

AUDIENCE: So the idea was, whatever the new technology is, we're going to take an average with the potential maximum we can get. It's like a weighted average so that we can account for the maximum efficiency that these buildings can get, because these are old buildings, so they cannot achieve the efficiency of the new buildings.

HAZHIR So what you need to do here is to be tracking how much improvement you can do for each vintage. And that improvement that you can do for each vintage is a characteristic of that vintage itself. So it requires a coflow that tracks that characteristic over time. So this one doesn't seem to be doing that. Is that correct?

AUDIENCE: Exactly. It just assumes whatever the best technologies out there, just a fraction of those.

HAZHIR Yes. So it makes some fractional assumption.

RAHMANDAD:

AUDIENCE: And that fraction is actually coming from the average consumption, like before being retrofitted. So because the average consumption of the old building is already low, it kind of adjusts for that.

HAZHIR Yes. So you are getting the average consumption from the old building energy efficiency.

RAHMANDAD:

AUDIENCE: That sort of was the characteristics of that group of buildings.

HAZHIR Yeah, that's how it is working as a characteristic. And because you are separating retrofitted versus old buildings

RAHMANDAD: that have not been retrofitted here, it kind of works. That is, that characteristic is telling where it currently stands. You are putting, now, the bottom in a time-moving parameter.

And then just say a fraction of that is what you can achieve. So I think it can work. I haven't looked through this specific formulation closely enough to see what is happening. OK, good. This is doing something that is reasonable. Nothing is obviously wrong. Now, this part I haven't thought through the extreme conditions for the formulation you have.

This is a little bit complex, but it's probably a good time to switch to some of the other models, see how they are laid out. But here, let me just understand what is this. This is the New Building Energy Consumption. So this is capturing the change in technology. And this is exogenous, basically.

AUDIENCE: We're assuming that the baseline technology consumption is 1 and whatever innovation that we have is trying to reduce that maximum 1, that maximum value.

HAZHIR OK. So the technology can be exogenous here. By and large, that's not a problematic assumption. So I'm OK with

RAHMANDAD: that. Although, a better formulation would allow the limits of technology to depend on the vintage as well. But this formulation wouldn't capture that.

Yeah, so for me, the better formulation would be a coflow that captures the potential for improvements for each vintage. And then you can change that potential endogenously. OK, let's look at some other models. Next one is Jake's.

AUDIENCE: First time working with coflows or subscripts, so I learned a lot.

HAZHIR OK, good. That was a challenge. So you have your three vintages-- new buildings, mature buildings, old buildings.

RAHMANDAD: You have the three time constants for them, some construction rate, which is exogenous. That's good.

Then, we have the energy usage of new buildings, energy usage of mature buildings, energy usage of old buildings. So these are the coflows similar to Ali's formulation. You're calculating the averages, pushing things forward based on the averages. That's also fine.

AUDIENCE: So for those two flows, I had an assumption that for energy usage, there would be some, as you age, that there would be some inefficiency that's added in to energy consumption kind of is how I thought about it.

HAZHIR Yeah. So that's basically kind of wear and tear reduces energy efficiency idea. So that's an interesting

RAHMANDAD: mechanism. Even though we didn't ask for it, it's nice that you captured it. I think it's a meaningful idea. Perhaps you could include it for the new buildings as well, because new buildings are subject to the same type of dynamics.

Let's look at the equation for that. So you're saying the mature buildings are increasing their energy consumption with a rate that is coming from new buildings aging and mature building energy flows per unit. So in a way, if I'm understanding you, and tell me if that's an incorrect assessment, you are saying as soon as you enter this stage, some additional flaws come with you, which increases your energy consumption per unit.

So that's why you're using the inflow into this stock for adding these flaws. And that's fine. Conceptually, that's one way to capture it. Now, it has a little bit of a challenge in terms of robustness when I change the time constant, for example, for becoming old. So why is that? So this is an interesting kind of wrinkle here. So we have these mature buildings staying in this stock for time to become old.

And during that time, they are accumulating these flaws. That's the idea. But to keep things simple, Jake said, OK, well, as soon as these guys go into the next stage, I'm going to give them all of the flaws they will acquire or half of the flaws they will acquire, some measure of that, and be done with it and not worry about this introduction of flaws during the time you are in this stock.

So that means if I change this time constant because I want to have more stocks, so I break it down into smaller steps, the mature building energy flaws per unit will not change automatically. Whereas, it actually has to. In fact, it is something about per unit of time, how much kilowatt hour per square foot you are adding, you multiply that by time to becoming old to get this parameter you have.

So doing that makes it robust to this extreme condition I'm talking about. Now, this is one way to do it, which puts everything at the beginning. What's an alternative way to do this?

AUDIENCE: You can separate the time constant to accumulate.

HAZHIR So can you speak up, Aldan, and explain what you're trying to?

RAHMANDAD:

AUDIENCE: So I think you can separate the time to become old and the time to accumulate those flaws. So you can have the rate, so you can have another auxiliary variable coming from the start, the maturing building, for example, and divide it by time to the flaw.

HAZHIR So you could take that new parameter that I mentioned, which is how many flaws per unit of time per mature

RAHMANDAD: building will be added, and use that parameter, multiply that by the number of mature buildings to create a new flow into the energy usage of mature buildings. That works just as fine and gives very similar results to what Jake has. So I slightly prefer that alternative because it is a little bit closer to how things happen in reality.

That is, continuously, these things are being added based on how many buildings you have, rather than at the very beginning when these buildings come in, you're dumping them with this kind of step function reduction in energy efficiency. But that's a nice addition that Jake had conceptualized.

Now let's look at the thing we were focusing on, which is the energy efficiency gains for mature buildings coming from retrofits. So that flow variable is, if average efficiency of mature buildings is higher than the lowest feasible efficiency, then retrofit benefit, otherwise 0. Yeah, tell us.

AUDIENCE: I don't know that this is necessarily the best way. I unfortunately did two ways of getting the retrofit benefit from technology. One is on these two flows, and then one is going to be on the new building, like new stock.

So the idea was, I just didn't want the benefit you would gain from efficiency to bring you below a minimum average efficiency for the buildings there because they can't go below a theoretical minimum. And I was running into issues specifically with these flows where it was, even though I have limits involved elsewhere. So I add it here.

HAZHIR Yes. So whenever you see if-then-else, you need to be a little bit kind of thinking, is there a better way to do it?

RAHMANDAD: Not always, but sometimes, most often actually you can find one. Here, you have also mature and the cohort subscripts, which kind of confuses me. So can you tell what the subscripts are doing here? Because I didn't realize this is also subscripted here.

AUDIENCE: So that's a bit of me learning how to use subscripts. Everything in this whole model has cohort basically on it. But the lowest feasible efficiencies, there is a different lowest feasible efficiency of kilowatt hours per square foot for old, new, and mature.

And so I basically wanted it to be, as soon as new buildings enter into these mature or old stocks, you get some inefficiencies. That whole average is going to go up above that. So you're going to get retrofit benefit bringing back.

HAZHIR Got it. Got it. So first of all, I think let's recognize what Jake is doing here with the cohort subscript. So he's

RAHMANDAD: creating a copy of the model, the model that we are seeing on the screen, for different cohorts and running that through the simulation for different cohorts, which is good. It's actually a better way to capture the cohorts than just age-tracking the cohorts.

I didn't tell you to do it this way just to keep things simple, but if you have done it, that's great. The formulation here is then saying there is a lowest feasible efficiency for the mature stage for any of the cohorts, that if you're above that, you can get benefits of retrofits, otherwise not with this if-then-else. That's the idea.

Now let's see where this lowest efficiency comes from. It's just a number. So this one, for new versus mature versus old, it is using different numbers. So that's just the parameter. So this parameter is the thing that we thought could depend on the technology. That is, basically the technology for retrofits could shift up or down this parameter.

So the idea was to capture the technology through this lowest feasible efficiency. Or at least that was the idea that I had in mind for the technology effect. Now, that is not what you are doing here. So what you are doing is changing the technology for the new buildings, if I'm getting it correctly.

AUDIENCE: So realistically, at the top of this model, there's technological limits. And that's coming to a value, technological effectiveness of retrofits. I have that as like, it becomes an S-curve as there's more investment. And then when I was trying to think about how to really get the benefit from that, incorporating it below, I introduced what I think is probably wrong of another.

There's technological limits overall that come from what the overall benefit would be and then for each cohort. Or for each stage of building, I wanted there to be its own minimum efficiency that you're working toward.

HAZHIR I see. So this technological effectiveness of retrofits is subscripted based on cohort. So you are getting a change
RAHMANDAD: in the technological effectiveness per cohort. And then where does it go? And, Anne, you asked a question, we should get to that, if I didn't, please bring it up again. So it's going into New Building Tech-Enabled.

AUDIENCE: Yes, it goes both into, there's a retrofit benefit for new buildings and one to retrofit.

HAZHIR I see. So this is a little bit doing two different things with this concept. One is that for new buildings, you are able
RAHMANDAD: to have lower energy efficiency to start with. Is that how it operates down here? New building efficiency?

AUDIENCE: Yeah.

HAZHIR Yes. So that would be one path. And then it is also helping with retrofit benefits, which comes from the
RAHMANDAD: effectiveness of retrofits. So per unit of investment or per unit of retrofitting, how much benefit you will get, how much reduction you will get. So that's, I think, what Jake is trying to capture here.

AUDIENCE: Yeah.

HAZHIR OK. So it may work. It is also complex because this concept here, really, one thing is how much retrofits can
RAHMANDAD: bring down your energy efficiency, another is, per unit of investment. And you don't have investment explicitly, you're just doing a fractional thing, but per unit of activity, how much consumption do you bring down? How much do you bring down the energy consumption?

These two are kind of convoluted here a little bit. The affect through the retrofit benefit captures the second one. The effect on the original level of energy efficiency that goes through the new building minimum efficiency is setting the baseline level. But neither of those actually captures the effect on how far down you can bring it, which is the lowest feasible efficiency.

So this is all about assumptions. If you assume the mechanisms that are important are these ones, that's OK. But what I think I had, at least in mind in defining the problem, was more focused on changing this lower limit and how much you can bring it down with retrofits. And then the efficiency of retrofits per unit of investment, we could still make that dynamic based on how close you are to that limit.

That is typically the efficiency of investment goes down as you get closer to the limit. So the first units of retrofits are very cheap, very effective. They bring down things very quickly. The later units are less effective and so on. But we could have that conversation separately. Anne, bring up your question, I didn't get it.

AUDIENCE: Yeah, I thought that for one of the parameters, he had like an if-then-else.

HAZHIR Yes.

RAHMANDAD:

AUDIENCE: It's just more of like a methodological question. I was wondering if that was necessary?

HAZHIR So, no. Yeah, it is not necessary. So basically this equation, and this is just kind of simple, you can just write it as
RAHMANDAD: 5, 6, 7, and that's it. And it should never be 0 because the cohort will always be one of those three. So this is how you define parameters that depend on the subscript levels. You just put the three numbers separated or N numbers for the N different elements.

AUDIENCE: Now I've learned more.

HAZHIR Yeah. Great. OK, let's switch to another model. For each of these models, we could go one level deeper and do
RAHMANDAD: some more real analysis of seeing how well they behave. But I want to get more of the different conceptualizations in place before we do any deep dive. If we get a chance, we will do some deep dives. OK, next one is coming from Jason.

OK, so we have the buildings, similar story-- average building life divided into three. That's all standard, straightforward. Then, energy for new buildings, energy for mature buildings, energy for old buildings-- pretty similar. Those are all in place. Then there is the energy reduction.

And this one, again, you could have it for new buildings as well. And the amount of energy that you can bring down, here, let's look at the equations you're using here, Jason. So you have a current energy efficiency factor, which I assume is time based.

AUDIENCE: Yes, it's for new construction, they're being built with that.

HAZHIR Yes, so that's the current. And that sets the max achievable energy efficiency for mature buildings.
RAHMANDAD:

AUDIENCE: With a delay.

HAZHIR So let's take a look at this formulation, see what is happening here. So you have a smooth function that says,
RAHMANDAD: take the current energy efficiency of buildings, delay it by some time, and that becomes the achievable energy efficiency for mature buildings.

And what is this time to develop mature state of art? So you're saying, as we improve our energy efficiency technology for new buildings, that also determines our ability for retrofits, but with a delay for changing those technologies into technologies for retrofitting?

AUDIENCE: Right.

HAZHIR Am I getting it correctly?
RAHMANDAD:

AUDIENCE: That's the assumption I'm playing with.

HAZHIR Yeah, that's OK. We want to be clear about our assumptions first, and then we could discuss whether that is the
RAHMANDAD: best assumption or not. So the assumption here is that there is new building technology that improves energy efficiency. And then for retrofits, they basically follow the same technologies.

That is the technology that sets the lower bound for energy consumption. So that only comes with a delay, and that sets the energy efficiency for the mature buildings at any point in time. And similarly, a very similar thing but with a different time delay impacts the old buildings maturity level or energy efficiency.

AUDIENCE: Yeah.

HAZHIR OK, so that's the idea. Now let's do a few mental extreme conditions. So let's say buildings take a long time in
RAHMANDAD: this first state before they go to mature. So let's say this is 30 year before they go to the mature state. But the time to develop mature state of the art is very fast.

Then, what will happen? We have buildings that are the old designs, but very soon they are able to absorb a lot better technology in terms of enhancing their energy efficiency. That's not fundamentally wrong. I don't think that's necessarily something that I can say is breaking some law. So it could happen.

AUDIENCE: I considered anchoring that time to develop mature state of the art to that transition constant, but I couldn't come up with a good story to do it.

HAZHIR Yeah, so it is really the question, the conceptual question is whether the technologies for improving energy
RAHMANDAD: efficiency are tied to the technology or to how the building is built or they are tied to some external technologies that are being renovated and improved regardless of how the building is built. And these two conceptualizations are not wrong. It really is a matter of expert opinion on how much you put a weight on one versus another.

But what is, I think, helpful is to have something that really ties to the building, and then change that based on the technologies of the day. That gives you a lot more flexibility. So if you tie your ability to get mature buildings, bring down their energy efficiency to mature buildings, that is it is a feature of mature buildings, then you can play with that.

You can bring it down faster or slower, and you can get that hint from the existing technologies in the marketplace and have any delay for that. That all works. And then you set that limit in a way that remains with that mature building. And when it goes to the old building stage, it goes with it. So it is a coflow that carries that underlying potential with it.

So that would be a more robust, general way of doing it than what you have here, which kind of may work OK, but may also, in some settings, miss this correspondence. And that creates a problem. So I think the rest of this model is fairly straightforward. It's doing the same thing for the energy of old buildings. And then there is some kind of aggregation, correct? Or is there something else?

AUDIENCE: That's all that's happening. I just averaged over all of them to get the full, so I could compare system level and cohort effects.

HAZHIR Yeah, yeah. And you do want to have an improvement here as well.

RAHMANDAD:

AUDIENCE: Yeah.

HAZHIR So conceptually, there is nothing different from old building versus new buildings versus mature buildings for
RAHMANDAD: being candidate for energy efficiency retrofits and so on. But because they have better energy efficiency at the beginning, they are closer to that potential. It's not very cost effective, so people may not do it. So that decision to how much you invest in energy efficiency is important. Right now, you're taking that decision just buy some time constant.

Actually, let's look at that equation. So right now, you're saying we take the energy efficiency, we compare it with the minimum, and you just close that gap. Yes. So this minimum energy required for mature buildings is coming from the technology and how many buildings you have. And you try to close that gap over a time constant.

That's an OK first-order approximation but really kind of skips all of the decisions on how do you allocate limited resources, how do you decide whether it is cost effective, and so on. You can't do that with this formulation. But as a first cut, it is a decent starting point.

AUDIENCE: Can I ask a question? We're just talking about potential retrofitting for new buildings. I think it actually may be very cost effective to do this when you're building a building if there is a recent jump.

HAZHIR Yeah, exactly.
RAHMANDAD:

AUDIENCE: Because they last a lot longer.

HAZHIR Exactly.
RAHMANDAD:

AUDIENCE: They're not as close.

HAZHIR Exactly, exactly. Yeah. And that's actually a good reason also to include them, but also to make the decisions on
RAHMANDAD: retrofit investment subject to some measurement of lifecycle cost benefits of doing the retrofits at that stage for that building.

So you would basically have the life expectancy of building and the delta in energy consumption that you will get from that. And then that marginal benefit multiplied by the time horizon gives you the total benefit. And then you can compare that with the total cost of retrofit. And that becomes a more solid decision heuristic.

AUDIENCE: Just one last question. Regarding that second coflow part, I didn't have that much information. Is the reason that we need that coflow, is it because that this first coflow gets contaminated by the cost?

HAZHIR Exactly.
RAHMANDAD:

AUDIENCE: It's not in the original.

HAZHIR So it is really that they have different purposes. So one of them is tracking what is happening now inside the
RAHMANDAD: energy consumption story. The other is tracking some underlying feature, some underlying feature about how much you can actually go towards building more efficient.

So these are two different features of buildings. So you need two different coflows for them. That's basically the core insight from this. So let's look at another model. So Gerardo has a simpler model. I suspect it is not.

AUDIENCE: Yeah, I didn't want to remove--

HAZHIR OK, you have subscripts here for building type. And what you're doing is that technology advancement brings
RAHMANDAD: down the cost of energies.

AUDIENCE: I have different groups.

HAZHIR Oh, you have different, also, you have building groups here. Got it. Yes. Yes. I see, I see, I see, OK, thank you. So
RAHMANDAD: you have the buildings that are constructed. Interesting. And so basically you have built-- yeah, tell us.

AUDIENCE: I use subscript for how buildings are built. Like, for example, for the three types of buildings in subscript. And that, in my opinion, my assumption would be the winter effect in the subscript. And I would put improvement with the retrofit in the float. And so this is our--

HAZHIR Yes. So actually, one thing, so this is a general comment beyond this specific case, is that if you have a subscript
RAHMANDAD: like here, TypeA, TypeB, TypeC-- you also have Class A, Class B, Class C buildings. It just makes it hard for us to follow. I don't know whether, for example, these are the same thing you're trying to model or very different concepts. Class and type are the same or are they different? Can you tell what is TypeA, TypeB, TypeC versus Class A, Class B, Class C?

AUDIENCE: Yes, OK. I'll explain it to you. So in my assumption, the subscript, I did subscripts for modeling the technological, for example, I was thinking about a good house more or a house building segment or technological type of building.

HAZHIR OK, so that's the type?
RAHMANDAD:

AUDIENCE: The type, exactly. And the class is the energy class.

HAZHIR Yes, got it. So basically, you are capturing retrofits through moving buildings in different categories. So it kind of
RAHMANDAD: gets close to Ali's formulation. That is, you're moving buildings from those that don't have retrofits. So call it building Class C, to Class B to Class A. So rather than a continuous conception of, OK, we invest and we bring retrofits continuously, this is kind of two steps for bringing things down.

And then there is a cost for each of these steps of improvement. And you may have a budget, so that tells you how much the building goes down. And this is a messy formulation. So let's actually look at this formulation that has a few things that should be done in a different way. So first of all, you have this if-then-else Buildings Class Type. Don't worry about the subscripts BuildingType.

It's the same. The formulation is the same for all of them, so it doesn't matter here. If this thing is above 0, do drain it. Otherwise, go to 0. So this is basically what Gerardo has done to avoid draining the stock Class C below 0. And this is not a good way of doing that. It's basically a very hard constraint that says, do whatever rate you want to do, and then kill the outflow as soon as you get to 0.

And this is a recipe for going under 0, small amounts under 0, because it has to go under 0 for this solution to kick in. It also kind assumes that every last building is available for retrofits, for improvements, it's visible, it's easy to find it, it's easy to convince the owners to do the retrofits. So that's also another problem with this formulation. So what's the standard formulation here?

We have seen versions of this in the basic course. Anybody wants to share what the standard solution to this might be? Kathy, do you want to take a stab? So don't worry about the rest of the formulation. Just how to get rid of the if-then-else and replace it with something that is a bit more robust and cleaner?

AUDIENCE: Would you just want a first-order draining?

HAZHIR Would you speak up?

RAHMANDAD:

AUDIENCE: Would you just want a first-order draining?

HAZHIR I can't hear.

RAHMANDAD:

AUDIENCE: Sorry. Would you just want to do a first-order draining?

HAZHIR So you could do a first-order limit on draining. That is, you say maximum drain rate, and that maximum drain

RAHMANDAD: rate is the stock divided by a minimum time to retrofit. And then that becomes the constraint as a maximum level. Then you take the minimum of that maximum drain rate and whatever is your formulation.

So is that clear? That's a very simple, standard solution that we use whenever we want to put a first-order constraint on how fast we are draining. So stock of tasks in a project model, you don't put a if-then-else tasks are above 0, do it, otherwise don't do it. You put, it's the minimum of max task completion and task completion from resources.

For shipments, it's a minimum of maximum shipment rate and shipment from demand or whatever you want it to be. OK, so that's kind of basic stuff on that front. Then, you have other things coming into this efficiency improvement for classes, which is the budget divided by cost multiplied by building type, cost sensitivity, some sensitivity fraction.

So why do you need two parameters? Why do you have cost for improved building from C to B and building type cost sensitivity? Can you tell what was the idea, Gerardo?

AUDIENCE: The idea was that for the type of buildings that we add into the subset, it will be different for how much you need to deliver.

HAZHIR Yes, so that would be the cost for improving building from C to B. Why do you need a separate sensitivity

RAHMANDAD: parameter? I'm just not following the need for two different.

AUDIENCE: One's enough?

HAZHIR Yeah. Yeah, because this also has three different drivers. So there is a little bit of a proliferation of parameters that don't do anything here. So you don't want to have that. That's generally the idea. So this is taking buildings one level down and allows that to happen.

Right now, your demolition is 0 for all of these things, which is not going to work well. You would just accumulate buildings and they will never be demolished. Yes. So the demolition rates, right now you don't have aging of buildings, which is another problem. But putting that aside, you definitely need to have outflows from these stocks of buildings.

Otherwise, buildings will stay around forever. So a set first-order delay, a first-order draining would be the simplest formulation that would be Building Class C divided by life of Building Class C or lifetime of building in general. So those are some of the key feedback here. Then you have all of these buildings at different classes being accumulated into Cumulative Building Type Consumption.

So tell me what this thing is doing. So I think I know what it is doing. And it is not the exact right way to do it. So basically, what you need here, you are trying to add up what is the total building's consumption of energy or consumption rate for energy.

AUDIENCE: Yeah.

HAZHIR And that is the sum of the buildings multiplied by energy use per building, in this case. And this is in kBTU per
RAHMANDAD: month. Yes, so this is your total energy consumption, I see. And then you have the cumulative energy consumption from beginning of the time up to now. So this is not wrong. This is also fine.

So the core idea is now you have this other technology side that is changing the cost of efficiency improvements, I think. Yes. So the cost of energy efficiency improvements in this model is being improved exogenously through some technological advancement. And then that makes it cheaper to shift buildings from one stage to the other one.

Now this one is not capturing the effect we were talking about. So there are two different possibilities. One is that I'm making it cheaper to bring down the cost to retrofit. The other is, I'm making it possible to do more retrofits, that is, get to lower levels of energy consumption per square foot.

I was more focused on the latter. This formulation tackles the former. This captures reductions in the cost of energy efficiency, but doesn't capture the fact that your Building Class A may now have even a lower energy efficiency because now we have developed better technologies.

Or you could, in fact, think of other classes that are not typically available to be visited at the beginning of time, but then by 2000s, you have new classes of buildings in terms of energy efficiency that become available to others. So that's kind of the effect we are talking about.

And then the other problem is that every building, with enough investment, can go all the way to Class A, so this is missing on the part about, OK, some things are just not realistic or feasible. For that vintage of buildings that was built in 1950s, you can't make them zero homes unless you completely got them and rebuild them, which is a different story than retrofits. OK, so that's a good conversation on this model. Let's go to the next one. This is Hassam's.

AUDIENCE: Presentation on this maybe a little bit different from how we worked on the conceptualization together. It has a subscript.

HAZHIR This is subscripted so that you can basically add the number of vintages as you want. Great. So you have the built area, which is buildings, and you have retrofitted areas. So let's look at the subscribing part because that's something that is new for some of the folks here. So here, Hassam is subscribing items on vintage ranges.

AUDIENCE: These are subranges I ended up using.

HAZHIR Yes. So you have the subscript range vintage. And this vintage accounts for, so you can have V1, V2, V3, et cetera. And if I look at the vintage members, elements, right now it is only 3.

So the way this formulation is formulated, it is not incorrect. This is fine, but it is not the most efficient way to formulating these. And the reason is that now if I want to add a force element, I have to define a force formulation. But that force formulation would basically be the same as V3 formulation.

AUDIENCE: The goal was to have a first, a middle, and an end.

HAZHIR Exactly. So that's how you would do.

RAHMANDAD:

AUDIENCE: But it didn't work well, so I ended up using this.

HAZHIR So you couldn't figure out how to do the subranges so that you can get the first, last, and middle formulation to work. That's fair. It's not a trivial thing. It needs playing around. I gave an example age model inside Vensim that does it, I think. So check that out. That's a good way. But for those who are not yet following what this is doing or what this one can do, right now we have three vintages.

That's easy. You just build them. But if you wanted to have 100, then doing it manually just becomes so messy, you're not going to even try it. The structure that Hassam has here allows him to basically do that without creating copies of the model 100 times. You can just do it with the same formulation that you have done for three.

So that's the thing that is nice about it. Now, for that to work, you need to do a little bit of subscript manipulation in Vensim. That is, you would say, OK, new buildings only enter into the first element of the subscript, and demolition only happens to the last element of subscript.

For everything in between, what is happening is that they are getting aging buildings from the previous cohort and they are sending elements to the next cohort. So you need to do that using subranges, in Vensim lingo, to do it effectively. It takes a little bit more time than I want to allocate to do that here. So let's not do it together.

If I get the chance, I may put together a model that has that, but that's the idea. And then conceptually, essentially, you are doing a similar thing as Ali, in terms of moving buildings into a retrofitted stage and with that, moving their energy consumption to the level that is corresponding to the retrofitted ones.

AUDIENCE: This allows for retrofitting on all three vintages.

HAZHIR Yes. And this allows for retrofitting on everything. The technology for retrofits--

RAHMANDAD:

AUDIENCE: So I'm doing the same thing that Ali did, which I have a new technology and I'm assuming that the new technology for new buildings is the same as the gold standard for retrofitting. So the new technology for retrofitting will be a weighted average between the current energy efficiency and the best that they can get right now.

HAZHIR Yes. OK, weighted average between the current energy efficiency of that cohort.
RAHMANDAD:

AUDIENCE: And it's going in to retrofitted.

HAZHIR Yes. OK, OK, good. Yeah, that basically hard codes the limit that you can achieve as this weighted average. It
RAHMANDAD: doesn't allow you to dynamically change that based on new technologies and so on. So that's kind of the downside of not having a third coflow.

AUDIENCE: The impact of retrofitting, for example, which can make it endogenous, but that is not trivial.

HAZHIR Yes. Well, but that limit is the key. That is, right now you are basically getting everybody to this new retrofit level.
RAHMANDAD:

AUDIENCE: Yeah, the new retrofit level, but it is a weighted average between--

HAZHIR Yeah.
RAHMANDAD:

AUDIENCE: Actually, we were thinking that the new efficiency or energy consumption is somewhere between the maximum and the original of that cohort. The simplest way is taking the average. It will be exactly the middle point.

HAZHIR Yeah. And that parameter impact of retrofitting is shifting whether it is in the middle or not. Yeah. So you could
RAHMANDAD: make that parameter a function of basically the cohort you are looking at, the vintage you are looking at. And then that could change dynamically in some way.

That would be how you would do the history or kind of capture the history. Good. I'm not going through the details here. I think the rest is probably sound. So let's look at maybe one more model before we take a break. So let me do this. Yes. So this is Anne's. Go ahead, Anne.

AUDIENCE: I tried to do like the subscripts thing. But there's also a very big wrong, as I'm showing here, where I don't know why I thought that an efficient building consumes more energy. I think I did it late at night.

HAZHIR Yes.
RAHMANDAD:

AUDIENCE: Yeah.

HAZHIR It's OK. We can define efficient as inefficient. So energy inefficiency of building vintage.
RAHMANDAD:

AUDIENCE: Yes, that's the word.

HAZHIR Yeah. Yeah. So basically, this is energy consumption type of a thing, so variable namings.
RAHMANDAD:

AUDIENCE: Yes, the variable name is off as well. It should be energy consumption.

HAZHIR Yeah. So the units are OK but not OK. So you have kilowatt hour per square meter, which is the right unit, but it
RAHMANDAD: should be kilowatt hour divided by square meter so that your buildings would be in a square meter and then the average energy efficiency-- OK, you have the units building.

So this is actually important for unit consistency. Yeah, this is hard to make unit consistent if you don't do it right. So the buildings, they are in square meters. That's easy. You could also go with just number of buildings, but then you're missing the square meter, which is probably better, or square feet, which is a better.

AUDIENCE: Yeah, I think went with number of buildings.

HAZHIR Yes. So if you do that, then the unit for energy consumption per building would be kilowatt-- it's actually not
RAHMANDAD: kilowatt hour, it's kilowatt per building rather than per square meter. Or you could make it kilowatt hour per year per building or per square meter. So those are the options.

AUDIENCE: The averages, it was then per building.

HAZHIR Yes. But I'm just saying the units that you are putting here should be kilowatt hour per building per year or
RAHMANDAD: something like that so that when you multiply that by the number of buildings, the total energy consumption-- or actually, no, this is not per building. This is for all buildings.

This is kilowatt hour per year. This is for the stock. And then for per building value, it becomes kilowatt hour per building per year. So the time units are kind of missing from this formulation. And the unit consistency is not enforced when you don't have the right units here. So that's the unit part.

Now let's look at the constructs. So you have one stock for buildings, so you don't have multiple life stages. You have the vintages captured using subscripts, if I'm understanding you correctly. So you're using subscript year. And by the way, using the subscript year is going to be very confusing because you can have built-in units of year, so things will become messier when you use year as your subscript name.

It may even result in some errors in Vensim. But let's not waste time on that. So the way you are capturing it is that you are looking at the retrofit potential, which is coming from maximum possible efficiency of building vintages, and that is determined by the technology that is affecting that max possibility.

So the way you are capturing that is for each unit, there is an initial vintage, then there is a gain from technology for each type of a unit. And then the technology goes up that shifts the marginal unit of benefit from retrofits. And this creates the maximum possible efficiency. And then you look at the gap between the current energy efficiency, minus current energy efficiency.

So this is kind of where, again, lack of units become a problem. Because right now, retrofit potential is going to impact. OK, you're looking at the gap and then closing the gap with the time constant. So that's kind of similar to Jason's formulation. But here, for different, what you call vintages, which are not aging, but that's OK, you have for different vintages, different potentials.

So that's nice because now you do have that underlying feature of vintage captured kind of inside these two parameters. So in the marginal gain and initial possible efficiency parameters, you have captured how much energy efficiency is feasible to get for different buildings. Now we have this confusion about energy efficiency versus energy consumption that may actually create weird behaviors here. I haven't thought that through.

OK, good. Thank you, Anne. Any questions, comments on this one? Why don't we now take a break? I think it's a good time to spend a few minutes resting and refreshing. It's dense, looking at models.

So perfect mixing assumption comes basically with everything. You can't get rid of it. So it will always be there. If you need more resolution, that is, separating whatever you have into categories based on some feature, you need more stocks. That is, you need to explicitly separate them. So there is no avoidance.

Once you have a single stock, you have the perfect mixing assumption. Now, in these cases, you may think that I'm doing something that removes perfect mixing by doing a fixed delay. So I have entry and the removal with a fixed delay, or with the first sixth-order delay or whatever.

That is actually not doing the job in the way your mind kind of sees, because it creates six different stocks for a sixth-order delay that is in the background happening. So it is doing the disaggregation. It is just not showing it to you. But you don't have access to those intermediate stocks and therefore you can't manipulate them directly.

So that means you cannot fully use the additional complexity you have introduced. You cannot really get information from those intermediate stocks, and that makes it harder to actually do things consistently. Now sometimes that is OK. That's why we do use higher-order delays.

But as soon as you use higher-order delays, usually the stock that is capturing the sum in the middle, you can't do other things with it. You can't add a flow variable to it because you lose control. You don't have control over what is happening in the 6 stocks that need to, in parallel, happen to this. So that's why it's better to just not do it in most cases.

AUDIENCE: So just be comfortable with that.

HAZHIR Yes.

RAHMANDAD:

AUDIENCE: Know that it's happening.

HAZHIR Yes. But the bigger kind of the process lesson is, if you need heterogeneity, you need to disaggregate. And if you

RAHMANDAD: are using higher-order delays going around the stocks-- that is, you also have the stock that is impacted by inflow and outflow of that higher-order delay-- don't manipulate anything else inside that stock. That is, don't use other flows coming in or out of it, or otherwise you lose control because now you have lost your parallelism with the hidden stocks in your delay function. Those are the key ideas.

OK, I think we have one more model left and that is Alban's. So let's bring that up. So this one is also doing the subscript-based formulation for the cohorts or for the vintages. So this is similar to Hassam's model. If you look at the formulation here, for C1, the cohort 1, the inflow is New Building Construction. The outflow is Building Aging for C1.

For C2, it is Building Aging for C1 that is increasing it, Building Aging for C2 that decreases it. For C3, it is Building Aging C2 minus Building Demolition. So very similar, and also Alban hasn't done the more general formulation that would allow him to basically solve this problem at a scale without adding new equations, but that's a separate thing.

We can actually probably do that, take a quick look at that together. OK, so Building Demolition and Time for Demolition, et cetera, those are straightforward, I think. So that's for just the demolition. Sorry. And the Building Aging is aging cohort. So this Average Time for Demolition should be 30 years. So after you got 40, then you have another 30 years to go.

Is that how things are working? OK. So this is not the uniform distribution that others had used, 20-20-20 or something, this is 20-20-30. And that's OK. There is nothing wrong with that. So building aging is straightforward. Then you have the total energy consumption for buildings of each age. You have the average energy intensity of buildings. So that average energy intensity controls the movement of item.

And then you have the increasing energy consumption that is coming from new buildings. This is fine. And then you have the retrofit. So this is really the interesting space that we have. And this is done through comparing indicated total energy consumption after retrofit versus the current total energy consumption divided by time constant. So this is a very similar formulation to a couple other formulations we saw.

You just look at the total minus indicated divided by time to finish retrofit. And this is because it is decreasing, so it is an outflow. It is the total minus indicated. If it was an inflow, it would be indicated minus total. So this is working fine. Again, with the caveats that we mentioned, that this kind of time-constant-based doesn't allow you to think about investment and allocation and all those things that you may care about.

And then where does the indicated come from? It is total buildings multiplied by average energy intensity of buildings that are retrofitted. And we have this thing that is fraction of buildings under retrofit. So let's look at this. I don't know what's happening inside this. So you have buildings. This is just for units, for scaling of the per building item to everything. So this part you don't need to worry about.

The next part is what the meat of the equation is. So fraction of buildings under retrofit multiplied by average energy intensity of building retrofitted plus 1 minus fraction of buildings under retrofit multiplied by average energy intensity of buildings for this cohort. So tell us what you are trying to do, Alban, here. I'm not completely sure.

AUDIENCE: So the fraction of building under the retrofit is controlled by investment. So the investment increased the fraction of building under retrofit. And then the indicator total energy consumption is lowest retrofitted multiplied by the energy intensity of those retrofitted plus those not retrofitted multiplied by the energy intensity of those not retrofitted.

HAZHIR So at any point in time, you're saying there is a fraction of buildings that are being retrofitted. Is that the idea? So
RAHMANDAD: if that fraction is small, then everything will be smaller.

AUDIENCE: If it's zero, then--

HAZHIR Nothing happening, yes. And if that fraction is 1, then everybody is moving towards--
RAHMANDAD:

AUDIENCE: The retrofitted.

HAZHIR --the retrofitted. So this is kind of thinking of retrofitting as a continuous process. And at any point in time, you
RAHMANDAD: could be retrofitting, or some subset of buildings could be retrofitting. And it is a random subset.

AUDIENCE: Right.

HAZHIR So that allows for assuming that they are the average. They have the average and they can go down to the
RAHMANDAD: required level.

Yeah, I think this should work because as you turn it on, it will drain things. You turn it off, the average has come down and there is less room to do, but there is still room to do. OK, yeah, this looks fine. And then that gives you flexibility for investment formulation that determines fraction of buildings that are under retrofit.

Now, this is a little bit more tricky. So you have the fraction. You get a number between 0 and 1. And you can do a step function or whatever you do. And you are saying retrofit cost per square foot. How do you make sure this fraction remains between 0 and 1?

AUDIENCE: Yeah, I missed it. Yeah, this is not accurate.

HAZHIR Yeah, it's not obvious that it would remain between 0 and 1. Because that fraction needs to be between 0 and 1.
RAHMANDAD: Now, what is conceptually also tricky here is that you have a cost for retrofitting that you're trying to reflect in this parameter, retrofit per square foot, but you also have the time to finish retrofit, which controls how much retrofitting actually happens.

So if I allocate some amount of investment, so this is investment in retrofit that I allocate, how do I know? OK, so let's actually run this model because you have a step function. So it's possible to see what's happening. So we can have an investment that goes up.

So the fraction of buildings goes to 0.2 or something, I think. Yeah. OK, so that's good. Then, average energy consumption is going down beforehand because newer buildings are coming in with lower energy efficiency. And then retrofits turn on. And average energy intensity can go down even further.

Max energy efficiency here is, for C1 is 0.2, for C2 it is-- so we have that same issue that these maxes are now fixed. Of course, you could, I guess, change them with the step functions here. So that is where you would be changing those. But they are applying to the C1, C2, C3 rather than the buildings.

So this is kind of where a coflow would associate these maximums to the underlying buildings and track them moving with the buildings as new buildings are added and so on. Whereas the current formulation fixes them. So this, you start in year 1900, you have the same underlying values as you would have for buildings that are introduced in 2000 and so on.

So that's why this is not the best way to do it, even though it is good that it is separated for the three different cohorts and allows you to set them separately, how far they can go down. And you have formulations here with investment that similarly would bring down this. Now, OK, let's look what is happening here in energy intensity of buildings.

And so for C1, we had higher or we had lower. We could get a lot of efficiencies that what C1 has. C1 has a gain of 2. So what is this gain doing exactly? So that's the formulation for average energy intensity of retrofitted building. So that formulation is 1 minus this max.

Ah, so this is actually an interesting formulation. So who wants to take a stab at critiquing this formulation? So we have the max energy gain from retrofit. For now, assume it is a constant. Right now, it was 0.2 for C1 and 0 for C3, I think. And then average energy intensity of buildings is the average for that cohort. So what could go wrong with this formulation?

AUDIENCE: Where is average? Where is the output variable?

HAZHIR Yeah, let's look at that. So the average energy intensity of buildings is distinct here. And then the output of this
RAHMANDAD: average energy intensity of buildings retrofitted is going to the indicated total energy consumption, which later brings down the total energy consumption.

So what can go wrong here? To see what can go wrong, let's run this simulation a little bit longer. So do we have final time here? Oh, no. OK, let hit stop.

OK, so we added a little bit of investment. Actually, quite a bit of investment. And now rather than going to whatever year we are going, let's go a little bit longer. OK, let's see what is happening here. Average energy efficiency.

Oh, sorry. So this is 2060. So let's make this between 2050 and 2100 so that we don't get weird behaviors here. And now if I increase it to a little bit longer, let's see what happens. Let's actually go further than 2100. 2200, OK.

AUDIENCE: Negative.

HAZHIR OK. So total energy consumption is going negative actually for one of the groups.

RAHMANDAD:

AUDIENCE: The first cohort.

HAZHIR Yeah. And average energy consumption also going 0 and negative. So why is this happening? Well, first of all,

RAHMANDAD: why is it going to 0? Because Alban put a constraint, 10% or 20% improvement. How is it going 90% improvement and it's still continuing improving?

AUDIENCE: It's a different time. 90% of that fraction is being improved.

HAZHIR Yeah, exactly. So this is the problematic assumption in the formulation here, is that the average energy intensity

RAHMANDAD: of buildings that are retrofitted is whatever is this max efficiency gain, or 1 minus that max efficiency gain, multiplied by current average energy efficiency. So if I brought down average energy efficiency, let's say, from energy consumption, let's call it, intensity, from 1, I brought it down to 0.8.

It should stop there, but it doesn't because now it is 0.8 multiplied by 0.8. Now it can go 0.64. And then it is 0.64 multiplied by 0.8. And it continues to go down. So that's why this can go down to any number. Now, that's number one. The second thing is, why does it go negative?

AUDIENCE: Because of the time step maybe. It should have been stopped.

HAZHIR Yes, so this process should have stopped it at 0. And therefore a little bit surprised why this is going to negative values. So for that, I like Ali's suggestion of looking at the simulation time step. That could be a culprit. Looks small enough. I'm not sure if that would explain it.

RAHMANDAD:

AUDIENCE: Isn't the average going below 0?

HAZHIR So the average is going below 0 as well. So let's look at this. You see at the very end, you get negative numbers

RAHMANDAD: here.

AUDIENCE: For the blue.

HAZHIR Yes. It doesn't matter. If you get it for one, there is a problem. So this should not go negative at any point in time.

RAHMANDAD: The buildings are there. Let's just make sure the buildings are not doing something weird. No, the buildings are in equilibrium, so that's good. And then energy consumption is just going out from the stock.

AUDIENCE: It's probably the intensity for the new building. The red string going down.

HAZHIR Ah, it might be. It might be. Yeah, so if the intensity for new buildings is going to negative values, then we would

RAHMANDAD: have that problem. Yes, so that's the reason. So that's just the ramp function. So this is not a formulation issue. So this is a good summary on this one.

OK, I think, kind of big picture, the formulations that several of you have for multiple vintages and capturing the energy consumption, those are good. That's the basics you want to have. Everybody is missing kind of the best way of formulating the underlying potential for enhancing energy efficiency, which you should do as a separate coflow, as a separate coflow that tracks what is the underlying potential.

And that can go up and down with investments in its own sake. So that would be the cleanest way to capture all the things that we want to capture. Then, there are two additional things that you can do to enhance the model. One is this way of building the model with subscripts so that you can add more cohorts or less cohorts, or more or less vintages without any problem.

I'll show you how to do that in a simple example. Second is thinking through the allocation of resources, or whether it is cost effective to invest in energy efficiency based on the parameters of the model in a more rational formulation. That starts to become more challenging. And that wasn't really part of the problem definition the way I set it up, but it's a nice challenge.

So those are the two things. If I get the chance, I may try to do something around those, but I don't know how much time I will have for that. Let's do, then, one other thing, and that is looking at this subscript-based way of doing cohorts or doing vintages.

AUDIENCE: I have a question.

HAZHIR Yes?

RAHMANDAD:

AUDIENCE: Is there a way to rescue Alvin's formulation with the averages?

HAZHIR Yes, so that's a good point. Sorry. Thanks for bringing that up. So basically, this formulation doesn't need the

RAHMANDAD: effect of this average intensity of buildings. So to rescue the formulation, the simplest is to make the average intensity of building after retrofit a number that is coming from the underlying technology.

AUDIENCE: And not anchored to that.

HAZHIR Not anchored to the current average energy intensity. So that would be a very easy solution. You just remove

RAHMANDAD: that multiplication, basically. Then, of course, you need to be unit consistent so the efficiency gain from retrofit cannot be dimensionless.

It then needs to be the maximum energy efficiency or kind of minimum energy consumption feasible for that cohort or something like that, which is what we want to actually capture in a coflow explicitly. That's exactly what you would have in the coflow structure. Yeah, other questions on this one?

AUDIENCE: I just have a general question on multiple coflows.

HAZHIR Yes?

RAHMANDAD:

AUDIENCE: When is a good place to start? Where is a good place to start? Because I was working on a model, which I can't remember how many complex chain, maybe like 20 or so. And it was just very bizarre.

HAZHIR So why did you need 20 different?

RAHMANDAD:

AUDIENCE: I was working on developing it. That was exactly my point. How do you reduce the number of coflows? Because it would have made the model very dense. That's grown an aversion to me in multiple coflows.

HAZHIR Yes. So I haven't actually seen anything with 20 different coflows. I have a hard time seeing the value of it, just

RAHMANDAD: because it is very hard to keep track of the interactions in a consistent way. That's the core issue.

That is, you want to have these dynamic things if they're adding value for the dynamics of the model. But if you have 20 features, then the interaction between these features becomes a big mess. You can't really track in your mind how things are interacting. So I would be hesitant to have that many.

AUDIENCE: My understanding from today's discussion was when you have two different characteristics of the main chain, which are inherently different, it makes sense to have multiple coflows. Then the question is, when is it way too many different tracks?

HAZHIR So it is really the question is, does it impact the dynamics you really want to capture? So in this case, the

RAHMANDAD: dynamics we really want to capture-- the first-order one is the energy efficiency that has to be there. It's kind of or energy consumption. And then the underlying limits or underlying opportunities is also important.

That is the heart of retrofitting and how far you can retrofit. So that's why we include it. We are not including coflows for the color of buildings or whatever else. There are hundreds of other dimensions you can think about about buildings. What's the height of buildings? Yeah.

AUDIENCE: I guess one signal that you would need one more is, as you're building this and this average thing that Alban has done, which is attempting to capture that effect doesn't work. You might be like, OK, there's some other dynamic attribute that needs to be tracked.

HAZHIR Yeah. OK. Any other questions? Let's then take a look at this. This is a simple Vensim model that comes with
RAHMANDAD: Vensim installation. So you can inspect it yourself as well. But let me remove the subscripts for a second. So this is an aging chain model, age model, whatever you call it, that has births and aging, which aging includes death.

That simplifies the formulation for reasons you will see. So rather than demolition in our previous example, you could just have aging to include demolition for the buildings. Now, let's look at the formulations here. So it is saying for population, it's coming on this other screen.

So there are two equations. For infant group, their rate of change is birth minus aging of infants. Very straightforward. The trick is in the next equation. So for all but youngest group, which is a collection of all of the other groups-- so if you look at the age elements, it has child, teen, middle, and old as well as infant.

So the model includes a subbranch which is a subset of the full range called All But Youngest, which includes child, teen, middle, and old. And I'll show you how to make that. It's saying for all of those guys, the formulation is aging of previous cohort minus aging of all but youngest. So now you have another complex thing. What is this previous cohort?

So the previous cohort is another subrange consisting of infant, child, teen, and middle. This is the previous two All But Youngest. So it takes the previous element. So now think about what Vensim does. For every element of All But Youngest, so it starts with child, it says, OK, what is the aging of the previous cohort's first element.

The previous cohort's first element is infant. So it looks at the aging of infant as the inflow and aging of that first element of All But Youngest as the outflow. Then it goes to the next element. For the teen, it says, what is the second element of previous cohort, which is child?

And what is the second element of All But Youngest, which is teen? Calculates it and third and the fourth until it ends that subrange. That's how it calculates everything. So the logic is simple. That's all you need to do. But note that you need two new subranges to track what is happening and to make these movements.

Now, all of this is fine, except that these subranges also need additional features for them to work, for Vensim to know that these two subranges are mapping to into each other, that is the first element of the first one, and the first element of the second one can work with each other in the same equation. Otherwise, Vensim will give you an error that you are comparing apples and oranges.

You are trying to mix infants and children, I don't like that. So you have to instruct Vensim that it is legitimate to map the first element of this subrange to the first element of that subrange, and so on. So then you need to do that within the subscript definition thingy, which is usually somewhere around here.

AUDIENCE: It's in the upper row.

HAZHIR Yeah?

RAHMANDAD:

AUDIENCE: Yes.

HAZHIR Yes, here it is. So this is All But Youngest. You see when you go into this definition, it highlights these four

RAHMANDAD: elements. This is previous cohort. It shows the other four elements. The way you define these is you can New a subrange or you can Edit subranges. So I'm going to edit this subrange so that you can see how it is defined.

So the previous cohort is defined as infant, child, teen, and middle. And then this is the critical piece that is not trivial. You need to do it. It takes it and says it maps into All But Youngest. That is, there is a one-to-one mapping from elements of this to All But Youngest. And you actually need to do it also for definition of All But Youngest.

Oh, actually, it just needs one of them because in one equation it is using one mapping to the other, but not the other to the first one. Kathy?

AUDIENCE: If you're using the previous cohort, if you're using a separate age that maps onto another for some reason, but you're not using it in a way that it has to map, does that mapping specification mess that up?

HAZHIR So the key to mapping is that they should have the same number. Otherwise, it wouldn't work. I don't know if it

RAHMANDAD: gives an error or not. It probably should.

AUDIENCE: Yeah, I guess If you want to use the mapping we defined subrange for something separate for some reason with the fact that it maps onto something, like cause Vensim to say that you can't use it in isolation?

HAZHIR No, no. So mapping doesn't restrict you. It just gives you options that you can use. Mapping does not add any

RAHMANDAD: restriction. Now, let's see what this does for you that is valuable. So let's say rather than five groups of population, I wanted to have also another group, oldest.

So I can just add in this subrange. Oh, actually, I shouldn't add it in this subrange. First, I should add it in the main range. Otherwise, this gets confused that this subrange includes elements that are not in the range. So let me close this. I would go into the age.

I'll do Edit the range. And I'll add the oldest here, then close this. Then I can go into All But Youngest, edit subrange, add the oldest. And then I can go to previous cohort, edit subrange. And then what should I add here?

AUDIENCE: Old.

HAZHIR Old, exactly. So now the model should be fine. That is, if we run this model, it just works OK. Now we have added

RAHMANDAD: another element to the cohort. So that's the basic idea. Now, you can do this in a much more flexible way even-- not much more, but more flexible than this even.

And the way to do that would be, I'm going to create the subscripts here without applying it to the model so that you just see how to create subscripts that have this characteristic. So I'm going to say, I need a new subscript range. So let's call it test. And the way I define it is t1 and tlast. I'll call it tlastset.

Or actually, let's do it this way, tmid, tlast. OK, so now it seems like it has three elements. But in reality, I'm going to add a lot more elements. So then, I'm going to create a new subrange. So let's look at test. Right now, test has only three elements.

Now I can go and create a new subrange and call it tmid. Oh, it is already defined. So Vensim doesn't let me do that. So that means I have to first define tmid then do this. So that means I need to kill the equation for this range before I can do that. Sorry.

OK. I can kill it on this screen, so I just delete that variable. And, yes. Yes, the best software ever. And somehow it didn't go away. I think Vensim is crashing on us. Oh, no. OK. Now it is removed. So first we create a new range, call it tmid. New Subscript Range, tmid.

And the equation then comes here. Let me bring it to the other screen. So here, I'll just define it as t2 to t10 or whatever you want the range to be. So now we have tmid that includes t2 to t10. Now, we define a new range, test. It consists of tfirst, tmid, tlast.

Now you see that tmid thing went away. It's now incorporated into the test subscript range because it saw that, OK, it consists of tmid and other things. So now it has all of these elements built into it. Now we can create new subranges. So we can have a subrange for the first until number 10. And to do that, we would say tbefore. That consists of tfirst and tmid.

So now tbefore is the first one until the 10th one. And then you do another one that says tafter, which is tmid, tlast. So tafter is now this subset. Now you do your mapping. So you can go into the equation here and say this maps into tbefore. Oops, sorry.

And in fact, you can make the mapping two way by this sign, which will then take care of both way mappings. So this takes care of any equation that uses one for the other or the other for the one. Oops, maybe it doesn't like this. OK, so if it is not liking this, then you need to do the mapping separately.

At some point, it used to be working that way, but that's OK. So now you can do also the same in the tbefore if you need to. So all of this mess that we did allows us to have very efficient editing of all of these subscripts in one step. So now I can go to subrange, editing tmid, and rather than t10, I will say no, I want to have 100 population groups. And voila, you have it all.

And everything is internally consistent. And your model now goes from 10 subscripts to 100 subscripts with just one small edit. So this is a useful efficiency thing. Now, most of your normal models for this class doesn't need any of this. I just highlighted it as a capability you will benefit from for more operational models that do need detailed complexity. Any questions on this part?

AUDIENCE: One detail I just want to deconstruct. When you did the mapping, why was it going into tbefore? I lost track of what you showed.

HAZHIR Yes. So for the other equations, in definition of tafter, I had it go into tbefore. So what does it mean? It means
RAHMANDAD: that when you are writing equations for tafter, elements of tafter, or equations that use tafter, you can use on the right-hand side of the equation, things that are subscripted with tbefore.

So the bearers or the kind of aging of tbefore should come into the equation for tafter. That is why I need that mapping. So that's the idea. OK. This is really not in conceptual, just Vensim tips and tricks, but useful for building more complex models.

Let's now switch. Any questions on the modeling task for this week? I think we actually haven't quite gone through showing one that has all of the characteristics we want. Again, if I get the chance, I'll try to build one. But I think we have discussed the core ideas. Let's then switch to our task for next week.

OK, so next week in exercise 4, what you are going to build is a predator-prey model with carrying capacity for the prey. So think about it as kind of wolf and deer model or kind of different incarnations of this. There are different fishes that one is caught by the other one. There is rabbit and fox example. You can use your own favorite or unfavorite animal.

But this version, what you want to build is also including vegetation. That is, the herbivore is going to need food for their own sustenance and survival. It's not that they'll grow infinitely no matter what. So this is a little bit more complex version of the traditional predator-prey model.

So let's have a little bit of a conversation around the key architectural choices for this model so that we are aligned on that as you get started working on this for next week. This is perhaps less complex in terms of the detail complexity than what we worked on this week, but it is a dynamically more complex model. So going through the testing of the performance is really key.

If you don't do the performance tests and understanding of the model, you are losing a lot of the value that this model may generate. Of course, you can go online and find predator-prey models. This is one of the oldest models in mathematical biology, going to 1920s, and Lotka and Volterra independently kind of formulated similar models in the 1920s. So it's now known as Lotka-Volterra model as well.

Don't go and pick up other people's models. Just build it from scratch and wrestle with any challenges that you may see. With that in mind, let's define a good problem definition. So how would you see your model as a good model in this case? Or what's a good problem rather than the model? We'll talk about the model features later.

AUDIENCE: We could talk about any challenges with the population of one type of animal can be addressed with this model. We have policymakers. We have, for example, too many animal crossings with deers.

HAZHIR
RAHMANDAD: Good, so kind of one policy-type of application is we care about an ecosystem and its sustainability, its effect on the surrounding environment. It might be side effects of animals who may act as pests. They may eat your crops, they may create accidents, or they may be threats for your wildlife.

The question is, you need to understand what this ecosystem is doing before you can intervene in any meaningful way, because these things are very messy. You go and kill the predator, the whole ecosystem may collapse or get into weird dynamics that will create lots of side effects for you. So that's the policy space question. Now, for policy questions like that, this would probably be too simple a model because usually you just don't have just two species that are interacting.

So then you need to actually capture the core species within the whole ecosystem. And that may end up to be a kind of a predator-prey model on a steroid, where you have multiple species that are eating each other or coexisting with each other, eating the same food. And so that becomes an extension of this model for the more serious policy applications.

What else might be relevant as a problem definition for our case? The policy one is pretty good. It's a good guiding one, but also more complex than what you can handle in the one week time you have.

AUDIENCE: Build a model for how can we explain oscillatory patterns of population sizes that have the same data. But what relationships give rise to this kind of repeated cycle of births?

HAZHIR Yeah, that's a good alternative formulation. So this is more reference-mode-based problem definition. There are good examples in the data. This is actually how, I don't remember whether it was Lotka or Volterra. One of them started it. It was basically the fish populations in the fisheries in Atlantic Ocean that they were measuring and seeing these oscillatory modes over multiple years.

And it was very confusing what is happening that creates oscillations in the fish population. So that was kind of one of the major drivers. Now, if you focus only on the oscillatory mode of behavior, the way I'm defining the problem here to include the carrying capacity for the prey may not be that relevant. That is, down the line, you would say, why do I even include this carrying capacity thingy?

So that, partly in this case, is a problem definition more driven by mechanisms that could then generate a few different reference modes. So oscillations would be one of those reference modes, but perhaps there would be overshoot and collapse possibility perhaps. So it is basically expanding the reference modes to include things that may come from these mechanisms, rather than just having a fixed reference mode that we are trying to replicate.

And that means we are focusing on mechanisms and capturing them well without adding other mechanisms that don't directly help with this subset and seeing what kind of reference modes come out of it. That becomes a more interesting, relevant exercise for our purpose than just capturing a single reference mode.

AUDIENCE: That makes sense to me. But what I find I struggle with is articulating that as a problem statement. So the idea conceptually makes sense to me, But it's not really good enough to write down what other patterns of behavior might arise from it.

HAZHIR Absolutely. So in that memo also I kind of discussed these three types of problem definitions. One is reference-mode driven. One is policy-question driven. That was closer with what Hassam said. And the third is mechanism driven. That is, you have a set of mechanisms. You want to investigate what comes out of those and only those mechanisms.

And in this case, we are saying we have two populations. They interact with each other, one eating the other one. That's a core mechanism. They have their deaths and births. That's kind of implied in this. If you don't have that, nothing works in this system. And then the one that is being eaten also eats some other resource that regenerates itself.

That is grass or trees or shrubs or whatever it is, the food for the deer in this case example. So that's the set of mechanisms that are relevant. Now, how to formulate it in a robust manner? That's the primary task. And the second task is exploring what kinds of behaviors can come out of this combination or these set of mechanisms.

So I think that is the problem definition close enough for what you need. What is stocks? What do we need? What are the sources of inertia? And what are good stock variables? Thoughts on that? Let's hear from somebody online. We have been keeping you too quiet. Anybody wants to take a stab on identifying the stock variables that are relevant?

AUDIENCE: Predators.

HAZHIR Predators, there you go. You have one in your hands. Excellent. So this was a very good show-and-tell from Jake.

RAHMANDAD: So predators, for sure. Basically, that's the population that we care about. Now there is a question in the selection of stocks, whether we want to put everybody together as a single stock of predator or perhaps separate them based on age groups.

I am OK with putting everybody into a single stock. That's what the traditional Lotka-Volterra does. Adding age groups may be relevant because it introduces some additional nuance delays that may actually contribute to more of the oscillatory mode of behavior. So if you have time or interest, feel free to explore that.

But don't go more than two stock variables per species because you don't need that much resolution in terms of age here. So that's good. So for predators, one or maximum two. Similar thing for prey, that's also all you need. Anything else? Any other stocks? Kathy?

AUDIENCE: I would put something about vegetation in there.

HAZHIR Yeah, something about the vegetation, the resource capacity, carrying capacity for the prey. So for that, you

RAHMANDAD: could also use a single stock or consider larger number of stocks, maybe two. Again, very much depends on what reproduction process the carrying capacity has.

So for example, if kind of trees were the primary source of food for the deer, then breaking down into two would make sense. Because if you eat the smaller trees, they wouldn't grow to the age that they would be fruitful and so on. And that will have some interesting additional dynamics. Again, for your use case, feel free to go with one.

Don't go more than two. And perhaps start with one anyway to keep things simple for yourself. And then if you have time and interest, explore having more. OK, so those are some of the stock conversations. Let's spend the last few minutes on what are the good tests for performance and robustness of the resulting model.

What are the things that should happen in the model? What are the robustness conditions you can test? What are the key inputs to change and outputs to track for those tests to be well specified and useful? So what are your thoughts on that? I'm happy to write down your suggestions for tests.

AUDIENCE: This might be kind of the thing we were just talking about of, can we actually create the expected reference mode behaviors we can by introducing shocks that we think will create them?

HAZHIR Good. Can we recreate the expected reference modes, e.g. oscillations? What else? Actually, thinking about

RAHMANDAD: inputs and outputs is also good. So what inputs would this model potentially take?

AUDIENCE: The reproduction rate of each species.

HAZHIR So you would have various parameters that are potential inputs.

RAHMANDAD:

AUDIENCE: Initial states.

HAZHIR And initial states, yeah. Good. So we haven't really introduced much else in this model. This is a very self-contained model the way we have conceptualized it so far. You could consider shocks from, OK, let's go and hunt the deer or hunt the wolf type of a situation. So hunting could very much be part of your most policy levers, but also shocks to the system if you want to consider that. And it kind of makes it closer to the policy application questions you have. So hunting of both species might be useful to consider.

AUDIENCE: In the same line, you have changing land application.

HAZHIR Yes, changing land availability. Good.

RAHMANDAD:

AUDIENCE: What is changing land?

HAZHIR So basically, build houses, cut the trees and build houses or something like that.

RAHMANDAD:

AUDIENCE: Yeah, like environmental encroachment.

HAZHIR Environmental encroachment would be another relevant shock to the system.

RAHMANDAD:

AUDIENCE: Should we also include the area available, like the size?

HAZHIR So that's a good question. If you want to try this alternative, then area becomes another stock variable rather than a parameter. Now, you could still deal with it as a parameter, but it is a messier system to do it as a parameter. It might be easier to think of it as a stock variable if you want to go down that road.

AUDIENCE: Similar to hunting, you could think about disease killing one of the populations.

HAZHIR Yeah, so basically this would be exogenous shocks that are reducing I think this is a good set of inputs. So

RAHMANDAD: outputs that you want to track, the obvious one is the populations of all species and carrying capacity is a pretty basic important thing. We don't have very clear policy questions so we don't need to define more KPIs. OK. Now, other robustness tests, tests that you would feel are worth considering?

AUDIENCE: The extreme conditions of the population, like if I take out some of the population.

HAZHIR Yes, take out some population. Good. That's a good suggestion.

RAHMANDAD:

AUDIENCE: Compliment is expanding one population.

HAZHIR Yeah, perhaps making carrying capacity not a binding constraint, for example. You could also consider adding

RAHMANDAD: one of the other species at the beginning of the simulation. So that's more playing with the initial states because that's more continuous. 0 is a qualitatively different thing for these models.

AUDIENCE: Just a clarifying question, are we thinking we might have to figure this out on our own? Carrying capacity is a stock variable.

HAZHIR So you should decide how it works best. But conceptually, it is what your deer needs to survive. So that's what
RAHMANDAD: you need to model. Yeah. And the other general point for this model is, try actually doing it in more than one iteration. That is, don't try to put everything in the first iteration.

You could even do it in three iterations. That is, build the part for deer, just the deer population in infinite, happy life, and then introduce the wolf, and have the two-species version without any carrying capacity. Then, add the carrying capacity. And at every step, test that your model does the right things. Make sure you have inputs and outputs.

If you wanted, you felt more comfortable with jumping through these, you can build that deer and wolf at the same time, then add the carrying capacity. Make sure your models are unit consistent. Make sure you understand what is happening in your model. So we will probably do more simulations next time on this one.

OK, I think this is a good coverage of the key items. So, go through iterations-- deer, then add wolf, then add carrying capacity. And that recommendation is based on where you stand modeling-wise. This is not a very complex model. So by the end of this course, you may feel comfortable that, OK, I just bring all of them together in one round and that's fair as well. Any questions for this assignment?

AUDIENCE: I have question. When we talk about carrying capacity, we are talking about what the deer eats, right? So vegetables are what they eat.

HAZHIR Yes. Basically, that's it. The key thing we are focused on on carrying capacity is food for the deer. Now, that food
RAHMANDAD: itself is not a fixed amount that is out there in a form and the deer eat it and then everybody goes extinct. But it is a rejuvenating thing on its own. It can regrow when it is not fully eaten. So that has dynamics and that requires a stock variable, as we discussed, and perhaps even two stock variables if you want.

AUDIENCE: Should we submit simulations with our models?

HAZHIR Good question. Actually, so let's do it this way. So analyze one interesting scenario. And you can pick it from your
RAHMANDAD: final model, whatever is your final model. Set the parameters so that it creates the scenario you think is interesting.

It might include oscillations or some other behavior, overshoot and collapse or something, and analyze it. And by analyze it, I mean, be able to tell the story, what structures are generating that behavior at different points in time. And come prepared to share that. If you get a chance to write it down and copy and paste a few graphs, that's great.

So that would be good. Analyze one key behavior out of the model and fully understand it. Excellent. Anything else? Online folks? OK, great. So enjoy your weekend. Enjoy, we have something here happening in a few minutes, I guess, some journal club. Yep, OK. Those online, have a good rest of your day or night. And we'll see you next week.