# Using Storytelling and Teaching Materials to Share Systemic Insights to the Public during the COVID-19 Pandemic

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**Abstract**: In March 2020, our team initiated a modeling effort with two purposes: (1) to create semantically rich stories about the pandemic aimed at the public and (2) to create teaching material for students of system dynamics. We have described the technical details of the models that have supported that work in Mashayekhi et al. (2023). The purpose of the present paper is to document the modeling process that we have undertake: the origins of the project and how the team was assembled, how the team set about developing and writing model-based stories, the iterative process through which a COVID-19 simulation model was developed and refined, and the development of sets of teaching and learning materials about epidemics. We conclude with a reflection on this process.

## Introduction

The COVID-19 pandemic has been, without doubt, a life-changing experience for all of us, and its short- and long-term impacts on aspects of interpersonal, social, professional, or economic interaction have yet to be fully appreciated. From the first days of the pandemic, simulation scientists across the world worked to develop models that would assist in creating policies to manage the pandemic and its consequences. A recent literature review found 372 published papers that applied dynamic modeling to understand various aspects of developing policy and managing the pandemic (Zhang *et al.*, 2022). Major topics of these efforts included elucidating transmission dynamics (72 papers), assessing potential interventions (204 papers), and anticipating health and socio-economic impacts of the pandemic (67 papers). Fifty-four of these papers used system dynamics as modeling approach.

In this paper, we describe a modeling project whose main purpose was to communicate useful systems insights about the pandemic, principally through storytelling, that could lead to useful, positive behaviors. Our work was inspired by the work of Donella Meadows (1989), who was convinced that the field of system dynamics provides "valuable insights about the world" that are worthy of being spread widely. We note that, as discussed by Farr and others (2022), documenting the modeling process is different from merely documenting the model itself. We describe this process and identify the products produced along the way. This paper will not describe those products - stories, models, learning environments, or other curriculum materials – in detail, except as occasional examples. We believe that model-based stories need to be accompanied by complete, transparent information about the model for technically competent readers, and for the model documented well enough to be refutable by other professionals in the field. To that end, we have posted all these details online at our project website and described them in a System Dynamics Society webinar, *Using system dynamics to teach and learn about COVID-19.*[1]

[1] The webinar can be accessed at https://systemdynamics.org/using-system-dynamics-to-teach-and-learn-about-covid-19/. All project-related materials are also open to the public and available at https://newfadumfarm.org/.

The paper is organized into five sections. We introduce (i) the origins of the project and how the team was assembled. We then (ii) describe how the team set about developing and writing model-based stories that were aimed to share systems insights with a general audience. The following section (iii) describes and documents the iterative process through which a COVID-19 simulation model was developed and refined. The next section (iv) describes the development of sets of teaching and learning materials about the epidemic. We conclude with (v) a reflection on the process of developing heuristic materials and sharing system insights to a general audience.

## Project Origins and Timeline

In March of 2020 one of the team members (AM) created a system dynamics model of the COVID-19 pandemic, loosely calibrated to the demographics of Iran that was intended to create epidemiologic scenarios to support policy making at the national level. The model was a classic SEIR (susceptible, exposed, infected, recovered) population model, with the crucial addition of behavioral feedback loops through which the population's response to the perceived death rate modified contact frequency and hygiene behavior. It also contained a sector that modeled the hospital system's ability to respond to the increased demand for care, and the effect of hospital capacity on the course of the epidemic. In early April, he contacted a US-based colleague (DA) to explore ways to further develop the model, to publish it and to use it contribute to the improvement of pandemic-related public policy. Although both are well-trained and experienced in System Dynamics, they decided to invite onto the team two additional modelers who possessed extensive experience in system dynamics and public health policy (DG and ATC). One member of our team had recently retired from the New York State Department of Health; he had contacts with persons who were informed about current policy making at the state level and with others who had some knowledge of the kinds of modeling that were used at the Centers for Disease Control and Prevention to support national policy making. External and internal discussions led us to a consensus that our modeling efforts were unlikely to find an audience within a governmental public health policy arena. As an alternative, the team hit on the idea of using the model to develop and communicate system-level dynamic insights to the public, and to disseminate these via the weblog. We were aware of Dana Meadow's use of storytelling to convey dynamic insights to the public at large and decided to launch a project modeled, in part, on her work. Our first published story, entitled "Ali Calls from Tehran on Palm Sunday" [2], ends by setting out the general goal of the blog and stories to follow:

> *the audience for Ali's model was not the governor of New York, let alone places such as the White House or the US Center for Disease Control. Instead, the audience for Ali's model should be ordinary people who need to understand what's going on with COVID-19 well enough to figure out what to do with their daily lives. This audience does not need precise point predictions about when the first wave will peak, nor how high it will be and exactly how many hospital beds and respirators will be needed.*
>
> *My daughter's family needs guidance on how to think through scenarios to keep their soon-to-be born daughter healthy and well. The pastor at our local Presbyterian*

[2] See https://newfadumfarm.org/ali-calls-from-tehran-on-palm-sunday/

*church needs to figure out how we can return to face-to-face worship while at the same time protecting the health of frail elderly in our church. My brother needs to figure out how to meet the payroll for forty or so employees of his actuarial consulting firm during a time when many of his clients, themselves small business owners, are struggling financially.*

*These stories translate the saga buried within the differential equations of Ali's model and piles of data that Dan collects and analyzes into ordinary language that we hope you find to be a useful and interesting guide to your thinking about how to manage your lives over the next 18 to 36 months."*

The core modeling team was completed by incorporation of one more modeler (BB) who was specifically interested in the challenge of using web-based tools to communicate model results.[3] The project team started writing a series of stories about life during the pandemic, narrated from the point of view of a sheep farmer living on a small farm in upstate New York. The stories are intended for a non-technical audience but are carefully based on lessons derived from a complex system dynamics model. The stories were shared through a dedicated website under the titles of "Diaries During Lockdown" and "Diaries After the Lockdown."[4] The group published 35 stories from April 2020 to December 2021.

In the Spring of 2021, an academically based system dynamics modeler (HK) learned about the project and proposed to develop a set of self-paced learning modules that would guide her students to build a simulation model to explore pandemic dynamics. These materials, published as an Open Educational Resource (OER) and are also available through the team website, have been used as learning modules in a system dynamics simulation class.[5] Finally, during the Fall 2021, an additional academically based modeler (LLR) learned of the project, and worked with the team to develop a case-based policy simulation tool for a class primarily interested in policy making rather than simulation and modeling. The tool was part of a package that included a case statement, supporting class materials and a simulation interface. The materials were developed as an OER and were used and assessed in an undergraduate policy capstone class during the Spring 2022. [6]

The team has met via teleconference once a week since March 2020. Our project strives to meet three goals: (1) to create materials that can reach as wide an audience as possible with dynamically-grounded insights about living in a world with COVID-19, (2) to create and deploy teaching materials related to COVID-19 for students of public policy and of system dynamics, and (3) to refine and augment the model as may be needed to accommodate emergent epidemiologic or policy scenarios. During the weekly meetings we reviewed emerging events concerning the COVID-19 pandemic; discussed and

[3] This tale of origin was our project's first story. You can read it at, https://newfadumfarm.org/ali-calls-from-tehran-on-palm-sunday/

[4] Stories can be found at https://newfadumfarm.org/diaries_during_lockdown/ and https://newfadumfarm.org/diaries-after-the-lockdown/

[5] See https://newfadumfarm.org/learning-material/

[6] Class materials are available at https://newfadumfarm.org/classroom-activities/ and the model interface – developed using Forio tools—is available through the following link https://newfadumfarm.org/covid-19-policy-simulator-and-learning-environment/

probed all aspects of our model's structure (including current and new structures); projected behaviors and derived resulting insights; we assigned ourselves simulation exercises to complete between meetings; reviewed draft stories; reviewed the website structure and content; and discussed the teaching materials and user interfaces that were being built. Individual team members also led specialized activities: convening and coordinating the group; conceiving and writing stories; developing and documenting the model; editing stories; developing summary Causal Loop Diagrams; developing teaching materials; developing and maintaining the website; and translating our Vensim models into Stella versions for online simulation.

## The Process of Developing & Writing Stories for a General Audience About COVID-19 that are Based on a Formal Simulation Model

Although our efforts were modeled after the pioneering storytelling work of Dana Meadows, our context differed from hers. First, our stories are all set in a single dynamic domain—the COVID-19 pandemic. Second, our stories were to be based on a running system dynamics model that was being continually updated by a modeling team (see Figure 1 below). We soon hit upon two patterns of work, i.e., of modeling and writing, that could be worked into descriptive "scripts" for other system dynamics teams interested in the storytelling approach[7]. One set of scripts would address how we worked together to develop dynamic insights that could become the basic "lessons" for stories (the left side loop in figure 1), while the second set of scripts would be a guidebook, based on our team's experience, for converting lessons into stories (right side in Figure 1).

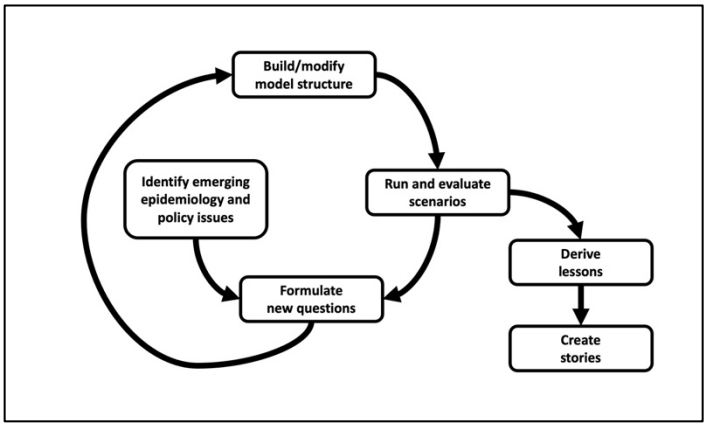


**Figure 1** ***Model development and story creation process***

During the weekly meetings, the team engaged in broad discussions involving model exploration in the context of current events both in upstate New York and around the globe. These discussions served as kindling for the development of new modeling structures and for the emergence of dynamic insights into the COVID-19 pandemic. The way we organized that work would be familiar to formal modelers who have spent time developing a model's structure and exploring the connections between model

[7] We are suggesting here that there may be an analogy between "dynamic storytelling" and "group model building". Both of these areas began with early practitioners describing how their teams worked together using scripted behaviors to do their work, all with the intent of helping others to learn a new suite of behaviors for working with system dynamics models.

structure and behavior. To those processes we added another step--the translation of quantitative behavioral insights into lessons for stories aimed at a general audience. As an example, early on we observed that our model as formulated was very nearly a limit cycle oscillator. Indeed, if the model was modified so that the number of persons who died in each time period was added back to the population (so that the total population remained stable), the model was precisely a limit cycle oscillator. This technical insight was exciting and instructive to us as modelers, but we saw no way to craft an engaging story about limit cycle oscillation for a non-technical audience. Instead, the lesson fleshed out in the stories was simply, "There is (very likely) going to be another surge, and there may be successive surges, and this is why". In this way, the team turned dynamic systems insights into "lessons" to shed light on how to live with and make sense of the pandemic.

Drafting stories that would embody lessons that emerged from the model-based discussions and analyses, was the specific charge of one team member. The early-draft stories then went to the rest of the team for discussion revision and editing, until they were deemed ready for posting on the project blog.

The stories featured a lesson; devising "good" lessons that would be true, useful and comprehensible was the hardest part of our work. The story writer's first task was to devise a "hook", a concrete real-life incident that might draw readers into a short narrative serving to reveal the chosen lesson. We decided to locate our stories in one concrete and realistic domain—a small sheep farm in upstate New York named "New Fadum Farm". Since our storyteller indeed did live on such a farm, this task reduced to thinking about the details of his daily life for such a "hook". This hooking idea was written up as a short trailer to the larger story. Next, the storyteller thought of a title for the story that might have some sort of a question or implied cliff hanger in it. Finally, a story always included an image to illustrate it. This was usually a photograph from the real New Fadum Farm, but occasionally some public-domain image or cartoon downloaded from the internet was used. With a lesson, trailer, title, and photo already selected it was easy to assemble the bare bones structure of the story.

The narrative was always intended to stay under 800 words. The purpose of these 800 words was to use the situation in the trailer to develop a very local and specific view of the general lesson with which the whole process always started. The last several sentences of each story returned to the situation depicted in the trailer giving some resolution to the issue kicking off the whole story. From time-to-time, the lesson loomed larger than this simple story and it was somewhere between difficult to impossible to tell a complete lesson without addition more technical language. In these cases, we added a "Read More to Dig Deeper" section on some of the stories. When we began this effort, we had a rule never to show model output and to avoid talking in numbers and equations whenever possible (there were several important exceptions to this rule). Subsequently, in the "Diaries After the Lockdown" portion of our work, we relaxed the rule about not showing model output and experimented with incorporating a small number of carefully selected model runs, most often in the "Read More" sections. We made this change because most of the comments we were getting back at that stage were coming from an audience that had at least some familiarity with system dynamics. All stories had direct links to the Vensim version of the CORONA1 model plus links to the technical PowerPoint briefings with which the project began.

Early stories captured uncertainty related to the pandemic and the lockdown. For example, the second story – "When will this Pandemic End? "— was inspired by travel plans disrupted by the

pandemic and the lockdown, and used that as an entry point to the main question related to the continuity of social and economic activity more in general: when will the pandemic end? The story included a reflection on the need to use data and models to develop policies and guide decision making. Several stories that followed included insights on how every individual in society had a role in stopping the pandemic by observing rules and protocols of social distancing. For example, story "How to Stop a Pandemic" concludes,

> *To be clear, there was nothing at all silly about Deborah and David going out in public proudly wearing face masks. Those were not low-tech, largely symbolic gestures. We were deadly serious. We were showing our solidarity with the only currently viable option to stop this pandemic before it kills hundreds of thousands of Americans. If we follow procedures for low contact and social distancing measures as prescribed by New York State and the CDC,* ***and importantly if everyone else does the same****, we will for sure halt this pandemic in its tracks.*

Other stories during the lockdown included insights on how to keep in touch safely. For example, reflecting on the way that "a trusted group of good friends can sit to chat face-to-face and maybe even take a garden or barn tour while picking up a dozen spare eggs," the group developed the "egg club protocol"[8], a set of simple ideas that could be used by anyone to keep in touch with close family and friends. The protocol included basic organizing principles such as *Trusted Responsibility* (we are all responsible for each other), *Social Distancing* (no shaking hands, no hugging) or *COVID-19 Testing for Members of the Egg Club* (if you have a temperature or don't feel well, stay home).

Team's model-based reflections and discussion on current events also discussed the possibility of a second wave of COVID-19, encouraging caution during April 2020, at least until better testing and a vaccine was made available to the public. The team posited the likelihood of a second wave as a hypothesis based on the model behavior, set in the context of planning a party for the Summer 2020. The story concludes

> *Ali's explanation for a second wave, like all model-based explanations, is a hypothesis that needs careful evaluation. Decisions are made based on the mental models of human actors, not by mathematical models. That said, it would be foolish to make plans for the future until we can reject Ali's hypothesis with confidence. What we all decide to do next is of great importance to the health of our population and to the prosperity of our economy.*

In total, 55 stories were drafted of which 35 have ultimately been posted. During the most severe period of lockdown, stories were posted on Diaries During the Lockdown. Once this period of lockdown had passed, subsequent lessons and stories were posted on a companion website, Diaries After the Lockdown. All stories were reviewed, discussed, edited, and improved (or, occasionally) deleted by several members of the team. We consider these stories to be jointly authored.

[8] Read the full story at https://newfadumfarm.org/converting-the-egg-club-to-a-covid-19-safe-trusted-network/

## The Process of Refining and Developing a Model of COVID-19

The initial model was often revised and extended as we often reviewed emerging events concerning the COVID-19 pandemic. For example, a second (and third) surge did emerge. New vaccines were developed and administered with wide-spread reporting of effects in both the popular and scientific press. New variants emerged. There were large-scale differences (and disagreements) in the public reactions to these events. Each time an event was put forward, we had a broad open-ended discussion on the topic and on how we might analyze each event within the framework of our existing model. If new structures were needed (e.g., we needed to add a "vaccination sector"), we discussed how best to formulate such structures and one of our two modelers made the necessary changes and tested them with multiple and comparative runs. Reports on changes to the simulation model's structure and the model's results created part of the material for our next meeting.

We started with what we called the "CORONA1" model – a system dynamics simulation model representing a viral epidemic modeled after COVID-19 in a hypothetical small country – and three PowerPoint slide decks describing the model structure and behavior in detail. The first PowerPoint briefing, entitled "The spread of Corona",[9] presented the basic model structure in several layers of increasing complexity. Then the briefing presented a detailed discussion of three scenarios designed to demonstrate a broad range of base behavior in the model. These scenarios were prefaced with several disclaimers, including, "In the absence of solid empirical data about key variables and relationships, scenarios let us explore the model's overall behavior, and view the possible range of plausible results".

The second briefing, "Waves of Corona", made the case that the COVID-19 virus would be characterized by multiple waves of infection, not just a single surge. One of our modelers had demonstrated this point by showing 8 variations of the same scenarios (with an extended timeline) that he had presented to us previously. He revealed that repeated surges are an inherent consequence of the dynamic structure he had formulated in an exploratory version of CORONA1. The team worked these results into a story asserting the likely multi-wave nature of the COVID-19 pandemic even before the first wave had peaked. As it turns out, the behavioral feedback loops missing from the classic SEIR model proved to be the key structure driving the multi-surge behavior mode of the COVID-19 pandemic.

The third briefing, also produced in April of 2020, was based on set of runs to help identify public policies that could help slow down or control the pandemic. For this briefing we introduced a new structure to the model meant to simulate a national testing program. The briefing presented 18 simulations that walked the reader through how the testing program interacted with the three scenarios discussed in the first two briefings. Recall, that these policy runs were run in a hypothetical "what if" mode because the testing programs that later in the pandemic became ubiquitous were not yet developed. In addition, two other mechanism that we have in our model, one is fatigue and the other is government lockdowns were anticipated in advance, carefully thought through, modeled, and discussed as policy options before they happened.

[9] The initial version of the model –CORONA1—as well as the technical briefings and the latest version of the model can be accessed at https://newfadumfarm.org/resources/

Subsequently, we expanded the model well beyond the structure of the original CORONA1 model and its associated three technical. To date, the team has developed eleven distinct versions of the model structure, with increasing sophistication and ability to address issues appearing the in the popular and scientific press. Although the model is not precisely calibrated using data specific to any geographical region, the model is grounded in robust theories from epidemiology and extensive sensitivity analysis and uses empirically derived values for parameter whenever possible. As the model's structure emerged, we posted the revised version as a resource on our public website.

The process that we used to elaborate and refine the model's structure would be familiar to any team that has spent considerable time exploring the connections between the structure and behavior of a complex feedback system. Our discussions benefited from the fact that we met regularly for one hour every week, giving us ample and relaxed time to discuss emergent issues, and sufficient but limited time between meetings to do additional model development, sensitivity testing and policy testing. Our discussions almost always emerged from our awareness of current events and the scientific literature concerning the COVID-19 pandemic. Our team members were distributed around the globe, so we collectively experienced firsthand differential timing of surges and types of public policy responses. We always had in our meeting at least one member who regularly read the public health literature and was current with recent research on medical and epidemiological developments. From these discussions, we formed "hunches" about changes that seemed to be going on with the COVID-19 pandemic and the policy and public response to the disease itself. We pushed ourselves to convert these "hunches" into hypotheses—alternate dynamics hypotheses—about what must be going on with the pandemic. On any fruitful Thursday discussion, we would wind up with one or maybe two such hypotheses to be investigated within the model.

Sometimes to test these hypotheses, we would devise a program of sensitivity and policy tests usually involving scores or dozens of runs and reruns of the then current model. From time to time, we realized that we simply had to expand the causal boundary of our model's structure to address the issues that were forming the core of our hypothetical thinking. For example, during one period we seemed to always be talking about vaccinations and how best to formulate them in the model. Another set of discussions centered on how to conceptualize and runs tests on new variants. Another set of discussions were concerned with public fatigue with continuing surges with a special emphasis on difference in time constants for tightening versus loosening voluntary constraints by the public. For discussions such as these, one of our lead modelers would propose new code for the model and then we would put the revised structure through another set of behavioral tests. In sum, some "during the week" tests involved behavioral "stress tests" of the current structure while other involved creating new structure that responded to the concerns that we saw being raised in the public press and scientific literature.

## The Process of Developing Materials to Teach about the Dynamics of COVID-19

To group members joined the team specifically to develop learning materials based on the COVID-19 model. This section includes a description of the three sets of materials developed as part of the project;

all these efforts are available as OER with a Creative Commons CC BY license; these learning modules are free to distribute, adapt and remix with attribution.[10]

## Creating Learning Modules for Building the COVID 19 Model

Convinced of the value of storytelling and simulation modeling, one member of the team developed a series of asynchronous online learning modules to guide users in replicating the CORONA1 model. Although the materials have been used as modules of a formal curriculum to teach system dynamics, they were created with the broader goal of helping a general audience to acquire basic familiarity with system dynamics and get a deeper grasp of the dynamic insights shared in the stories during and after the lockdown.

For this sub-project one of the lead modelers broke down the model into 13 steps or iterations, so that the learning modules included model development step by step. The team member in charge of the development of these materials shared with the rest of the team each module for comments. As a result, the team discussed proposed revisions during weekly meetings until they were ready for posting on the public website. While assisting the replication of the CORONA1 model, the learning modules cover key modeling concepts and techniques typically covered in an introductory/intermediate system dynamics course.

The diary stories play a key role in each module. Each module is connected to a story in the diaries relevant to the model structure and behavior introduced in the model. The story is used as a motivation and practical application of the module. The stories explain why the model structure is modified, what implications a model parameter might have, and/or why certain scenarios might be tested. The modules help audiences to fully appreciate the model-based insights discussed in the diary stories.

As of January 2023, 9 out of the 13 modules have been released to the public in the project website.[11] When all 13 modules are finalized and available, they will constitute a self-paced tool to learn system dynamics modeling as well as teaching materials that may be adopted by formal system dynamics or public health courses. The first module starts with a simple SIR model; in each subsequent module, a small structure is added on. By building and simulating the model in Vensim, users of the materials explore both the relationships between model structure and behavior, as well as their real-world implications. In each step of the modeling process, key assumptions are identified, and they become the basis for model modification in subsequent modules. Various system dynamics modeling techniques covered in the modules can be applied to problems beyond the COVID-19 case.

Anyone can use the modules, even those without extensive knowledge in system dynamics. Besides the 9 modeling modules currently posted on the project website, the materials include 2 additional modules introducing basic concepts in system dynamics. Modules are distributed as an Open Educational Resource (OER) under the Creative Commons License. This allows these materials to be freely available for adaptation and use.

[10] See https://creativecommons.org/
[11] Modules are available at https://newfadumfarm.org/learning-material/

Creating a Model-Based Case for Public Policy

Although developing skills for model development and simulation is a useful tool to understand problem dynamics, there is a long tradition of using simulation-based cases and learning activities to explore policy and decision making (Silvia, 2012; Ku et al., 2016). Inspired in this tradition, the team collaborated in the development of a capstone experience for undergraduates in Public Policy using a simulation-based case study. The main goals of the Capstone experience were: (1) to demonstrate knowledge and understanding of public policy issues and analytical tools, (2) to communicate complex ideas clearly and persuasively in written and oral forms, (3) to evaluate applied theoretical and empirical work in policy-relevant research, and (4) to apply skills and knowledge acquired in the curriculum to analyze policy issues and make policy recommendations.

To accomplish these learning goals, the team developed a series of publicly available materials, involving effort of one of the lead modelers and two other members of the group. Materials include a case, a web-based interface to provide students access to the model for policy experiments, and a series of in-class exercises and handouts to support the use of the simulator.[12] The case is inspired by the story titled "Even the CDC has flip-flopped on mandates to wear masks—why is that?"[13] which reflects on the public's uncertainties regarding mask mandates and potential lockdowns just as a third wave with the new Delta variant was starting; these uncertainties were compounded by governments' seeming hesitation or inconsistency in establishing policy. A former local county executive was recruited to provide additional feedback on the contextual information and main stakeholder characters included in the case. Materials were pilot tested with a Capstone class during the Spring of 2022.

The case sets the stage to work with a task force of stakeholders and community leaders in the preparation of a set of recommendations to a fictional County Executive, Sean McAllister, which is preparing for a re-election process. The case lays out the individual --sometimes contradicting-- perspectives of stakeholders in the task force, including their concerns about vaccination, masking, social distancing, and business continuity. Members in the task force included the county Commissioner of health, the CEO of the Chamber of Commerce, the county Press Secretary and other members of the community involved with decisions in schools and churches. Students supported their work in the case with extensive research, discussions with community leaders with the same roles of the stakeholders in the case and experiments with the COVID-19 simulation model using a web-based interface. The interface was developed using Forio Epicenter using the latest version of the model as of January 2022.[14] Students present their conclusions developing a poster and a policy memo.

These materials are also distributed as OER under a Creative Commons License CC-By, allowing for its adoption in policy-oriented classes and providing a tool that allows the public to interact with the model without knowledge of simulation software.

[12] Materials are available at https://newfadumfarm.org/covid-19-policy-simulator-and-learning-environment/
[13] See https://newfadumfarm.org/even-the-cdc-has-flip-flopped/
[14] Model interface is available at https://forio.com/app/naspaa/dcd-simulator/index.html#introduction.html

### Creating a White-box simulator for teaching of system dynamics and policy analysis

Inspired by the previous learning materials, another team member used Stella capabilities to combine these two learning environments into a single OER that contains both a step-by-step tutorial on how to make a reasonably sophisticated model based on epidemiology, and a web-based interface where users can run and compare different what-if scenarios. Users can progressively study and build the model by following the modules. In addition, they can benefit from the interface built on the model structure to combine the analysis of different parts of the simulator such as vaccination, quarantine, new variants, etc.

Each module comes with a story page on the interface. The storytelling feature on the Stella software gives us the ability to highlight the corresponding parts in the model view. The impact of any structural changes in the model is graphed so that changes in the behavior of key variables can be traced. Based on the specifics of each module, various gadgets are added to each story in a way that users can run scenarios based on different policies and uncertainties. Because applied modules are built on each other, a system dynamics learner can get grasp of how models evolve when more insights reveal themselves over the course of a study. On the other hand, the Whitebox simulator contains the full model and its own interface. The interface contains multiple options for setting up what-if scenarios with which user can engage or disengage certain parts of the model. The interface creates a virtual lab where users can run experiments with varying assumptions. Comparable graphs for key variables are available after each simulation run.

This simulator can be used both for system dynamics educational purposes and for analytical epidemiology. The current version of the material is available at isee systems' online exchange service.[15]

## Reflections on Modeling and Storytelling

In this final section of the paper, we present two sets of reflections on our overall effort. First, we reflect on what we have learned (and failed to learn) about creating materials aimed at the public and then actually disseminating those materials. Second, our process of exploring and developing our model has taught us some important lessons about system dynamics models of the COVID-19 pandemic.

### On sharing insights/ Finding better ways of reaching a wider audience

A stated purpose of our effort was to create materials that could be used to reach and instruct a wide audience, including the general public. We have learned that creating such materials and deploying them to a mass audience are two quite different things. We would give ourselves at least passing grades in producing good-quality materials, but we did not succeed in giving them the widespread distribution. Our records and informal observations suggest that our stories and models materials have been seen by only by a few hundred people or, in some cases, a very few thousand.

[15] See https://exchange.iseesystems.com/public/babak-bahaddin/diaries-during-lockdown/index.html

Below, we reflect on the challenge of sharing systemic insights to a wider audience (Meadows and Meloy, 1991; Meadows, 2002; Forrester, 2007). Finding better ways of reaching a wider audience for system dynamics models is a key goal for the development of the field but is commonly a less developed skill among modelers (Forrester, 2007). By sharing our experience and reflections on this project we hope to motivate other members of our community to engage with the public in sharing model-based stories, and to advance this vision that combines storytelling, teaching system dynamics principles and public policy analysis. System dynamics modelers have used several distinct modes to convey dynamic insights to a broad audience. These include (1) creating semantically rich stories grounded in ordinary experiences in the mode of Donella Meadows (1989), (2) writing a book that achieves mass attention, (3) developing materials for "hands-on" manipulation of a model, (4) using social media including webinars, and (5) organizing complex, multifaceted programs with a clear policy focus (and funding), like the Climate Interactive suite of online tools. While writing a book and creating a complex program were far beyond the scope of our project, we did work in the other three modes.

- **Create semantically rich stories grounded in ordinary experiences**. in contrast to Meadows' work, we worked in a single domain supported by one formal running simulation. We lacked a connection to a media outlet like her syndicated column, *The Global Citizen*. She also enjoyed an international reputation derived from the *Limits to Growth* work. Be it modelers' prior reputation, more engaging stories, or connection to effective distribution media, achieving widespread awareness of dynamically complex phenomena demands more than semantically rich stories alone.

- **Develop materials that allow for "hands-on" manipulation of a model**. All the learning modules that our team developed allowed students and learners to experience "hands-on" manipulation of running simulations. Our outreach with these materials has so far been confined to system dynamics and public administration communities. Nonetheless, our experience with these teaching materials suggests that working with them may lead to more in-depth engagement than simply reading semantically rich stories would. Our initial attempts to explicitly link simulation experiments in the learning modules to individual stories are a step in that direction.

- **Use social media including webinars**. As discussed above, we presented all our materials, including technical documentation in readily accessible format online. We also presented our project in an online webinar and created a few editions of a newsletter for people who expressed interest our online offerings.

On the emergent nature of developing insights along this project's journey

As our project progressed, we also took time to reflect more broadly on what we were learning about system dynamics models of the COVID-19 pandemic in the process of creating, updating, expanding, and refining this exploratory model.

Everything about this project was and still is emergent. The pandemic emerged over time, driving new questions into view of the public and government officials. In the beginning, the primary question being asked of modelers was when infections would peak and at what level, and how many deaths (and other stresses to the public health system) would probably occur. Later, attention turned to examining

the likelihood of additional surges. If or when they occur, how should the public respond to these new surges and in some (very insightful) cases, how might public response shape the surge itself. Still later came questions of vaccination policy and the emergence of new viral variants, posing additional questions for modelers and public health officials. Finally, analysis of an endemic phase of the pandemic emerged as a major focus.

Our model evolved in response to these new questions. We were continually formulating new dynamic hypotheses, modifying model structure, and conducting new sensitivity and policy tests. The lessons featured in the stories emerged in parallel with these activities. A first major lesson, for the team as well as for the stories, was that there will be multiple surges. Many of the early story lessons focused on protocols and other shifts in personal behavior; our simulations had shown that stabilizing the behavioral reactions feedback pathway was key to controlling surges. Later lessons centered on the "us" versus "they" nature of the pandemic driven by new structures we had added to the model incorporating disaggregation between vaccinated and non-vaccinated individuals. The "us versus them" lessons blended over to ethical ruminations culminating in one story that cites prophetic wisdom from the Hebrew scriptures.

New stories were built from our emerging technical understanding of the model's dynamics. We have already discussed how a technical awareness that the COVID pandemic was a limit cycle oscillator drove many lessons. While this dynamic insight was already built into our original CORONA1 model, it took weeks of model exploration to focus on it clearly and articulate lessons. Perhaps our most important dynamic insight was a recognition that the basic SEIR model is not an adequate starting place for understanding COVID-19 dynamics—not even for simplified teaching models. Below we discuss how that dynamic insight emerged over time in our project.

A major insight from our exploratory analysis of the CORONA1 model (and its descendants) is that the standard SEIR model, which ignores human behavioral responses to the spread of disease, is inadequate to explain the range of dynamics seen in the pandemic. Behavioral feedback was, however, present even in the first version of Ali's model, which projected repeating surges of infections. The magnitude of the surges varied with sensitivity and rapidity of the population's behavioral response to the perceived intensity of the epidemic.

Repeatedly throughout the project, two parallel feedback paths—one connecting Perceived deaths to Infectivity and one connecting Perceived Deaths to Contacts--emerged as critical structures necessary to understand and tell stories about the COVID-19 pandemic (since infectivity and contacts are both multiplicative determinants of overall infections, some might say that these effects are only one additional feedback loop). Evidence for the critical importance of this pair of loops accumulated throughout our project:

- Multiple alternative dynamic hypotheses explored in the original model and developed more fully during the **storytelling** such as surge dynamics (lockdowns, fatigue, voluntary isolation) all operated through the two missing feedback loops.
- The systematic development of the model in a step-by-step sequence of **learning modules** illustrated once again and conclusively that the behavioral feedback loops were necessary

components of the structure necessary to generate the base reference model of repeating surges.
- These same behavioral loops re-emerged as key in our **revisions to the model** when we included vaccines and new variants into the model's structure.

Hence, our exploratory modeling process led our modeling team to the conviction that future epidemiologic models of infectious diseases in human populations are not likely to be properly specified by the standard SEIR model. Additional feedback loops describing population response to the perceived epidemic must also appear in the model.

This recursive process of emergent and exploratory model building allowed us to see these insights clearly as the work progressed. Some connections between model structure and epidemic behavior were present even in early versions of our model, but it was only as we continued to expand and revisit the model that we came to appreciate their importance.

## On future research and development

Finally, our project points toward research challenges for the field of system dynamics:

**On Storytelling as a system dynamics skill.** Dana Meadows knew that storytelling would be an important part of our field. Perhaps her consummate skill deters others from trying to follow in her footsteps. We remain convinced that the craft of telling stories based on system dynamics models can be taught and learned by most of us. We believe that good storytelling will be a team effort and that scripted behaviors will make it possible to learn and practice this craft. We challenge the field to experimenting with ways of telling dynamic stories and then compress that experience into scripts that can teach others how to do it well. We cite as an example the concept of group model building which in the late 1980s and early 1990s was broadly challenged as impractical except for truly exceptional or gifted modelers. In the ensuing decades, development of practical guidelines has transformed group model building into a recognized and accepted practice. With similar attention to documenting and teaching good principles of, storytelling can become another normal craft in our field.

**On Using Social Media.** Stories beg to be distributed via social media. Our project tried to use several social medial tools, but we do not believe we successfully delivered our dynamic lessons to a mass audience. Workers in our field who aspire to wide-spread dissemination of dynamic insights would be well advised to include social media experts on their teams and to allocate appropriate resources to media efforts.

**On Evaluating Attitude and Behavioral Shifts.** Our modeling and storytelling efforts were aimed at leading others into changed attitudes and behaviors, but no component of our project measured how well we accomplished that. We have some anecdotes but lack systematic evidence, whether qualitative or quantitative. Techniques for evaluating the impact of "programs' like ours have been developed for other fields. Our challenge is to adapt and incorporate them into our own practice.

On the usefulness of our process as an example for other modeling problems.

Our general process and products can be adopted for other modeling projects. We do not, however, propose the COVID-19 modeling process presented here as a universal paradigm for building and using dynamic models.

Our original external product, i.e., the stories, is directed towards changing human behavior on an individual basis. The stories are designed to guide readers to figure out a "right" way to act, for both individual and social purposes, in certain challenging situations. Whether such a translation of macro-level models to micro-level behavior is appropriate or necessary, depends on the modeling assignment.

The extended, recursive nature of our work was required by the evolving pandemic, but it also gave us the opportunity to refine and expand the model over a relatively long stretch of time. Our work was done in real-time, as the pandemic was unfolding. Our understanding of the environment we were modeling had to constantly respond to changes in the environment itself. The need we experienced to constantly revisit our understanding of the system that modeled, and to respond both to new data and to new understanding of the meaning of the data, may simply not be a factor in other modeling situations.

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