Hierarchical Behavioral Decomposition of Complex Problems

Karim J. Chichakly
isee systems, inc. and Worcester Polytechnic Institute
31 Old Etna Road, Suite 7N
Lebanon, NH 03766 USA
(603) 448-4990
karim@iseesystems.com

Abstract

Building, testing, and understanding large models can be a challenge. Modules break a model into several submodels that can be developed and tested independently, facilitating hierarchical decomposition, a process of dividing a large problem into smaller parts starting from the highest conceptual level and working down to the concrete level. At each level, a problem can be divided either i) structurally into logical structural groups or ii) behaviorally into groups with identifiable behavior. Behavioral decomposition extends the standard modeling process to several hierarchical levels, each of which has reference modes, dynamic hypotheses, and models. Benefits of this approach extend to all models, not just large ones, and include: (i) the model and its behavior are simpler to understand as the model is presented starting from the high-level view followed by details from the lower levels, (ii) the model can be developed and tested in parallel using separate model files for each piece, (iii) the model can be also be developed from the bottom up making it possible to start with a smaller scope (narrower model boundary) and extend the model as needed, and (iv) standard behavioral components can be built and reused across many modeling projects.

Keywords: modeling process, model behavior, model decomposition, model hierarchy, modules

Introduction

The standard System Dynamics modeling process is iterative, following these basic steps (Sterman, 2000):

1. Draw a reference mode
2. Develop the dynamic hypothesis
3. Build the stock and flow model
4. Verify the model behavior
5. Analyze the model
6. Perform policy experiments

For large projects, this can be daunting. Traditionally, large models are divided into sectors that represent functional areas of the model. As an example, consider a model of a company. It may have sectors that represent the major C-level groups, such as Marketing, Sales, Engineering, Manufacturing, Finance, etc. With the advent of modules, it has become possible to decompose the model recursively so that, rather than a flat set of sectors, we have a hierarchical structure where functional units can be broken down into their own functional subunits. For example, Engineering can be broken down into Research, Development, and Maintenance. These separate pieces can be developed, modified, and tested independently and then brought together into the larger model, making it much easier to build large and rich models. With care, sometimes modules developed in one project can be reused in another.

This new approach works quite well, but could there be another way to decompose models that is more consistent with the modeling process? Could there be a way that mirrors the modeling process at each stage of decomposition? If so, would such a method make it easier to develop and/or understand models?

Hierarchical Behavioral Decomposition

We propose that the modeling process be extended such that there are reference modes and dynamic hypotheses developed at multiple levels of aggregation. Figure 1 shows three layers of a sample model. The top level has an aggregate dynamic hypothesis with three highly aggregated key variables (usually stock concepts). For each of these three variables at the top level, there is a less aggregated dynamic hypothesis at level 2. Each variable at this level is then decomposed into a submodel at level 3. Note that each dynamic hypothesis, at every level, has a corresponding reference mode.

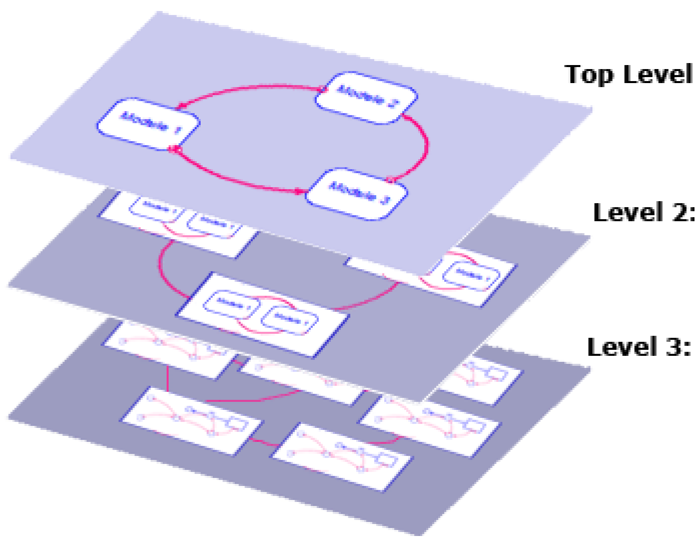

Figure 1. The aggregated dynamic hypothesis at the top level is decomposed into less aggregated dynamic hypotheses at level 2, which are then decomposed into submodels at level 3.

The proposed extended iterative modeling process is as follows:

1. Draw a high-level aggregated reference model
2. Develop high-level aggregated dynamic hypothesis
3. For each module in this dynamic hypothesis:
    a. Draw reference mode for that subsystem
    b. Develop the dynamic hypothesis for that subsystem
    c. If need a dynamic hypothesis for the next level, return to step 3
    d. Otherwise, for each module in this dynamic hypothesis:
        i. Build the stock-flow submodel

ii. Verify the submodel behavior
e. Combine the submodels at this level
f. Verify this module reproduces its the reference mode
g. Analyze this module
4. Combine modules to match high-level aggregated dynamic hypothesis
5. Verify the model reproduces the high-level aggregated reference mode
6. Analyze the model
7. Perform policy experiments

Note the similarities to the standard modeling process. The proposed process adds one "Combine" step and recursively includes the original process at step 3, but is otherwise the same.

This process can also be applied in the upward direction. In the case where you have an existing model for which you wish to extend the model boundary, you can pull that model up into a new higher-level dynamic hypothesis and then develop the additional new modules.

Application to the US health care system

In the United States, health care costs have been rising faster than the economy since the 1980s. The reference mode for this problem is given in Figure 2. Rather than compare directly to economy, the reference mode uses the population, which uses the medical services, to show that utilization and medical technology availability are both growing at faster rates that the population. If costs for services and technology are not decreasing as quickly, the overall cost of health care will grow relative to the population.

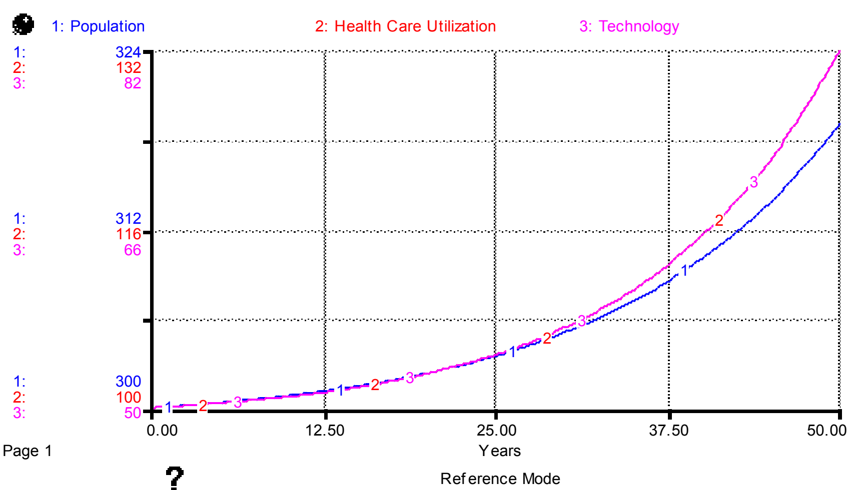

Figure 2. Top level reference mode for the US health care system, showing that both health care utilization and available medical technology is outstripping the population growth.

Figure 3 shows the dynamic hypothesis at the top level. There are two reinforcing feedback loops at play that explain these dynamics. The first feedback loop, labeled R1, shows that as the population increases, so does utilization. As utilization increases, there is more money available to invest in new medical technologies that save and extend lives, leading to population increasing again. The second feedback loop, labeled R2, shows that as the utilization increases, more money is available to develop new medical technologies. These new technologies, of themselves, create a demand for higher utilization because they solve existing health issues in new ways and/or more patients become aware of their availability through advertising and ask their doctors about them.

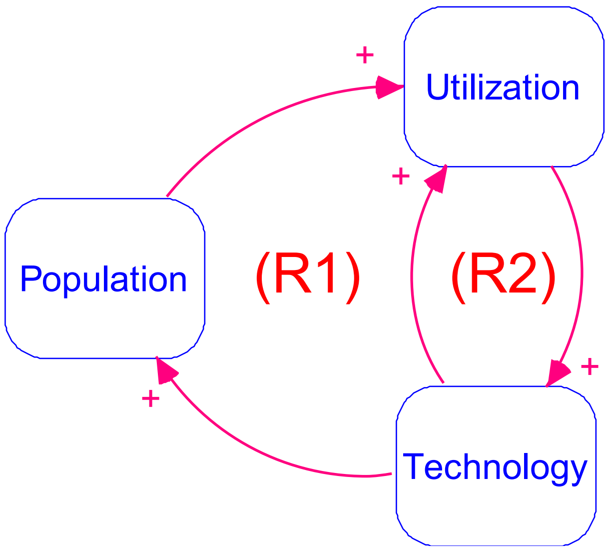

Figure 3. Top-level dynamic hypothesis for the US health care system.

Stepping down a level to flesh out utilization, we have the reference mode shown in Figure 4. The price is dropped at the beginning, leading to an increase in physician visits and per physician utilization. The result is a readjustment back up in the price, leading to a leveling off at a higher utilization.

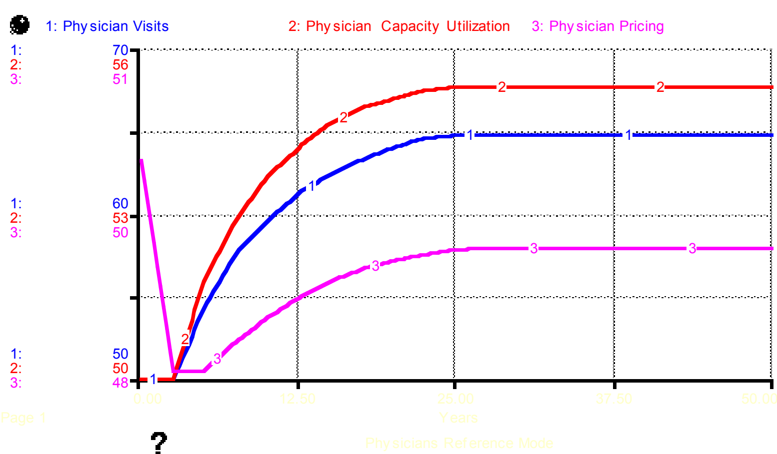

Figure 4. Reference mode for the Utilization module showing the effect of a price drop on utilization.

Figure 5 shows the dynamic hypothesis for utilization. One balancing feedback loop relates physician pricing to physician visits and capacity utilization. When the price of a visit drops, more people visit the physician, either on their own or at their physician's recommendation.

Given a fixed capacity, more visits leads to higher utilization of each physician, which creates pressure to raise the price again.

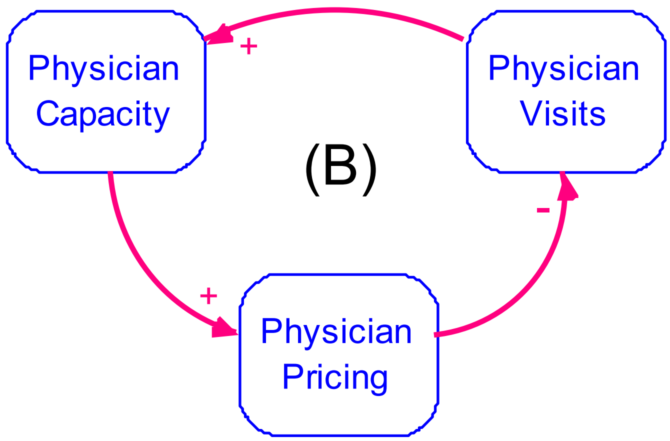

Figure 5. Second-level dynamic hypothesis for the Utilization module.

Each of these modules at the second level of Utilization are then realized as a stock and flow model. The specific details of these submodels is beyond the scope of this paper.

Decomposing Urban Dynamics

Hierarchical behavioral decomposition can also be used as a teaching tool, or as a forensics tool[1] to better understand an existing model. In this case, there are no reference modes at different levels and the stock and flow model already exists. It then becomes important to consider the model structure and determine how to decompose it hierarchically while considering how to show how that structure is leading to the given behavior at many different levels.

Urban Dynamics (Forrester, 1969) is a classic model that students find difficult to digest. The model developed as sectors appears in Figure 6. It is clear at a glance that there is a lot to absorb in this model. It is difficult from this diagram to determine the important feedback relationships in the model.

[1] This description was coined by David Andersen.

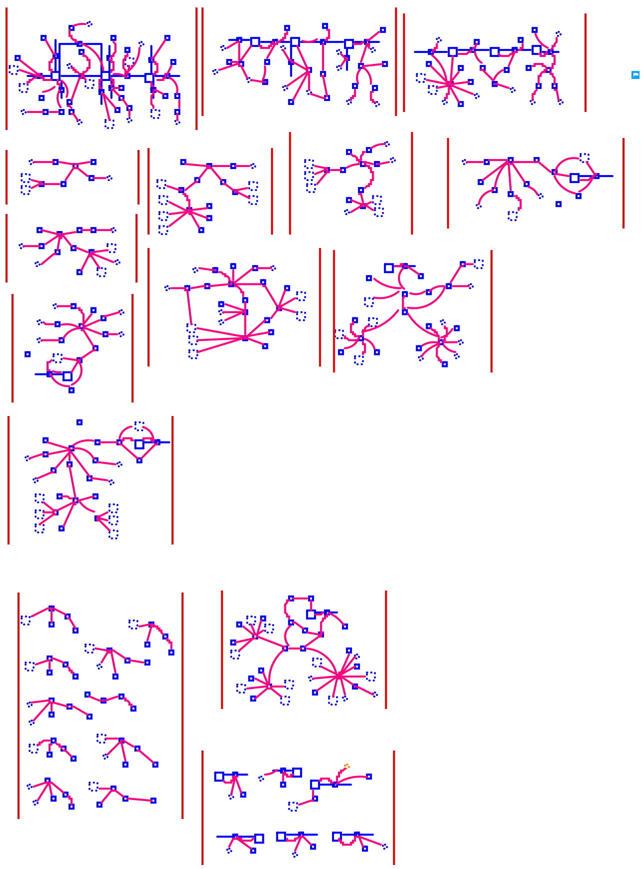

Figure 6. Urban Dynamics as a flat sector-based model.

It is tempting to take this sector representation and create a single-level model that structurally decomposes the model along the same lines as the sectors. The result of this is shown in Figure 7. As can be seen, this naïve approach does not shed any light on the model.

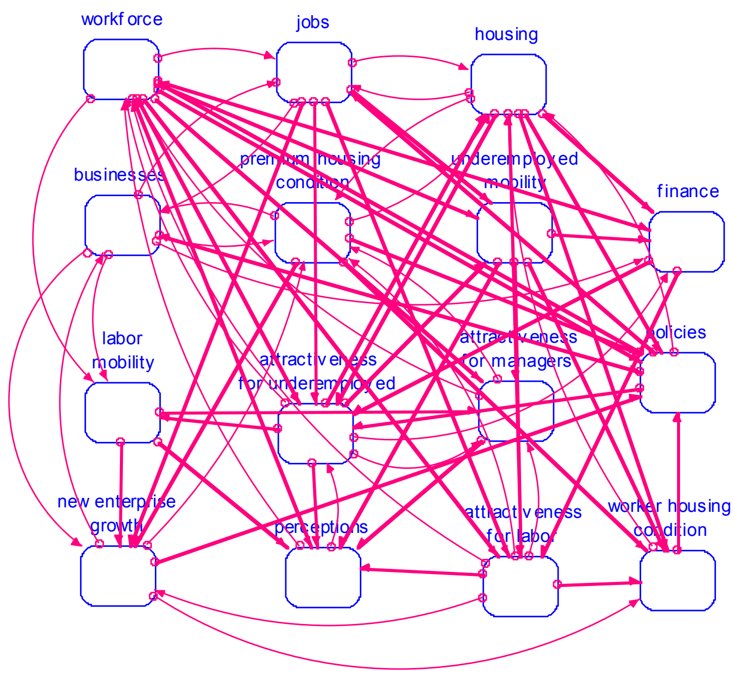

Figure 7. Urban Dynamics structurally decomposed along the same lines as the original sectors.

If we look at the key behaviors in the system, and then tie them to feedback relationships at the aggregate level, we can develop a suitable aggregated dynamic hypothesis. For Urban Dynamics, the top-level dynamic hypothesis is shown in Figure 8.

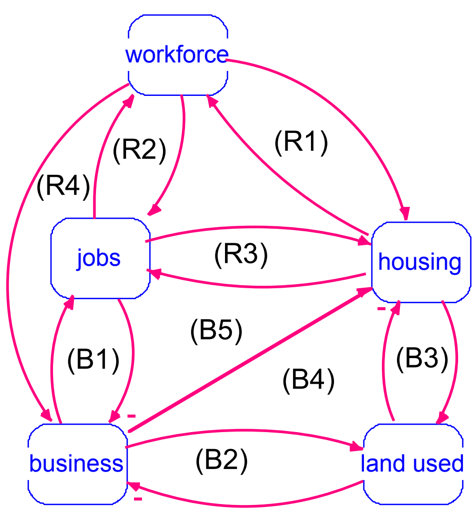

Figure 8. Top-level dynamic hypothesis for Urban Dynamics.

Feedback relationships can also be revealed at lower levels, as shown in the Workforce module in Figure 9. At this level, many balancing loops are apparent, as well as one reinforcing loop (population -> labor mobility -> manager attractiveness -> population).

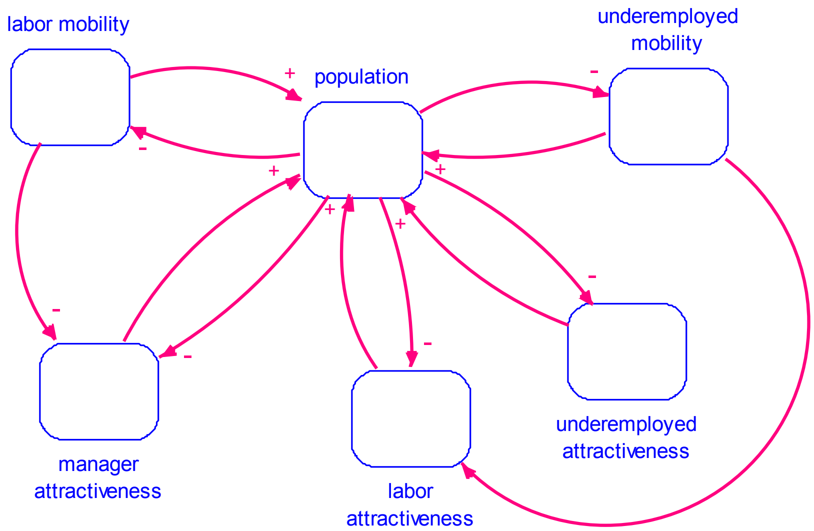

Figure 9. Dynamic hypothesis for the Workforce module.

Conclusion

Hierarchical decomposition is an important tool for modelers. It allows the highest level of the model to be the aggregate dynamic hypothesis of the model. With care, it can also allow lower levels to show less aggregated dynamic hypotheses with associated reference modes. This can increase the confidence in the model as it allows separate verification of the behavior of each substructure of the model.

The process steps presented here are a natural extension to the standard modeling process. The method helps the modeler focus on the important details at each level.

For existing models, hierarchical behavioral decomposition can be used to reorganize them in a way that highlights the most important feedback structures in the model. This increases understanding when people first encounter the model and also helps to explain why the model behaves the way it does.

This approach has only been used on a few models. One limitation has already been identified: The behavior at the higher levels of the model may not exactly match their reference modes due to problem with disaggregated variables in the model not exactly corresponding to the aggregated variables shown at the higher levels. In addition, structural decomposition is much easier to do, especially below the top level of the model. Additional research needs to be conducted to see if it is more generally applicable.

Acknowledgements

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The Health Care model is based on Jim Thompson's work and was developed with his help.

References

Forrester JW. 1969. *Urban Dynamics*. MIT Press, Cambridge.

Sterman JD. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World.* Irwin/McGraw-Hill, Boston.