

Verification and Validation of Agent-based and Equation-based Simulations: A Comparison^{*}

Ryan C. Kennedy, Xiaorong Xiang, Thomas F. Cosimano, Leilani A. Arthurs, Patricia A. Maurice, Gregory R. Madey
University of Notre Dame

Stephen E. Cabaniss
University of New Mexico

Abstract— Verification and validation of simulations has become increasingly important as our computing power has grown. Simulations are effective for modeling such complex and important issues as the spread of a global pandemic, the dynamics of crowds following a terrorist attack, or a natural disaster such as a hurricane or earthquake. However, such simulations are not valuable to decision makers unless they have been verified and validated. Traditional verification and validation approaches used for discrete-event system simulations are often not fit for complex newer agent-based models. Here, we perform verification and validation techniques on an agent-based scientific model and an equation-based economic model. We contrast the techniques that work best with each model and offer a general strategy for performing verification and validation.

Keywords—verification, validation, agent-based modeling, equation-based modeling, scientific simulations

1 INTRODUCTION

Using simulations to model and study phenomena has the potential to be informative to decision makers; however, the data produced by simulations is most valuable when it can both be verified and validated. In simple terms, this means the data produced is credible and indiscernible from real-world data. This proves very difficult to do, as most real-world systems contain far more constraints and details than computers allow us to reasonably model. Verification and validation is particularly difficult for agent-based simulations and those of social and economic phenomena. Because of these complications, most of our simulations are abstractions of real-world phenomena. Their purposes range from helping us to better understand natural phenomena to allowing us to predict the behavior of a system. With the varying purposes of simulations, verification and validation techniques also vary. The problem is that there is no universal verification and validation process that can be applied to all models. The purpose of our work is to explore and apply verification and validation techniques to two very different case studies. The first case study focuses on a scientific problem – the study of natural organic matter, or NOM. The simulation model has an agent-based backbone and was written first in Pascal and then transformed into Java utilizing Repast. The second case study involves an

economic problem – solving Ramsey problems in a stochastic monetary economy. This simulation model has a more numerical basis and was written first in Matlab and then in C++. We shall compare these two unrelated simulations that were each written in different programming languages and then compare the verification and validation techniques used for each. Additionally, we shall explore some general guidelines to use as an approach to increasing the confidence both of a simulation model and in the results of the simulation.

The organization of this paper is as follows. Section 2 outlines what is meant by verification and validation and introduces some general methods. Section 3 describes various aspects of the first case study, including background, validation, and implementation. In section 4, the second case study and the verification and validation methods used on it are discussed. A conclusion and some general guidelines are described in section 5. Finally, future work and references conclude the paper.

2 VERIFICATION AND VALIDATION PROCESS

Model verification is “solving the model right.” This means that that the model, in all its forms, is a sufficiently accurate representation of the real-world phenomenon for the purposes the model is intended [2,3,4]. Model validation is “solving the right model,” meaning that the correct abstract model was chosen and that the model accurately represents the real-world phenomenon [2,3,4]. It is important to note that verification and validation are key parts of the model development process. Additionally, they must be performed in tandem and throughout model development for best results. Effective verification and validation of a model will increase the confidence of the model, making it more valuable. An adapted version of Sargent’s [2] and Huang’s [5] verification and validation process diagram is shown in Figure 1. It has been modified for agent-based scientific and economic simulations.

Although there have been many verification and validation studies performed for general engineering purposes [3,6,7,8,9], verification and validation studies specifically for agent-based and social science simulations

^{*} A preliminary version of this paper was presented at the Agent 2005 conference in October 2005 and published in the conference proceedings [1].

are lacking. Some of this can be attributed to agent-based modeling not being as mature as more traditional engineering modeling. The point is that we can adapt what has already been done as well as create new tools to fit the needs of agent-based modeling.

Balci [4] outlined 15 general simulation principles, developed primarily for engineering or management science applications. His principles help engineers and researchers to better understand the verification and validation that they are performing. This understanding is directly related to model success. A few of his principles [4] that are relevant to scientific and economic modeling are:

- 1) *The outcome of the simulation model verification, validation, and testing should not be considered as a binary variable where the model outcome is absolutely correct or incorrect.* It is important to realize that models, being abstractions and not absolute representations of a phenomena, can never totally and exactly match a system.
- 2) *Complete simulation model testing is not possible.* As we cannot test all possible inputs and parameters for a system, we must choose the most appropriate ones.
- 3) *Simulation model verification, validation, and testing must be planned and documented.* Successful planning and documentation is critical and involves the work of many people throughout the lifetime of the system.
- 4) *Successfully testing each submodel (module) does not imply overall model credibility.* Simply because the modules work well independently does not mean that they will work cohesively in a system.

When performing verification and validation on a model, it is good to begin by identifying the key principles and techniques to be used for that model. Moreover, planning the verification and validation process, as outlined previously, makes the process more complete and effective. Utilizing Balci's [4] principles and techniques is a great starting point; from there, model confidence can be improved with further subjective and quantitative methods. Next, a general verification and validation process is outlined; it can be adapted to fit many agent-based scientific, social, and economic models. A hierarchy of such methods is shown schematically in Figure 2.

2.1 Subjective Methods

Subjective methods largely rely on the judgment of domain experts. They are often used for initial quick-and-dirty validation, but can also be more formalized. Whatever the purpose, subjective methods typically require less effort than quantitative methods, can detect flaws early in the simulation process, and are often the only available applicable verification and validation methods for exploratory simulation studies. We next describe some of the subjective techniques proposed by Balci [4] that may be

applicable to economic and agent-based scientific simulations. His techniques are widely used in validating the models of manufacturing, engineering, and business processes. The following techniques have been adapted from Xiang et al. and Kennedy et al. [10,1].

- 1) *Face validation.* This preliminary approach to validation involves asking domain experts whether the model behaves reasonably and is sufficiently accurate. This is often achieved by evaluating the output or observing a visualization, if applicable.
- 2) *Turing test.* This technique is performed by giving domain experts model outputs and real-world outputs and asking them to discriminate them.
- 3) *Internal validity.* This involves comparing the results of several replications of a simulation with the only difference being the random seed. Inconsistencies in the results question the validity of some aspect of the model.
- 4) *Tracing.* Here, the behavior of entities in the model is followed to determine if the logic of the model is correct.
- 5) *Black-box testing.* This technique involves how accurately the model transforms the input to output in a system.

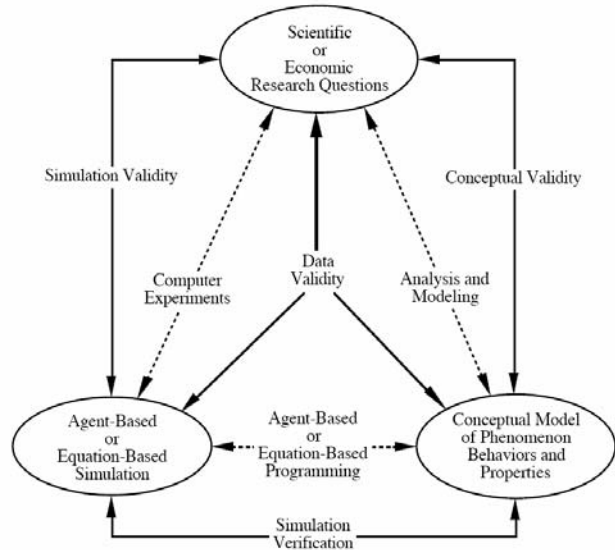


FIGURE 1 A Verification and Validation Process for Scientific and Economic Simulations (adapted from Sargent [2] and Huang [5])

2.2 Quantitative Methods

Incorporating quantitative, or statistical, methods into the validation process can significantly increase the credibility of the model. Model validation is conducted with statistical techniques to compare the model output data with the corresponding system or with the output data of other models run with the same input data.

The first step to quantitative analysis is to determine a set of appropriate output measures that can answer user questions [10]. After a set of output measures has been collected, various statistical techniques can be applied to

complete the validation process. Time series, means, variances, and aggregations of each output measure can be presented as a set of graphs for model development, face validation, and Turing tests. Confidence intervals and hypothesis tests can be used in the comparison of parameters, distributions, and time series of output data for each set of experimental conditions. These statistical tests can help model developers determine if the model's behavior is acceptably accurate.

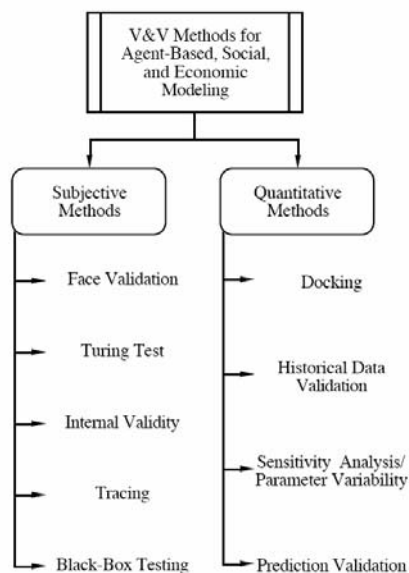


FIGURE 2 Verification and Validation Methods

The cost of the validation process increases exponentially with the confidence range of a model. There is no single validation approach applicable for all computational models. Choosing the appropriate statistical test techniques and measures of a system is important when conducting a validation study. It is important to note that there is no "correct set" of statistical tests to use for every simulation – the best results are achieved when tests are carefully chosen according to the model. Some of Balci's [4] more quantitative techniques that are relevant to our case studies are next described.

- 1) *Docking*. Docking, or model-to-model comparison or alignment, is used when another model exists (or can be created) that models the same phenomenon. Docking helps to determine whether two or more models can produce the same results [11]. The main idea is that model confidence is significantly improved when two or more models produce the same effective results, particularly if the models were developed independently and with different techniques. Additionally, the output from a model could be validated against real-world data to further increase confidence.
- 2) *Historical data validation*. When historical data exists or can be collected, this data can be used to build the model and the

remaining data then used to determine if the model behaves as the system does.

- 3) *Sensitivity analysis/parameter variability*. Here, one changes the input values and the internal parameters of a model to determine the effect upon the model and its output. Ideally, the relationship in the real-world system should be mimicked by the model. Sensitive parameters that cause significant changes in the model's behavior should be made sufficiently accurate before using this model.
- 4) *Predictive validation*. This technique is used to compare the model's prediction with actual system behavior. The system data may come from an operational system or specific experiments, such as from a laboratory or field experiments.

3 CASE STUDY I: AN AGENT-BASED SCIENTIFIC MODEL

Natural organic matter, or NOM, is a heterogeneous mixture of molecules. NOM plays a crucial role in the evolution of soils, the transport of pollutants, and the carbon cycle [10,12]. Its evolution is an important research area in a number of disciplines. NOM is complex – it is made of molecules with varying molecular weights, reactivities, and functional groups. This makes it difficult to model. Performing chemical experiments with NOM is difficult and time-consuming because of its complexity and because of our limited knowledge of its inner-workings. The ability to effectively predict NOM behavior as it evolves over space and time would be very valuable to scientists and an accomplishment in the modeling discipline.

3.1 Conceptual Model

The NOM conceptual model used here was based on the work of chemist Stephen Cabaniss working at the University of New Mexico [12]. He generated the model from extensive observation and experimentation in the laboratory, including a broad and detailed knowledge of the literature. The basic model outlined the use of the precursor molecules cellulose, lignin, and protein (among others) to be used in a controlled environment where parameters such as light intensity, temperature, and pH could be varied. A more detailed description of our model follows and has been adapted from Xiang et al. and Kennedy et al. [10,1]. Cabaniss also developed his own simulation based on this model, called AlphaStep [13], which will be discussed later.

Agent: The agents are molecules. Each molecule is a representation of its underlying elemental formula, meaning the number of C, H, O, N, S, and P atoms present. This gives rise to a molecular weight for each molecule. Molecules also contain a functional group count, such as the number of alcohol or ester groups present.

Behavior: In the environment, agents move around on a grid, interacting with other molecules and their local

environment. Molecules undergo chemical reactions based on specific probabilities. Reactions can result in structural changes in the molecule, such as the addition of functional groups. They can also generate new molecules from predecessor molecules and the predecessor molecules may leave the system. Twelve types of chemical reactions [12], including first- and second-order chemical reactions are modeled as described in Table I. The categories of reactions are as follows:

- 1) *First order reactions with a split.* The predecessor molecule A is split into two successor molecules B and C. Molecule B occupies the position of molecule A, while one of the empty cells closest to molecule B is filled with molecule C.
- 2) *First order reactions without a split.* The transformation changes the structure of the predecessor molecule A.
- 3) *First order reactions with the disappearance of a molecule.* The predecessor molecule A disappears from the system.
- 4) *Second order reactions.* Two molecules A and B are combined to form a new molecule C. Molecule C replaces molecule A and molecule B is removed from the system.

TABLE I Chemical Reactions

| Name | Type |
|-------------------------|--|
| Ester Condensation | Second order |
| Ester Hydrolysis | First order with a split |
| Amide Hydrolysis | First order with a split |
| Microbial Uptake | First order with the disappearance of a molecule |
| Dehydration | First order with a split |
| Strong C=C Oxidation | First order with a split (50% of the time) |
| Mild C=C Oxidation | First order without a split |
| Alcohol C-O-H Oxidation | First order without a split |
| Aldehyde C=O Oxidation | First order without a split |
| Decarboxylation | First order without a split |
| Hydration | First order without a split |
| Aldol Condensation | Second order |

Space: In the NOM model, the agents are associated with a location in 2D geometrical space and can move around their environment. Each cell on the grid can host multiple molecules up to a certain threshold.

Reaction Probabilities: The probability for each reaction type is expressed in terms of intrinsic and extrinsic factors. Intrinsic factors are derived from the molecular structure including the number of functional groups and many other structural factors. Extrinsic factors arise from the environment and include concentrations of inorganic chemical species, light intensity, availability of surfaces, presence of microorganisms, presence and concentration of extracellular enzymes, and the presence and reactivity of

other NOM molecules. The intrinsic and extrinsic factors are combined in probabilistic functions.

Molecular Properties: The reactivity of the resulting NOM over time can be predicted based on the distributions of molecular properties, which are calculated from the elemental composition and functional group data. They represent a measurable quantity that can be used as a predictor for environmental function and are useful for the calibration and verification of our conceptual model and simulation.

Simulation Process: The conceptual model is a stochastic synthesis model of NOM evolution, meaning the state of the system is represented by a set of values with a certain probability distribution, such that the evolution of the system is dependent on a series of probabilistic discrete events. At each time step, for each molecule, a uniform random number is generated. This number determines whether a reaction will occur, and if one does occur, its reaction type. After a reaction takes place, the attributes for the current molecule are updated and the reaction probabilities are recalculated. The molecule structure is changed to alter the outcome of the reaction and a new probability table entry is added for newly formed molecules, if there are any.

3.2 Implementations

The NOM conceptual model was initially implemented in Pascal, resulting in a program for Windows called AlphaStep [13]. Our implementation is coded using Java (Sun JDK 1.4.2) [14], J2EE, and the Repast toolkit [15]. Repast is an agent-based simulation toolkit written in Java. It contains a control panel to control and manipulate the model and has rich visualization capabilities. We chose Java for our model because 1) at the time the development began, Repast worked only with Java and 2) we also incorporate a web-based front end to the system where users can create and submit simulations, as well as view graphical results. Java/J2EE facilitated the online deployment of the NOM simulation with the web-based interface.

3.3 Validation

We followed the general technique previously outlined when validating the NOM model. We began with subjective analysis and then proceeded with quantitative analysis.

3.3.1 Subjective Analysis

The validation of the NOM model began with face validation of the conceptual model by domain experts. They evaluated the underlying mechanisms and properties and drew their conclusions. After achieving initial face validation, coding of the agent-based simulation took place. In this step, verification methods such as code walk-through, trace analysis, input-output testing, pattern testing, boundary testing, code debugging, and calculation verification were

used to verify the correctness of the simulation; Balci [4] further describes some of these techniques. Another useful technique used for simulation validation is visualization [16]. Visualization is often used in conjunction with face validation. A snapshot of an animated visualization of the flow of molecules through a soil column based on the preliminary model of Arthurs et al. [17] is shown in Figure 3. The corresponding animated graph of the molecular weight distribution shows how the molecular weight distribution shifts with time: initially favoring adsorption of lower weight molecules to mineral surfaces and gradually shifting to preferential adsorption of larger molecular weight molecules as the simulated time passes. These same behaviors were observed in the laboratory, increasing confidence in the simulation [17].

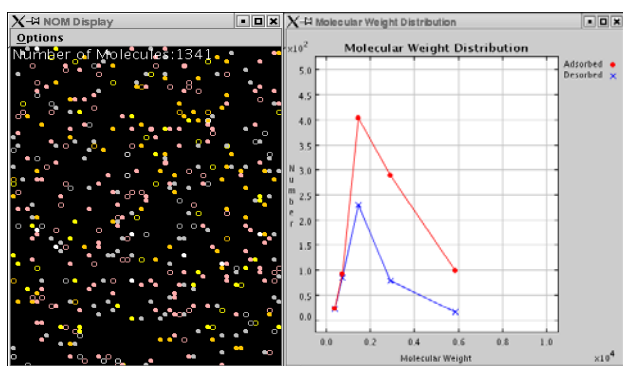


FIGURE 3 NOM Visualization

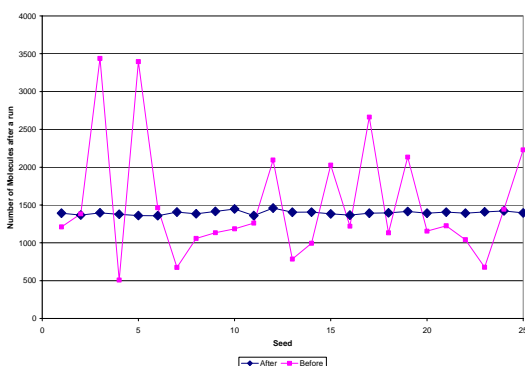


FIGURE 4 Results after and before random seed correction

A simulation model that uses random number generators must have statistical integrity in that independent simulations with the same input data should have similar results. This is also known as internal validity. If the simulation model produced large differences caused solely by the choice of the random seeds, the predictive utility of the simulation would be greatly reduced. To test this, we performed 450 simulations with our NOM simulator, each with a different initial random seed. We chose the total number of molecules in the system after the simulation had completed as our point for comparison. Initially, we found our data incorrect, leading us to discover a problem with our

random number generator code. This data is shown in Figure 4. After correcting this, we also observed that our simulations produced the expected normal distribution curve upon analysis. Figure 5 shows the histogram for this data. By verifying the independency of the random seeds in the NOM simulator, we were able to conclude that it is statistically robust in terms of repeatability. Further statistical analysis needs to be performed to verify how reliably our simulator conforms to a normal distribution.

3.3.2 Quantitative Analysis

Both our NOM model and the AlphaStep model rely on the same basic conceptual model. However, there are a few inherent differences. First, AlphaStep has no representation of space. Instead, its agents are described as parts of a “well-stirred soup,” each equally likely to react with any other molecule. Another key difference is the programming language used in each simulation. We summarize the main differences between implementations in Table II.

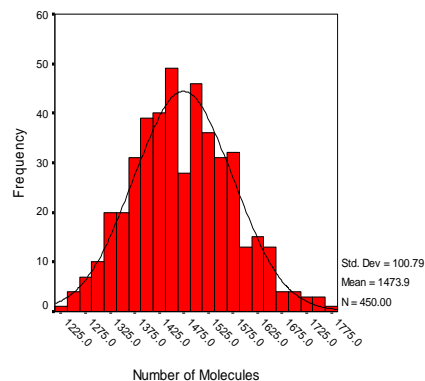


FIGURE 5 Histogram with distribution after 1000 simulated hours

TABLE II Implementation Differences

| Feature | AlphaStep | NOM |
|---------------------------------|--------------------------------------|--------------------------------------|
| Programming Language | Pascal | Java |
| Platform | Windows | Linux |
| Running Mode | Standalone | Web based or Standalone |
| Simulation Packages | None | Repast |
| Initial Population | Actual number of molecules | Percentage distribution of molecules |
| Animation | None | Yes |
| Spatial Representation | None | 2D Grid |
| Second Order Reaction | Randomly pick one from Molecule List | Choose nearest neighbor |
| First Order Reaction with Split | Add to Molecule List | Find empty cell nearby |

To dock these stochastic simulations, we performed 25 replications, each with different random seeds, for both implementations given effectively the same initial conditions. Among the many molecular variables, we chose M_n (number-average molecular weight), M_w (weight-average molecular weight), Carbon percentages, Carbon mass, and the number of molecules as metrics for comparison. We took ensemble averages from 25 replications and compared data points over time. These comparisons are shown in Figure 6. As one can see, visual agreement looks very good; however, statistical testing must be performed to assure that differences between the models are not significant.

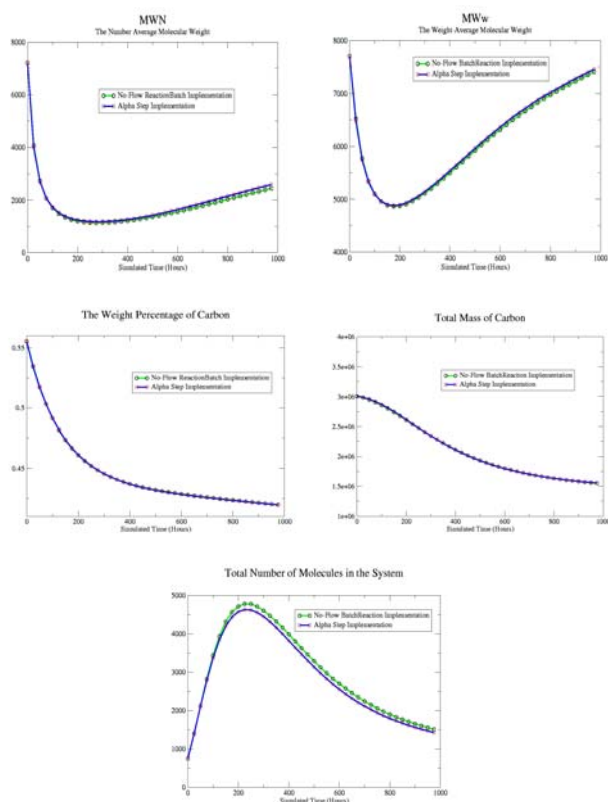


FIGURE 6 Comparisons between AlphaStep and NOM

4 CASE STUDY II: AN EQUATION-BASED ECONOMIC MODEL

Ramsey problems are concerned with setting specific economic variables, money growth and tax rate, to generate the best social welfare for a given economy [18]. In our model, nonlinear projection methods are used to solve these problems. The goal is to calculate the real or nominal interest rate for a given economy under the optimal money growth and tax rates. Our model creates a set of residual equations, utilizing bivariate Chebyshev polynomials.

The simulation was initially written for Matlab [19]. It effectively takes advantage of Matlab’s built-in functions

and capabilities, but execution is slow. The current model works off of four equations and on moderate-sized matrices. The next iteration of the model would include a fifth equation and much larger matrices, making execution in Matlab unpractical. Once the model was verified and validated in Matlab, we converted the code to C++ to make it execute faster, but also to provide an additional docking verification and validation opportunity.

4.1 Conceptual Model and Implementation Differences

Matlab is a *matrix laboratory*, meaning a rich interactive programming environment that supports many data types best suited for numerical analysis. Matlab, being a high-level language, is very user friendly and has many built-in functions and display options. Matlab is also useful for prototyping. It is, however, inherently slow – it is essentially a software package written in C and simulations written in Matlab are interpreted, resulting in slow execution. C++, on the other hand, is an object-oriented, lower-level language. Its standard template library incorporates many desirable functions and it is relatively simple to code. Because it has an efficient compiler and is a lower-level language, simulations written directly in C++ run much faster than equivalent simulations written in Matlab.

Converting the simulation from Matlab to C++ was much more difficult than expected. In Matlab, variables are not declared as they are in C++. Instead, most variables are assumed to be arrays. These arrays can contain real numbers, complex numbers, or even other arrays of real numbers, among other things. This creates a problem in C++, as variables in C++ must be declared with a data type. For example, the variable *array1* could represent an array of real numbers at one point in a Matlab program and an array of complex numbers at another point. The idea is that the variable *array1* is in essence overloaded to handle many data types. In C++, functions operate and are called differently depending on the type of data passed to them. Overcoming this step was pivotal to porting the code.

Another difficulty in going from Matlab to C++ was emulating Matlab’s built-in functions. The majority of the Matlab functions utilized in this simulation are part of LAPACK, the linear algebra package, and include functions such as taking the normal of a matrix or vector, inverting a matrix, conditioning a matrix, and the like. Not only are these not inherently included in C++, but they are again overloaded in the sense that you can pass Matlab’s *max* function a vector, a matrix, or a simple set of numbers and it will give the proper result. While it is possible to call Matlab from within C++ to make use of such functions, the desire of this project was to have everything run in C++ for maximum speed. Determining the inner-workings of Matlab’s many functions and implementing them in C++ proved difficult

and time-consuming. In the end, the simulations did the same thing, but with inherently different implementations, requiring a rigorous verification and validation effort.

4.2 Performance

Running time for runs of 5, 50, and 500 iterations of the simulation can be found in Table III and Figure 7. As evidenced, the speedup is significant, or approximately 30 times faster in C++.

TABLE III Running Time for Matlab and C++ Implementations

| | 5 Iterations | 50 Iterations | 500 Iterations |
|--------|--------------|---------------|----------------|
| Matlab | 58 seconds | 568 seconds | 8872 seconds |
| C++ | 2 seconds | 17 seconds | 176 seconds |

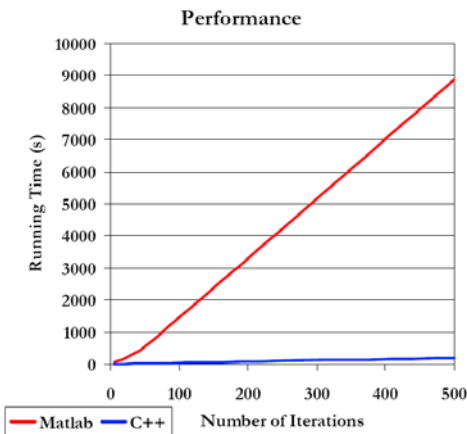


FIGURE 7 Performance Comparison of Matlab and C++ Implementations

4.3 Validation

Validating the economic model was a little different than with the scientific model described in the first case study. The validation process helped us identify some problems with the C++ implementation, so we focused on correcting those before proceeding to more formal verification and validation techniques. In this case, validation served the purpose of identifying what was wrong with our implementation. As a result, we did not get as much quantitative analysis finished as we had planned.

4.3.1 Subjective Analysis

Validation was performed throughout the code porting process. It was important to verify that the control flow was similar in both versions and that the data was handled in the same manner. To accomplish this, a sort of tracing was performed in which the behavior of certain entities in the models, such as the LaGrange multiplier variable, was followed in both versions of the model. This helped validate the C++ model against the Matlab model and also helped us identify where our code was going wrong. Table IV shows sample results from our code. The steady state data is taken from Cosimano [20]. Our results show that the programs produced very similar results for all the variables. Initially, we had some docking problems, but techniques such as tracing helped us correct discrepancies. When presented to a

domain expert, face validity was achieved for most of the values shown in Table IV. Because the core of the simulation is equation-based, output values should be consistent through both of our versions. This correlates to us performing more of a “face verification” technique in judging the correctness of our results.

TABLE IV Face Verification

| | Matlab | C++ | Steady State |
|---------------------|--------|--------|--------------|
| LaGrange Multiplier | 0.138 | 0.138 | 0.138 |
| Labor | 0.309 | 0.309 | 0.309 |
| Money Growth | -0.009 | -0.009 | -0.009 |
| Tax Rate | 0.188 | 0.188 | 0.188 |
| Cash Good | 0.486 | 0.486 | 0.485 |
| Credit Good | 0.621 | 0.621 | 0.620 |
| Real Interest Rate | 0.009 | 0.009 | 0.009 |

4.3.2 Quantitative Analysis

Simple checking, such as outputting key variables as the programs were running, helped validate that the calculations were being done correctly. In essence, the C++ version of the code was validated against the Matlab code in the docking process. Additionally, the labor, LaGrange multiplier, and other values were docked against the steady state data, further increasing confidence. The face validity checking helped identify some errors in our code, while docking helped us isolate and verify problems. More verification and validation techniques need to be performed for this case study.

4.4 Discussion

We have also demonstrated the feasibility and usefulness of docking as a verification and validation method in this case study. Since the primary motive for the conversion of the model from Matlab to C++ was performance, the opportunity to verify and validate the two models using docking essentially came free. If implementing the simulation a second time is difficult and time consuming (as it was in this second case study), the verification and validation by docking may not be cost-effective, unless another motive for the second implementation is present (performance in this case).

5 CONCLUSION

In this paper, we have shown how we performed verification and validation through docking on two very different models, one agent-based and one equation-based. We have shown that similar techniques can be applied to the models, regardless of the underlying model structure.

5.1 General Guidelines

When designing a simulation, it is important to have a concise abstract representation of the model in mind. This abstract representation will help lead to effective programming and implementation choices. Based on this, one can choose the correct environment or language for the model. As shown here, different environments and

languages have their own distinct advantages and disadvantages. It is upon these that our programming decisions must be based. It is important to note that the entire lifetime of the model must be considered when making these decisions. The choices must also be made with consideration to the verification and validation techniques that will be applied to the model. These verification and validation techniques must also be thought out in advance. We have listed some general ratings for the techniques used in this paper in Table V. Possible ratings are Fair, Good, Very Good, and Excellent. It is important to note that the ratings listed are specific to our case studies.

TABLE V General Ratings for our Case Studies

| | Agent-based | Equation-based |
|-------------------------------------|--------------------|-----------------------|
| Face Validation/Verification | Very Good | Very Good |
| Turing Test | Very Good | Good |
| Internal Validity | Very Good | n/a |
| Tracing | Fair | Excellent |
| Black-Box Testing | Good | Good |
| Model-to-Model Comparison | Very Good | Very Good |
| Historical Data Verification | Very Good | Very Good |
| Sensitivity Analysis | Good | Good |
| Prediction Validation | Good | Fair |

6 FUTURE WORK

In future studies, it is important that we use and develop more stringent and formalized verification and validation testing methods. Doing this on top of a strong statistical foundation would further increase confidence of the models. Gathering empirical data and generating statistical data would also serve as a better point of comparison when judging our models against real-world systems. Additionally, performing some goodness-of-fit tests, such as the Chi-Square test and the Kolmogorov-Smirnoff test, as well as performing the ANOVA test would help us better determine the validity of the models. "Invalidating" our models, meaning performing tests specifically designed to invalidate them, also has the potential to eliminate some of our "validation bias" [21]. Finally, a more in-depth verification and validation study should be performed on the second case study.

ACKNOWLEDGMENT

This work was partially funded by the National Science Foundation, Information Technology Research/(ITR/AP-DEB), under Grant No. 0112820, the Center for Environmental Science and Technology at Notre Dame, and the University of Notre Dame Office of Research.

REFERENCES

[1] Kennedy, R.C., Xiang, X., Madey, G.M., Cosimano, T.F., "Verification and Validation of Scientific and Economic Models," *Agent2005*, Chicago, IL, October 2005.

[2] Sargent, R.G., "Validation and Verification of Simulation Models," *Proceedings of the 1998 Winter Simulation Conference*, pp. 121-130, 1998.

[3] Balci, O., "Verification, Validation, and Accreditation," *Proceedings of the 1998 Winter Simulation Conference*, pp. 41-48, 1998.

[4] Balci, O., "Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice," *Book Chapter: Verification, Validation, and Testing*, John Wiley & Sons, New York, 1998.

[5] Huang, Y., Xiang, X., Madey, G., Cabaniss, S., "Agent-Based Scientific Simulation," *IEEE Computing in Science & Engineering*, Vol. 7, No. 1, pp. 22-29, January/February 2005.

[6] Ören, T.I., "Concepts and Criteria to Assess Acceptability of Simulation Studies: A Frame of Reference," *Simulation Modeling and Statistical Computing, Communications of the ACM*, April 1981.

[7] Kleijnen, Jack P.C., "Verification and validation of simulation models," *European Journal of Operational Research*, Vol. 82, pp. 145-162, 1995.

[8] Kleijnen, Jack P.C., "Statistical validation of simulation models," *European Journal of Operational Research*, Vol. 87, pp. 21-34.

[9] Balci, O., "A Methodology for Certification of Modeling and Simulation Applications," *ACM Transaction on Modeling and Computer Simulation*, Vol. 11, No. 4, pp. 352-377, October 2001.

[10] Xiang, X., Kennedy, R., Madey, G., "Verification and Validation of Agent-based Scientific Simulation Models," *Agent-Directed Simulation Conference*, San Diego, CA, April 2005.

[11] Axtell, R., Axelrod, R., Epstein, J.M., Cohen, M.D., "Aligning Simulation Models: A Case Study and Results," *Computational and Mathematical Organization Theory*, 1996.

[12] Cabaniss, S. E., Madey, G., Leff, L., Maurice, P., Wetzel, R., "A Stochastic Model for the Synthesis and Degradation of Natural Organic Matter. Part I. Data Structures and Reaction Kinetics", *Biogeochemistry*, Springer, Volume 76, Number 2, November 2005, pp. 319 – 347.

[13] AlphaStep. <http://www.nd.edu/~nom/Software/software.html>

[14] Java. <http://java.sun.com/>

[15] Repast. <http://repast.sourceforge.net/>

[16] Grimm, V., "Visual Debugging: A Way of Analyzing, Understanding, and Communicating Bottom-Up Simulation Models in Ecology," *Natural Resource Modeling*, Vol. 15, No. 1, pp 23-38, Spring 2002.

[17] Arthurs, L., Maurice, P., Xiang, X., Kennedy, R., Madey, G., "Agent-based stochastic simulation of natural organic matter adsorption and mobility in soils," *Eleventh International Symposium on Water-Rock Interaction*, Saratoga Springs, NY, June 2004.

[18] Cosimano, T.F., Gapen, M.T., "Solving Ramsey Problems with Nonlinear Projection Methods," *Studies in Nonlinear Dynamics & Econometrics*, Vol. 9, Spring 2005.

[19] Matlab. <http://www.mathworks.com/products/matlab/>

[20] Cosimano, T.F., Gapen, M.T., "Optimal Fiscal and Monetary Policy with Nominal and Indexed Debt," Working Paper, available at <http://www.nd.edu/%7Etcosiman/Optimapolicy.pdf>.

[21] Macal, C.M., North, M.J., "Validation of an Agent-based Model of Deregulated Electric Power Markets," *Proc. North American Computational Social and Organization Science (NAACSOS) 2005 Conference*, South Bend, IN, June 2005.

[22] Banks, J., Carson III, J.S., Nelson, B.L., Nicol, D.M., "Discrete-Event System Simulation," Prentice Hall International Series in Industrial and Systems Engineering, Fourth Edition, 2005.