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MODELING & SIMULATION IN SYSTEMS ENGINEERING: A SURVEY COURSE

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ABSTRACT

Systems engineering is a bit different from other engineering disciplines in that students from many disciplines are enrolled in the program. Therefore, the objective is not to teach a simulation subject in depth, but rather to introduce the students to different techniques so that they can work with and manage simulation staff on a project. However, they need some “hands on” experience so that they know how challenging simulations can be, avoiding the trap of underestimating the effort involved. This paper describes the approach used at Georgia Tech to teach a compressed 7 week simulation survey course called ASE 6003 Modeling & Simulation in Systems Engineering. We describe the techniques used, our approach and the results achieved over recent years of teaching simulation in this format. Finally we discuss lessons learned and offer suggestions for others interested in offering a similar course.

1 INTRODUCTION

Technology advances present complex system design challenges. Increased application of software-driven systems and a greater degree of system interconnections raise the complexity of new systems. The National Defense Industrial Association (NDIA) is among those who have studied this reality (NDIA 2016). What NDIA concluded is that system of systems and family of systems depend on interfaces and functionality to create emergent behaviors greater than the sum of the individual parts. Engineering approaches to manage this complexity led to Systems Engineering as a widely recognized discipline.

A chronicle of contemporary issues in systems engineering has been documented by numerous organizations (Shortell 2015; NDIA 2016; Standish Group 2015; Systems Engineering Research Center 2019). These studies describe why projects run into trouble, and document the need for systems engineering. Failure to understand the problem space, poorly documented and analyzed requirements, and lack of structured processes to develop successful systems continue to be rampant (NDIA 2016). A shortage of competent systems engineers is near the top of “must fix” lists and points to the need for formal education programs providing the knowledge, skills, and ability unique to this problem space.

In 2009 Georgia Tech responded to these issues by creating the Professional Masters in Applied Systems Engineering (PMASE) degree program. PMASE aims to produce high quality systems engineers adept in the practice and theory of realizing successful complex systems. Modeling & Simulation (M&S) has been part of the core curriculum since the beginning of PMASE (Georgia Tech Professional Education 2019). ASE 6003 is a survey of M&S, and how it’s used in systems engineering. The course introduces students to a range of topics, including M&S fundamentals, theoretical foundations, methods and methodologies, experimentation and execution, simulation in the systems engineering life cycle, and management. The course includes labs that cover different simulation methods (discrete event, agent based, system dynamic, continuous), as well as a group project that requires each team to develop and run a model. The goal is for students to understand how to use M&S to solve systems engineering problems.

This paper gives an overview of the PMASE program, describes the approach used to teach M&S in a compressed 7-week format, and describes our progress in developing the curriculum and lessons learned. The purpose is not to suggest that this course organization is better than other methods of teaching M&S. Rather, it contributes to the body of knowledge in Simulation Education, by sharing our approach and experiences and promoting novel ways to teach M&S in a compressed survey manner.

2 PMASE OVERVIEW

Graduate candidates are required to hold a science or engineering degree plus have a minimum of 5-10 years domain experience as a technical practitioner. PMASE uses a hybrid format combining curriculum delivered in resident, live, and on-line forums. Taking the philosophy that "Systems Engineering is a team sport" sets the stage for a heavy team-based focus.

2.1 Student Cohort Continuity

Cohorts start each August and the class remains together as a group for the entire program. For the past several years, PMASE has scaled itself to the current cohort size of about 30 students. Two overlapping 2-year cohorts have a freshman and a senior class present at any given time, with the cycle repeating each year: graduation occurs during early August and we welcome the next incoming cohort a few weeks later.

2.2 Curriculum and Mentors

The PMASE 2-year curriculum is presented in 10 separate 3 credit hour courses. Each of the first 9 courses is 7 weeks in duration, with 2 courses presented serially in a single semester. One course at a time permits mastery of a unique topic. ASE 6003 is presented as the 3rd of the 10 courses. It follows (predecessor relationship) the Fundamentals of Modern Systems Engineering and Leading Systems Engineering Teams courses. ASE 6003 is followed by System Design/Analysis and the advanced topics course Systems Modeling Language. In the second year, a final capstone course is required in lieu of a thesis. During capstone, student teams take on a complex problem over a 12 week period.

While looking at ways to scale (in 2013), the program adopted the use of mentors. This faculty role was generated to provide additional hands-on contact time between students and faculty, increase professional insights available from practicing systems engineers, and distribute the workload from the primary professor. Mentors serve in a coach role and augment the faculty by bringing practical experience. For example, in ASE 6003 the mentors bring 7 decades of engineering experience to the team, from both industrial and military organizations.

The challenges of teaching a 7 week course are obvious: what to and what not-to present in the limited time available. In ASE 6003, our focus on traditional applications of simulation serve to establish a foundation for the subsequent courses in the program. Each of the 7 weeks has assigned recorded lectures, required readings, and often a quiz to measure progress. Mentors conduct weekly office hours sessions remotely via the Blue Jeans (BlueJeans 2019) collaborative tool, which provides students with a stable and predictable opportunity to be coached on topics pertinent for that phase of class. Each team of 4-6 students interacts with the same mentor throughout the course. In our experience, the cohort greatly benefit from faculty contact - two live sessions, weekly office hours, and a blog (Piazza 2019) create a platform for faculty/student interactions that go beyond the basic schedule.

2.3 Predictable TEMPO

In practice, standardization of assignments and expectations is helpful. Lecture nomenclature, task formats, etc. permit the students to focus on content while instilling a habit for deliverable assignments. Students are commonly located in dispersed locations (e.g. New Mexico, Singapore, Nova Scotia, Japan, Hawaii, Australia, Chile, Brazil, Panama, France, Netherlands, New Jersey, California, Georgia, Iowa) and time zones. Additionally, recorded lectures delivered in compact form permit students to watch/review as many times as needed and in whatever their time-of-day availability. A weekly tempo helps the cohort manage their lives and heavy workload. The typical schedule for each week includes:

- Assignments are due early Monday morning.
- Student teams self-organize and extensively meet outside planned sessions as/required.
- Office hours occur Wednesday late afternoon/early evening.
- Assignments returned with specific and detailed feedback on Friday.

3 SIMULATION COURSE DESIGN

One of the fundamental design ideas behind ASE 6003, is that M&S is a broad discipline, and systems engineers need to understand the breadth of technologies, methodologies and uses of M&S to be effective in their jobs. However, most simulation courses at universities tend to be taught within a department, with a specific set of tools. For example, industrial engineering teaches discrete event simulation, computing teaches parallel and distributed simulation, mechanical engineering teaches model based design, electrical and computer engineering teaches continuous simulation, and aerospace engineering teaches surrogate modeling. For systems engineers, all of these methodologies are important to learn, and each has a different purpose in the systems engineering lifecycle.

Systems engineering is a bit different from other engineering disciplines in that students from many disciplines are enrolled in the program. Therefore, the objective is not to teach a simulation subject in depth, but rather to introduce the students to different techniques so that they can work with and manage simulation staff on a project. However, they need some “hands on” experience so that they know how challenging simulations can be, avoiding the trap of underestimating the effort involved.

There are many excellent M&S classes that provide a deep dive into specific simulation methodologies. Both (Doore et al. 2015) and (Kashefi et al. 2018) have good literature reviews on teaching M&S in different academic disciplines. The work by (Giabbanelli et al. 2012), which talks about the importance of designing computing courses for students with a wide range of disciplines, also has relevance to our work. While we have not looked at the possibility of using our curriculum for secondary education, our goals of teaching the broad use and application of simulation could apply to other student communities. Good examples of M&S courses for secondary education can be found in (Grgurina et al. 2018) and (Doore et al. 2015). Lastly, the multidisciplinary nature of systems engineering and the increasing reliance on data presents interesting challenges for simulation education. The work in (Giabbanelli and Mago 2016) discusses the challenges with developing an course that integrates computational modeling and data science. Our work has relation to this in that we also take the approach that teaching a range of modeling methodologies is critical for student understanding the interdisciplinary nature of complex problems. The result of our design effort resulted in the following course objectives:

- Educate students in different simulation technologies (e.g. discrete, agent based, dynamic, etc.) without getting bogged down in programming or getting lost in the mathematics.
- Teach in a very compressed time frame, just 7 weeks for the entire course.
- Introduce simulations across a variety of domains, so that students find the material interesting and are able to retain and use the techniques learned when they complete the program.
- Introduce the team concept, so that the students learn the dynamics of creating a complex simulation as part of an engineering team.

We believe that our unique approach works well for introducing students to the broad discipline of M&S that systems engineers need to understand to be effective in their jobs.

4 SURVEY APPROACH TO TEACHING M&S

There are multiple challenges in teaching M&S in a 7 week time period. This section describes the rationale and some operational issues associated with our approach.

4.1 Relationship of Systems Engineering to M&S

According to the International Council on Systems Engineering (INCOSE) handbook, "Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation" (Shortell 2015). As such, systems engineering focuses less on the tools of a specific discipline, and more on the integration of the efforts from *all* the various disciplines needed to create a system. That can include experts in different aspects of business, engineering, mathematics and science. Consequently, a systems engineer has to focus on coordination and integration of the efforts of professionals in many different domains.

It would be impractical, over a 7 week period, to expect students to become proficient in the many simulation areas they might encounter on the job. This was proved out in the design of nuclear power plant simulator (Berenbach et al 1991). The authors found that engineers working on a simulation project required several weeks to become familiar with the simulation tools, and somewhat longer to master the needed domain expertise. However, M&S is integral and essential to virtually all complex development efforts. Thus, our approach to teaching M&S ties it to useful purposes valued by systems engineering efforts. The systems engineering "V" is a common graphical representation of the system engineering life cycle, and a means to decompose system life cycle(s) into component phases. The V diagram serves as a tool to put context to M&S activities. Figure 1 shows the "V" as well as several common system life cycle points where M&S is highly valued as a systems engineering activity. The conundrum is this: how do we give the students a basic understanding of different simulation techniques across multiple domains in just 7 weeks, knowing they will be expected to work with simulation experts in different domains throughout their career? How do we make sure students understand how simulation is used in each of the systems engineering lifecycle phases? A starting assumption is that hands on experience is necessary - students must actually participate in developing and using simulations in order to understand how challenging it can be.

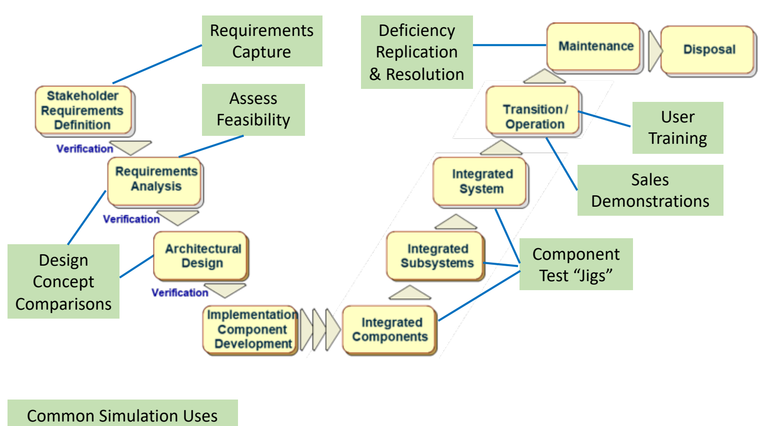

Figure 1: Relationship of systems engineering to modeling and simulation.

4.2 Schedule, Lectures and Quizzes

ASE 6003 is a fast-paced course, and each week students have a number of assignments that include lectures, quizzes, labs and a group project. The schedule is shown in Table 1.

A series of recorded lectures that cover M&S fundamentals; foundations; methods and methodology; experimentation, execution and results; use cases; and execution and management are spread out over the

7 week class. Figure 2 shows the lecture schedule. One of the benefits of the distance learning nature of PMASE is that the lectures can be recorded by experts in the field, and delivered to students in a seamless way. The 50+ lectures in the ASE 6003 catalog have been recorded by 30 individual experts, thereby bringing students the depth they need in the various areas of modeling, simulation and systems engineering. Involving the work and expertise of lecturers outside the immediate 6003 faculty supports the survey notion of the course, as well as the interdisciplinary nature of systems engineering teams.

Table 1: ASE 6003 Assignments by week.

Week 1	Week 1: Quiz
Week 2	Week 2: Quiz LAB 1: Systems Engineering Management of Simulation
Week 3	On-Site 1 Proposal Presentations Week 3: Quiz LAB 2: Discrete-event Simulation in AnyLogic
Week 4	Week 4: Quiz LAB 3: Agent-based Simulation in AnyLogic
Week 5	Week 5: Quiz LAB 4: Systems Dynamics Simulation in AnyLogic
Week 6	LAB 5: Continuous System Simulation
Week 7	On-Site 2 Project Presentations Final Report and Peer Evaluation HW: Project Evaluation

In addition to watching lectures each week, students also have a quiz which covers the top-level concepts that need to be mastered. Most quizzes are 10-15 short answer or multiple choice questions. For Week 5, students are asked to watch several required lectures, then select three use cases from the catalog to watch. The quiz is to write a short synopsis of each of the three use cases, synthesizing what they've learned about M&S, as well as describe the systems engineering life cycle phase that most applies.

4.3 Labs to Teach a Range of Simulation Methodologies

One objective of the course is to give the students some understanding of why simulation is important and where it fits in the engineering lifecycle. The result is a course that balances the domain and simulation activities to ensure students have some introduction to the technology behind their assignment, and some understanding of the simulation methodologies being applied. This goal is accomplished by five labs, which are completed individually. Each of the graded labs provides an introduction to one type of simulation, and has the students solving a common engineering problem using the tools provided. The labs include:

- LAB 1: System Engineering Management of Simulation Activities
- LAB 2: Discrete-Event Simulation in AnyLogic
- LAB 3: Agent-Based Simulation in AnyLogic
- LAB 4: System Dynamics Simulation in AnyLogic
- LAB 5: Continuous System Simulation

Lab 1 puts students in the mindset of organizing and managing a study that relies on simulation. In Systems Engineering context, the study itself becomes the project. Prior PMASE courses provide the foundations for properly specifying system requirements. These skills are called on in a simulation context. Early concept modeling and consequent scope activities introduce management activities. For example, for a few notional problems that we provide, they are expected to identify experimental data inputs/outputs, abstractions, simplifications, and problem boundaries. In addition, students are required to decompose study tasks into a work breakdown structure and a manpower plan with cost estimates and staffing requirements.

Week 1: M&S Fundamentals	**Week 4: Experimentation, Execution & Results**
Simulation Fundamentals	Optimization: Direct and Indirect Methods
Simulation Lifecycle Process	Optimization: Stochastic Methods and MDO
Conceptual Models	Design of Experiments: Overview and Basics
Data Models	Design of Experiments: Introduction to Surrogate Modeling
Fidelity, Resolution, Accuracy	Design of Experiments: Advanced Concepts in Neural Networks (optional)
Verification Validation & Accreditation	Monte Carlo Analysis
	Introduction to Wargaming (optional)
Week 2: Foundations	
Introduction to Simulation in Systems Engineering	**Week 5: M&S in the Systems Engineering Life Cycle**
Requirements Analysis	M&S in the Systems Engineering Life Cycle
Model Driven Architecture, Development & Requirements Engineering	Using M&S in Lifecycle Management & Short Use Case
An Introduction to State Machines	Use Case: Simulation in Manufacturing
Object-oriented Modeling and Simulation	Use Case: M&S in Electrical Equipment and Power Flow
Information Visualization	Use Case: Federated Model Simulations in Transportation
	Use Case: M&S in the F-22 Avionics Development
Week 3: Methods & Methodology	Use Case: Modeling and Simulation Visualization with the Test Matrix Tool
Discrete Event Simulation	Use Case: On the Modeling of Medical Systems
Continuous and Monte Carlo Simulation	Use Case: Executable Model Based Systems Engineering
Agent Based Simulation	Use Case: Physics-Based M&S for Real-Time Algorithms
System Dynamics Simulation	Use Case: Applications of M&S to Swarm Robotics
Introduction to Modeling Behavior with Artifical Intelligence	Use Case: Simulation for Simulators
Numerical Methods	Use Case: Simulation in ab initio flight training - Alsim simulators
Human-in-the-Loop Simulation	Use Case: Role of Simulation & Optimization in Data Science and Prescriptive Analytics
Hardware-in-the-Loop Simulation	Use Case: Testing Optimization Models with Simulation
Games and Virtual Worlds (optional)	Use Case: Building A Nuclear Powerplant Simulator
	Use Case: Machine Learning, Artificial Intelligence, and Modeling/Simulation
	Week 6: Execution and Management
	System of Systems & Architectures: Introduction to ASE 6102
	System of Systems & Architectures: Applied Case Studies
	Distributed Simulation & Standards
	Distributed Simulation SE Process & Interoperability
	M&S Return on Investment

Figure 2: ASE 6003 lectures by week.

Because of the short learning time for labs 2-5, we found that the tutorial approach works best. Students start by creating a simulation following a step by step tutorial. This mitigates tool orientation issues. Once they have successfully completed the tutorial, they extend it to solve an engineering problem.

For the discrete-event simulation in Lab 2, students create a passenger terminal with two types of passengers, standard and business, as shown in Figure 3. The passengers may either go to a desk to check in, or some percentage of them will go directly to security. Those passengers who go to the desk first will then also go through security, where there will be five queues. Students can experiment with the ratio of types of passengers, the number of passengers arriving, the rate at which passengers are serviced at the desk and by security, and how long they stay in the holding area before being allowed to board the airplane.

The agent-based simulation in Lab 3 is a wind turbine maintenance model. The turbines can go out of service due to failure or scheduled maintenance. If they fail, helicopters are dispatched, if scheduled, and trucks are sent out. The trucks and helicopters are kept in a hanger. The turbines change color when they need maintenance, green for normal operation, yellow for a scheduled outage, and red for failure. When the simulation runs, you can watch the turbines going in and out of service, and the vehicles coming and going to service them. Model variations include maintenance trucks also breaking down.

A bass diffusion model is used in Lab 4 to teach system dynamics. This lab uses a simple differential equation to describe the process of how new products get adopted in a population. After learning about market saturation, they extend the model slightly to consider adopters who change their mind and return the product.

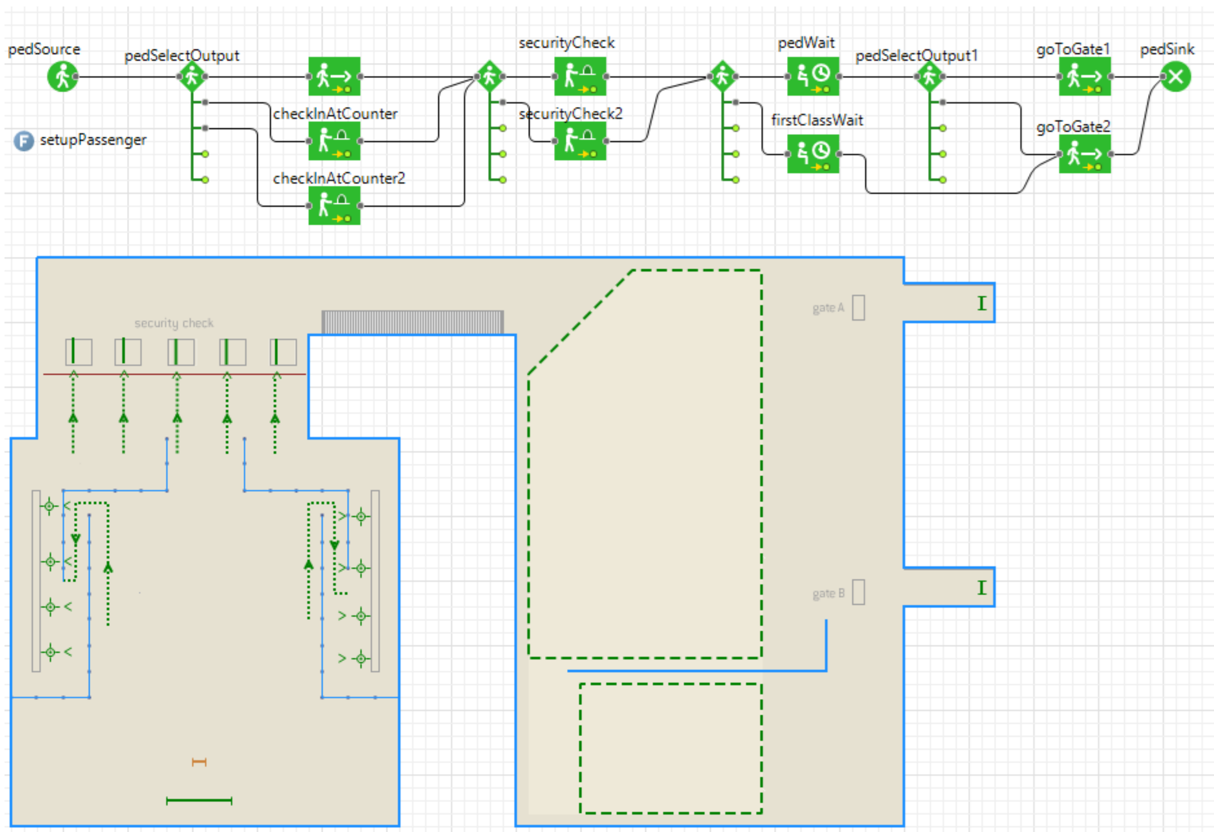

Figure 3: Lab 2 airport layout and flow chart.

In the last lab, students learn about numerical methods. Students use a provided program to gain an understanding of the impact on flow and coolant in heat exchanger design, as seen in Figure 4. The students vary flow rates, Prandtl and Reynolds numbers to study their effect on cooling and heating efficacy. This approach has been used for several years and has proven to be an effective introduction to numerical methods (e.g. for staff who must understand simulation issues but do not have to be experts).

4.4 Group Project to Teach the Simulation Life Cycle

In addition to the individual labs and quizzes, students also have a graded group project. The objective of the project is to apply M&S to a systems engineering problem in order to answer one or more design questions. The problem domain is open – teams can select a problem of most interest to them. Topics in past years have included autonomous systems, connected vehicles, Internet of Things, smart homes, and transportation. Each project must demonstrate they have learned each step in the simulation process.

Students are put on teams of 4 - 6 students. Each member of the team has a well-defined role (e.g., data collection, testing, implementation). The project requires all team members to participate in multiple roles, but there should be one person assigned to each major task in the project. Teams can pick any simulation tool to implement their project. Many choose AnyLogic since they used it for several labs, but some have access to other tools at work, and a few choose MATLAB, Excel or a language like Java or Python. The group project has several deliverables:

- Each team is responsible for submitting a proposal for their project. The proposal is presented at week 3 during the first on-site visit.
- At the second on-site in week 7, each team is responsible for giving a final presentation of their project. Presentations are made by each team member, based on their role in the project. The final report documenting the group project is due following the on-site.
- Everyone is responsible for submitting an evaluation of another group's project. Evaluations are done based on a set of established criteria.

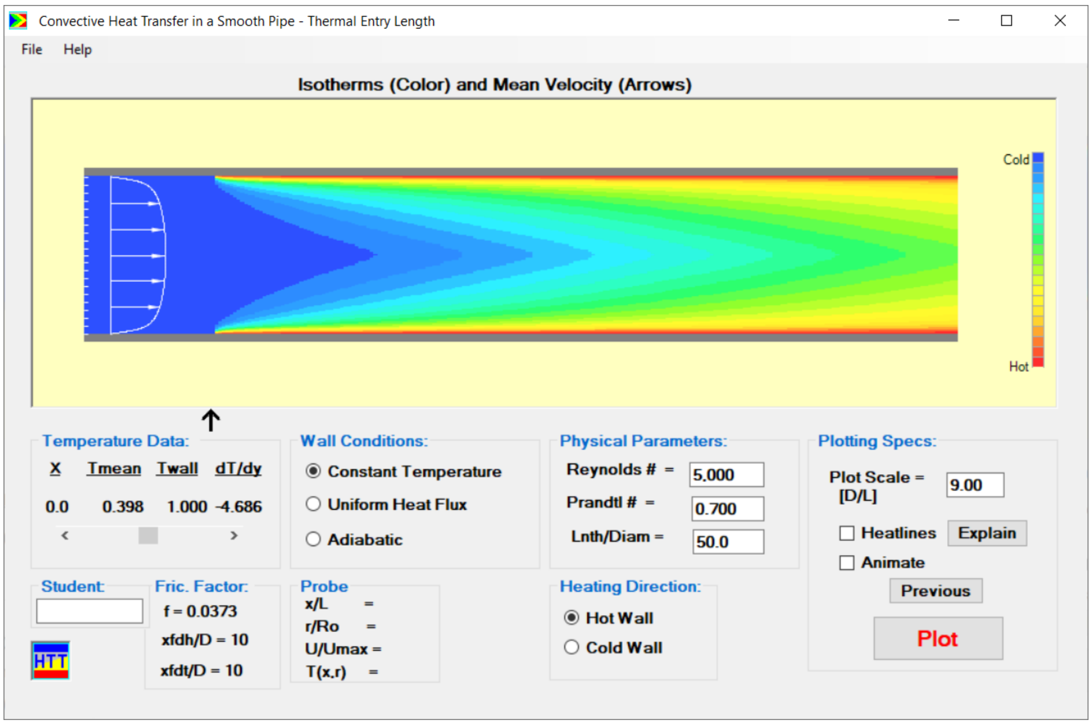

Figure 4: Lab 5 heat exchange in a pipe.

5 GROUP PROJECTS AND SYSTEMS ENGINEERING TEAMS

Student teams are formed based on a combination of student desires and self-identified programming skills. We balance composition to ensure the distribution of abilities provides the best chance for teams to succeed. Each team nominates a problem space to-be addressed and presents/discusses the problem/question to be answered with faculty to refine the objective. We ask the teams to identify suitable M&S methods and to scope the effort. Almost uniformly, the initial task identified exceeds the available resources (time, talent, available data, manpower, etc.) in one or more ways. We work with the teams on their initial concept model to bring scope within reason. Major steps for the teams include:

- Identify/refine the question to-be answered via M&S
- Build a conceptual model
- Propose project as they might when advocating an M&S study
- Find, assess and organize the data
- Build the simulation
- Perform experiments with the simulation to ensure/measure validity
- Analyze experimental results
- Form conclusions and recommendations

5.1 Example 1: We Are Trucks!

One team (de Silva et al. 2018) looked at a notional bidding process to support a non-profit organization charged to provide clean water to remote villages in Uganda. The WeAreTrucks! (WAT!) development team provided a simulation to provide the optimal number of trucks to keep villages water tank capacity above 25%. The WAT! concept model is depicted below, in Figure 5.

The model was built for two villages using real data for representing trucks behavior, roads location and conditions as well as demographic data and costs aspects. The simulation used the model built with a variable input of total number of trucks to output the behavior of village water tank levels. A secondary aspect addressed is the total operation cost. Assumptions and simplifications made were documented and justified.

Reasonable "next steps" were identified to include model extensions, use of additional data sources, etc.. Verification and validation processes relied heavily on intuition, subjective review and inspections. The model showed that ten trucks are the minimum number in order to supply the two villages with sufficient water to keep tanks above 25% capacity indefinitely. The associated costs related to this operation were determined as $29k per week ($0.052 per person per day).

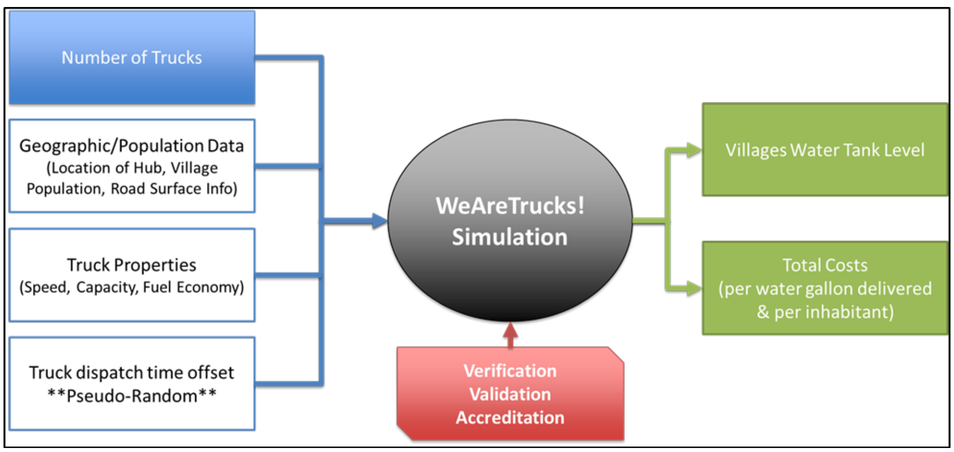

Figure 5: WAT! concept model.

5.2 Example 2: Power Rangers

In another student team project (Schoen et al. 2019), the "Power Rangers" team modeled an off-grid electrical power application for a location in remote Montana using AnyLogic. The team looked at a solar/battery hybrid power system that avoids expensive power storage infrastructure requirements and incorporates a 16kW backup generator (wind power was explicitly excluded). The team created a system dynamics model of the hybrid power system using irradiance data provided by a Physical Solar Model to determine hourly power production capability. The team created a notional periodic power demand profile based on expected electricity usage and optimized the solution based on solar panel azimuth and elevation angle for the solar array. They also identified the optimum combination of solar and battery components to minimize system cost while meeting requirements appropriate for the capacity needs they identified in model experimental runs. Figure 6 shows a screen shot of a portion of the model developed by the team.

The Power Rangers team utilized data from the National Renewable Energy Lab (NREL), NOAA, and other quality sources. The data was downloaded and converted to spreadsheet formats that could be ingested into AnyLogic. Model validation compared predicted to NREL-provided information favorably for a representative sample of summer days.

5.3 Our Experience with Simulation Tools

Simulation tools are needed that allow the students to create a simulation quickly, without extensive debugging. Furthermore, when creating a simulation, minimal domain knowledge and programming skills should be required. AnyLogic was found to be suitable for teaching discrete, dynamic, hybrid and agent-based simulation. Our experience using the tool in ASE 6003 has been generally favorable. Limitations in the Personal Learning Edition version reflect a few quirky issues building the models themselves and limits on scaling consistent with an academic use "free" version. For example, students report having to build/rebuild model stages several times before getting a configuration that properly runs. We develop and maintain lab exercise errata but this measure still falls short of covering each student's machine differences (MAC vs PC, operating systems version, etc). There is no cost for the personal version, and it is acceptable for introducing students to the techniques they may need post-graduation.

For continuous simulations using numerical methods, a canned program is used which enables students to focus on results, analysis, and conclusions. The course has also employed NetLogo and Excel to satisfy teaching objectives in the past. MATLAB does offer some free programs that could be used, however, licensing issues prevented their use in our course.

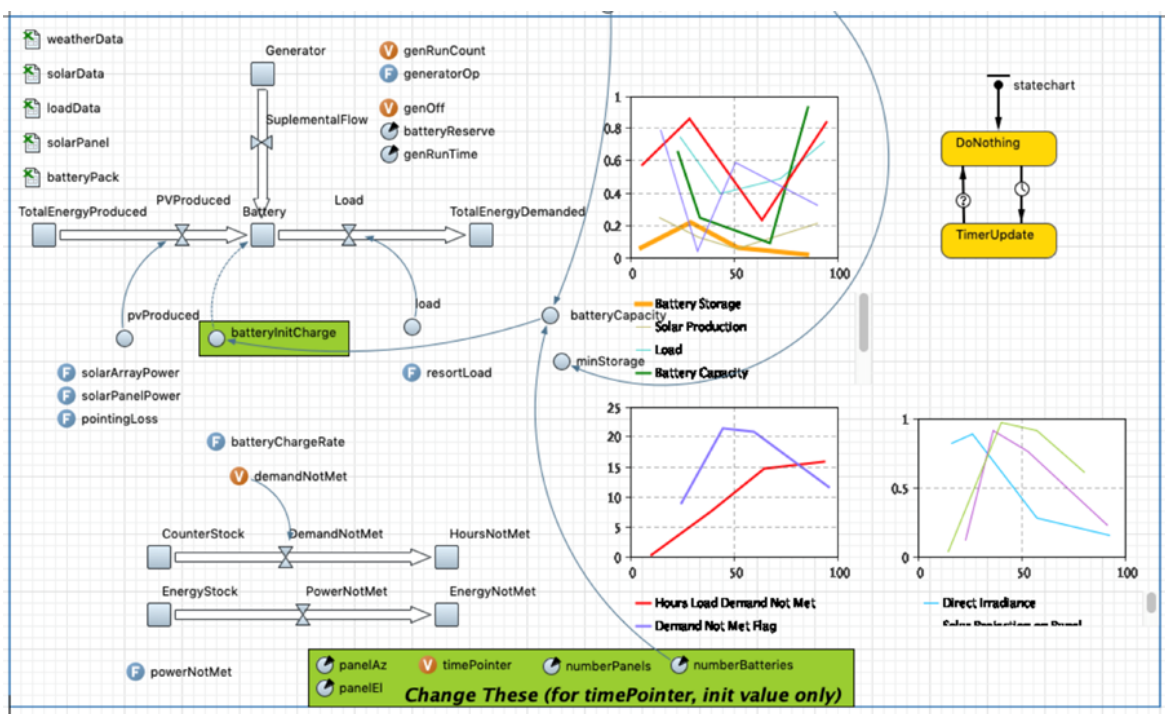

Figure 6: Off-grid power design.

6 CONCLUDING REMARKS

Several mixes of group vs individual work were attempted before settling on the current balance. We have found an optimum mix which ensures each student has practical/hands-on use of basic M&S methodologies and a significantly more complex group task. A balance between group and individual learning outcomes is maintained to ensure each student learns the fundamentals and each team is able to optimize use of student backgrounds and skills, much like a typical systems engineering or M&S study project. Our key has been creating assignments which clearly reinforce the topics students need to master, while connecting to topics they learned in previous courses and providing insight into topics they will learn in future courses.

Each year's delivery of the course enjoys benefits from an annual critique and refresh. The faculty team begins a cycle with critical review of "what can be done better next time". During the time between course conclusion and the next one's start, faculty meet and actively plan for improvements to the content, delivery, and content delivery. Lectures, exercises, and other content is reviewed with an eye to continuously improve the material. In addition, lectures and reading on emerging technologies (e.g. machine learning and digital Twin modeling methods) are updated to leverage ongoing research. Finally, lessons are actively synchronized with other PMASE courses to reinforce overall themes, like team leadership, critical thinking skills, and systems thinking.

The ASE 6003 course has evolved to a point where it covers enough of a survey of M&S, and gives students enough hands-on experience, that they can take these skills back to their work place and put them immediately to use. In fact after graduation, students have sent us email describing situations where they used the material learned in ASE 6003 at their respective companies, providing further validation of the effectiveness of the course. This email was sent by a PMASE student just two months after class ended:

> "I wanted to let you know that I actually used AnyLogic to model a relatively simple problem at work. We make fairly large silicon carbide mirrors used for astronomy and directed energy applications and one special custom part required a cyclic thermal annealing process in non-condensing environments. In the chosen furnace, we needed to maintain a specific dry N2 flow through the chamber to ensure non-condensation. My colleague was tasked to contact suppliers for liquid nitrogen and estimate the approximate volume of gas we needed. He received two widely different answers from two separate suppliers.
>
> Not having access to AL at work, I performed the hand calculation but I needed to verify my answer. When I got home, I modelled it in AL using the Flow Dynamics Library in under 45 mins, thanks to ASE6003. I verified my hand calculation to within less than 6L of LN2 (rounding errors). I then repeated the hand calculation with higher precision numbers, and my calculation was within a liter of LN2.
>
> In one case, the suggestion from one supplier was not enough and would have placed our >$200K part at very high risk. The other suggestion, was over double the amount we needed. This gov't program is cost sensitive, and we needed to save where we practically can without adding unnecessary risk, and I was able to confidently do just that!"

As described in (Loper and Turnitsa 2017), M&S educational programs should provide broad coverage of the discipline, and prepare graduates to be M&S professionals. Seven guiding principles for M&S programs were proposed by the Georgia Tech Modeling and Simulation Research and Education Center (MSREC) leaders and MSREC's advisory board (Fujimoto 2000):

Principle 1: A solid grounding in fundamentals is essential.
Principle 2: Basic knowledge and skills in computing fundamentals are important.
Principle 3: Tight coupling with application domains must be maintained.
Principle 4: Exposure of students to a broad range of core M&S topics is essential.
Principle 5: Fluency in multiple modeling paradigms is a key to intellectual development.
Principle 6: Students should understand the full M&S life cycle.
Principle 7: Effective communication skills are a prerequisite for success.

We believe ASE 6003 follows these principles and effectively teaches M&S in a 7 week period, enabling students to take these skills and put them use as systems engineers immediately.

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