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ENHANCING MODEL INTERACTION WITH IMMERSIVE AND TANGIBLE REPRESENTATIONS: A CASE STUDY USING THE LOTKA-VOLTERRA MODEL

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ABSTRACT

Dynamic computer simulations seek to engage the viewer by providing an intuitive representational mapping of common knowledge features to new knowledge concepts. Our research aims to provide enhanced understanding of complex systems through participatory interaction with our dynamic simulation models. Previous research has indicated that virtual and tangible models are well suited for use in informal education spaces, as they increase user interaction and curiosity amongst children and adults. We designed and implemented an interactive virtual environment as well as an interactive tangible “water computer” to represent the complex interspecies behavior of Lotka-Volterra predator-prey dynamic system. We designed our simulation models for use in informal STEM education settings, with a design focus on enhanced interactions and reflexive thinking.

1 INTRODUCTION

Forrester’s method requires an understanding of a symbolic language to understand the organization of systems. What we are proposing is an extension of Forrester’s models to include abstract representation and visualization of a system’s structure and behavior. By presenting multimodal representations of closed-loop dynamic systems, students will have a better chance of achieving a prescribed learning goal, will have longer retention of understanding, and will have better application knowledge than using traditional methodologies. We have created virtual and tangible models to represent the Lotka-Volterra dynamic relationship between predator and prey population levels. The two models reinforce how the relationship works by highlighting the mechanism driving relationship in different ways. We found that our methodology was effective in gathering interest and facilitating discussion about the relationship, but further refinement would be needed for the simulations to be as effective without the presence of an educator.

The paper is organized in seven sections. Section 2 covers the basics of system dynamics. In Section 3 we discuss a few aspects of our modeling approach as it relates to education. Section 4 briefly describes the Lotka-Volterra (LV) system of equations and the educational value of modeling this complex dynamic system.

Section 5 discusses some history of the use of water for computing and how we have used water in the predator-prey system. In Section 6 we discuss the use of virtual environments (VE) in education contexts, then we describe how we have used VE to represent the LV predator-prey mathematical model. We conclude the paper in Section 7 with our reflections on our work.

2 SYSTEM DYNAMICS APPROACH

The System Dynamics (SD) framework that Forrester (1996) developed has been used in a wide variety of domains. Forrester explained that using SD to model complex systems provides useful tools to understand complex situations. Some research has shown that many have difficulties in understanding SD concepts (Sweeney and Sterman 2000). Our research explores the design of tangible and virtual interactive representational forms to supplement current SD teaching approaches.

Traditional SD modeling uses the iconographic notations shown in Figure 1 (Fishwick 1995). Shortcomings notation are that they are static and do not reflect the behavior of their functions within respective systems. There appears to be a gap between these representational forms and how the model structure is related to a system's behavior. To make this notation more readable and transparent, we incorporate action and behavior in physical objects as the symbols themselves. When functional objects are used as the notation they become intuitive to the viewer and thereby make the systems easier to learn and understand. Our goal is to develop interactive, engaging models using Forrester's basic SD concepts, to enhance the understanding of the LV complex mathematical model.

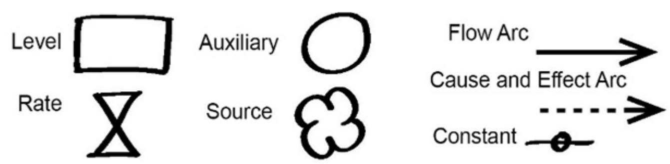


Figure 1: Taxonomy of System Dynamics Symbols

3 RELATED WORK

3.1 Multimodal Education

Richmond calls a self-teaching process "learner-directed" as opposed to "teacher-directed", and explains a learner-directed education happens when students take an active role in their own education (Richmond 1993). Modeling complex dynamic systems facilitates this learner-directed approach, and VE can provide an engaging medium through which we can scaffold and support learner understanding.

Chang et al. (2012) conducted a study that analyzed the effect of students taking an active role in reading through virtual interactive storybooks. Their research concluded that because the stories were interactive, and were designed to engage the children through commentary, questioning, demonstration, and diegetic reading, this resulted in students developing positive emergent literacy. Delaney et al. (2010) conducted research with high school student on effective teaching in secondary school and his findings appear to be related. Characteristics of effective teaching go beyond the teaching method because strong and effective because of three main aspects: communication is paramount, students have something to share about their experience in learning, and respectful relationships allow for positive individuality (Delaney et al. 2010).

Fumarola et al. (2011) used multiple representations to help drive design decisions. Her study used a model along with a virtual representation of the actual workings in order to better discern the implications of design decisions. Participants felt that having the added visualization helped them think through design decisions and improved their shared understanding of the systems they were designing. Therefore, we have designed our systems with the goal of engaging participants through interaction with dynamic visual, tangible, and physical representations to introduce them to alternate perspectives of the LV system. In addition, we have designed of our models to encourage multi-user participation and interaction in order to encourage discussion and conversation among participants and observers as this shared experience can support viewers in developing a greater understanding of the predator-prey relationships, the model structure and behavior.

3.2 Tangible Models in Education

Horn et al. (2012) proposes the advantage of combining tangible models with more traditional learning methods to create hybrid systems. In his research he found several potential advantages to tangible interaction which need further investigation. The idea that physical objects could play an important role in the learning process is relatively new. Until the 19th century, classroom education was exclusively based on lectures. One of the first "hands-on learning" entrepreneurs was the Swiss educator Johann Heinrich Pestalozzi (1746-1827). Pestalozzi proposed that students learn not only through reading and hearing, but also through all their other senses, arguing for "things before words, concrete before abstract". Several studies have shown that the use of tangible user interfaces may be beneficial for learning (Triona et al. 2005, Ishii and Ullmer 1997, Marshal et al. 2003). Barsalou and Weimer-Hastings (2005) explain that “if perception and cognition are closely interlinked, then using physical materials in a learning task might change the nature of the knowledge gained relative to that gained through interacting with virtual materials”.

SystemBlocks are a strong example of the use of tangible interfaces to support learning SD thinking (Zuckerman et al. 2005). Their research focuses on physical components that can be connected together to provide abstract models of the behavior of dynamic systems. Zuckerman et al. (2005) also emphasized the importance of concreteness in discussing manipulative and tangible interfaces. The tangible model proposed in this paper takes a step further than the one described by Zuckerman; it proposes a new path where the blocks are already integrated and the student learning occurs when he interacts with the manipulative objects in the model and observes the system’s dynamic behavior in real time.

3.3 Tangible User Interfaces

Ishii and Ullmer (1997) defined “tangible user interfaces” as UIs which “augment the real physical world by coupling digital information to everyday physical objects and environments” pioneering a previously unexplored paradigm. As Fishkin (2004) highlights, their idea was simple, “a user manipulates some physical object(s) via physical gestures; a computer system detects this, alters its state, and gives feedback accordingly”. There have been many research publications involving tangible user interfaces, most of them focusing on the technical aspects and the creation of descriptive taxonomies (Fishkin 2004, Fishwick 2007). We focus on the educational benefit of using tangible UIs by utilizing Forrester’s Systems Dynamics modeling framework to implement a tangible interface, which represents a LV predator-prey complex system. Students interacting with the tangible interface will experience the dynamic oscillatory behavior of the water machine. Users will see and hear gears grinding in a rhythmic pattern and they can learn how this observed behavior is analogous to a real-world predator-prey system.

4 LOTKA-VOLTERRA MODEL

The LV equations describe complex dynamic coupled systems such as a simple predator-prey ecological system. LV equations can be applied to model a wide variety of systems. We chose to create representations of the LV system because the models represented by these equations, are relatively simple, yet they show non-intuitive emergent behaviors, and are well suited for introducing the fundamental concepts of SD such as accumulation and feedback-loops. The LV model is a coupled system of ordinary differential equations, which exhibit complex oscillatory behavior over time.

The LV equations are:

$$\frac{dP}{dt} = -Pm + bPH \tag{1}$$

$$\frac{dH}{dt} = Hr - aHP \tag{2}$$

Where

$P = P(t) = Population\ of\ predators$
$H = H(t) = Population\ of\ prey$
$r > 0\ Birth\ rate\ of\ Prey$
$b > 0\ Birth\ rate\ of\ Predators\ per\ Prey$
$a > 0\ Death\ rate\ of\ Prey\ per\ Predator$
$m > 0\ Death\ rate\ of\ Predators$

5 TANGIBLE MODEL

5.1 Water Computing

Forrester introduced the basic concepts of SD using a water flow metaphor of stocks and flows, to provide a framework to model complex dynamic systems. He proposed that SD modeling should be included in K-12 curriculum to teach students about complex systems. In order to provide students with support to learn SD, we propose that students need to be able to observe the flow of data changing over time in the system; we concluded that the best way to demonstrate this behavior is using water. Water computing or hydro integration has been used for some time in the sciences to explain complex accumulation concepts (Szücs 1980).

The MONIAC was created in the late 1940's by Alban William Housego Phillips (1914-1975), a well-known economist from New Zealand. The MONIAC performed logical functions that no other computer of the day could match due to a combination of its analogue calculation principles and the use of water flow as the calculating medium. The only known working MONIAC is currently displayed in the British Reserve Bank Museum. Phillips himself used the MONIAC as a teaching tool at the London School of Economics (About the Reserve Bank Museum 2008).

We expect that our implementation, based on water computing, will enhance the canonical Forrester's SD iconic representation. We use the analog nature of water computing in terms of appealing to the senses. The user can see the water height and observe and manipulate the parameters. The underlying computation is digital, involving the use of finite differences for solving the differential equations. This hybrid analog-digital approach provides the analog benefits of human-model interaction while maintaining the numerical accuracy afforded by the system's digital electronic components.

5.2 Implementation

Our water computer was designed to simulate the dynamic behavior of LV predator and prey population levels as they vary over time. Forrester's SD modeling approach uses a water flow metaphor, where water is used to represent the flow of data. In our initial system prototype, the "water level" of the virtual tanks is represented using a TFT LCD screen; it provides visual feedback for the user as this simulates how the predator and prey populations change over time. This is intended to support users understanding of dynamic changes in populations due interactions of the predator and prey over time.

We designed the tangible interface to explicitly highlight the mapping between LV mathematical equation elements and the stock and flow model structure, which generates the dynamic behavior one would expect between a predator and its prey. Specifically, our tangible machine interface is composed of four physical flow valves that explicitly represent the four inner mechanisms of the LV equations. Dynamic movement can be used to capture the attention of students; therefore, including it in the model is crucial part of the tangible learning experience. For the valves, the control actuators that represent the different inner mechanisms of the equations are highly visible. In addition, users can readily perceive the dynamic visual and audible rhythm as the system behavior causes the valves to actuate. Figure 2 shows the entire tangible model with the control knobs.

In our water machine, each component is designed to represent an element of the LV equations; therefore, we arranged the layout of machine components so the user can easily understand how each component is directly mapped to the LV equation's mathematical symbols. Each valve is labeled with its corresponding mathematical function and connected through visible wires to its corresponding variable knobs. Table 1 explains the purpose of each valve and how it relates to the equations. Each valve represents a well-defined mathematical functional unit of the LV equations; this provides support for the user to infer how a negative term inside the equation represents a decrease in population, which corresponds to opening a "discharge" valve while a positive term corresponds to an increase or opening a "fill" valve.

On the LCD screen, the user can see how both populations vary with time over periodic intervals. Through interaction with the tangible user interface, and through the multi-sensory participatory experience of observing the entire model functioning, users can develop an understanding of the correlation between the abstract LV equation elements and the individual components in our physical instantiation of the SD model. This interactive experience provides support for learners to understand that the LV complex model is a highly interdependent system of dynamic components, and this same model structure and behavior accurately describes many simple predator-prey system ecologies.

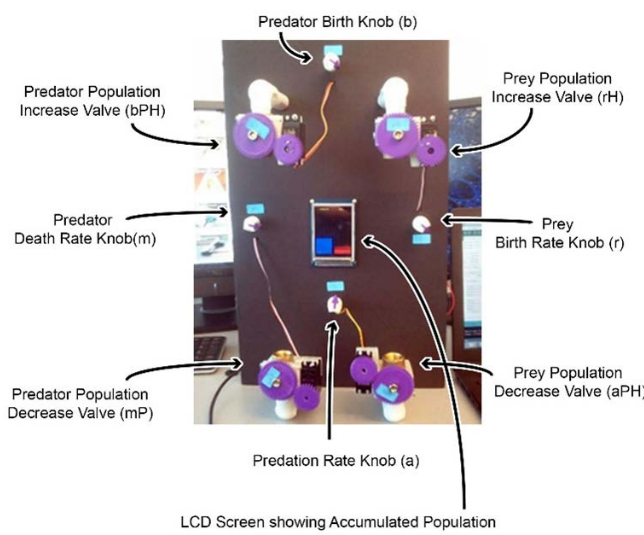


Figure 2: Tangible LV Model

Table 1: Relation of components in tangible LV model.

Position: Upper Left Population: Predator Equation: $b * P * H$ Purpose: Increase Population Related to Knob: b	Position: Bottom Left Population: Predator Equation: $m * P$ Purpose: Decrease Population Related to Knob: m
Position: Upper Right Population: Prey Equation: $r * H$ Purpose: Increase Population Related to Knob: r	Position: Bottom Right Population: Prey Equation: $a * P * H$ Purpose: Decrease Population Related to Knob: a

5.3 Multiple Representations

Extensive research has shown that even highly educated adults have difficulty understanding basic concepts of complex dynamic systems, such as LV, when they are shown traditional static plots of inflow and outflow over time (Cronin et al. 2009). However, other research has shown that multiple representations can facilitate learning (Mayer 2005). This suggest that students can grasp information more easily when information is provided in different formats, as this allows learners to integrate chunks of information acquired through multiple representations. This occurs because each representation provides a unique way of demonstrating the behavior of a complex system and therefore, facilitating viewer comprehension (O'Keefe et al. 2014). In our research, the tangible model provides users with a way to manipulate the variables of the LV equations and to observe how these modifications affect the behavior of a system over time. This manipulation ability aims to engage students by letting them interact with the equations directly in a dynamic manner.

Using a VE we can move beyond physical limitations of tangible models. With a virtual system, we can apply a predator-prey interaction model in a wide variety of contexts such as physical representation of the predatory animals or something more abstract like our water representation. Creative representations of SD models are designed to engage casual users who might not look twice at traditional graphs. Seeing SD in multiple contexts can provide the student with a greater awareness of where these systems might be found in their own world. We have started with a water-based representation because its abstraction can represent a multitude of contexts, moreover, the rates and levels may be easier to understand than contextually equivalent representations.

6 IMMERSIVE ENVIRONMENTS

6.1 Related work in virtual environments

Numerous examples exist which showcase VE used in conjunction with agent based modeling approaches to create training and education applications (Fishwick et al. 2009). These types of simulations have been used for safety training (Zhao et al. 2009), simulation training (Lukosch et al. 2012), navigation (Mekni and Moulin 2011), cultural modeling (Fishwick et al. 2008), healthcare (Ng et al. 2011), and production (Jones et al. 1993).

Some drawbacks to using VE for simulations are software (Jones et al. 1993) and hardware limitations (Liu et al. 2010). By using commercial game engine packages, we can eliminate most of these concerns. Liu also addresses issues of time-cost in developing behavioral models for simulations by substituting prescribed routines with abstract models. This use of game engines for simulation development are further enhanced by rapidly growing repositories, asset stores, and digital marketplaces, which have both free and low cost plugins and content to speed up development.

Maciuszek's work gives us frame of reference to where we fit in between learning, simulation, and games (Maciuszek et al. 2012). Martens et al. (2008) illustrates the interplay between three main fields within game-based training: Learning, Simulation, and Games. He expresses that the crossroads of training and simulation stress the learning of facts in the context of military, medicine, and business. Another overlap he discusses is edutainment, the crossover of learning and games. His work is said to be in the center of all three in what he calls, game based training. Where we fit into this taxonomy is in a similar place, but without the emphasis on training. Our work is positioned at the intersection of simulation and games, which we consider to be *interactive simulations*.

6.2 Moving from Agent Based Simulation to Virtual Dynamic Systems

Agent based modeling has a wide array of applications for simulations. One common application of agent-based simulation is in training contexts, where users interact to learn a set of social skills for cultural training (Fishwick et al. 2010). This modeling approach, and the related human computer interactions are typically experienced from a first person perspective using a keyboard and mouse. New forms of input devices, such gestural recognition and touch-screen interfaces, imply that new approaches for interaction and modeling need to be developed. Our VE is a departure from the agent-based modeling and simulation tradition. We are borrowing from the gaming culture, using their mechanisms and visual palette, and we are using them to represent and illuminate computing concepts.

Aesthetic computing is "the embodied nature of cognition" (Fishwick et al. 2013). We are creating a formal language, with a visual grammar, which has its roots in nature and reflects the actions of the model. This encoding of information is going directly into the VE itself. VE are ideal for dynamic systems modeling because we can pause, explore, and dissect these fundamentally "time-dependent physical systems" (Fishwick 2007). This VE creates a one to one mapping of the predator-prey system which does more to uncover the behaviors of the two equations than mimicry and memorization of facts. The strength of virtual dynamic systems is that they invite the user to interact and self-teach.

6.3 Virtual Environment Implementation

The VE was created as a means to represent the relationship between the structure and behavior of the predator-prey model. The flow of data is represented as a metaphorical river cascading down parallel waterfalls which control the change in population. The VE features were modeled using ZBrush, and Autodesk Maya; then the simulation was implemented using the Unity 3D game engine. The mechanics and LV simulation were programmed using C#. Code from previous project prototypes was repurposed, and the modeling and simulation development was completed over several weeks. Figure 3 shows an early conceptual design of the VE.

Figure 3: Concept Design of Virtual Environment

Our systems are designed to support inquiry-driven learning; to prompt the user to ask the question: *what is the underlying structure that is driving the system behavior*? This inquiry-driven interaction design approach can ultimately be applied to many systems. However, for this implementation, we are showing the dynamic behavior of two coupled equations in the LV relationship. Figure 4 shows the LV equation represented as block model diagram.

An important aspect of Forrester's modeling methodology is that provides a conceptual progression in order construct a structural model of a dynamic system. The initial step towards understanding the structural model is to identify the relevant variables in the system. This process can be illustrated through the conceptual steps required to build the stock and flow model shown in Figure 5. In our LV system, we have two populations, predator and prey. We have used the letter P to represent predators, and H, as in herbivore, to represent prey. In our VE, shown in Figure 6(a) and Figure 6(b), pools of water are used to represent population levels of the species, where the predator pool is on the left and the prey pool is on the right. Next, we can identify factors that cause changes to these populations. In the VE these changes are represented by water flow; where flow into each individual pool represents an increase in that population level, and water emptying a pool, indicates a decrease in that population's level. These dynamic flows represent births and deaths for each of the populations.

The water pools illustrate the concept of accumulation, where a population's current level can be seen to represent the memory of flows of water into and out of the pool over time. At each point in time, the change in the level is due to the difference between current inflow and current outflow for each pool. In the predator-prey system this means that current population level reflects the history of births and deaths over time, and instantaneous changes are due to the difference between instantaneous births and deaths. Feedback loops are an important concept in SD, identifying these structures is the next step in the progression of creating the system structure. In the VE, the feedback loop structure is not directly visible when viewing the waterfall elements. Similarly, in the real world, the feedback loops are not always explicitly visible. Feedback structure means that the current changes to the system actually depend on the current conditions of the system. For the prey population, it is easy to understand that the number of births at any time depends on the current population of prey. This is represented in Figure 5 as a float connected to an arrow that is connected to the upper flow valve and controls flow into the prey container. Figure 4 shows the control mechanism and structural model that drives the water flow dynamic behavior in the VE. While this component has not yet been fully integrated with the water flow features in the environment, our goal is that this mechanism will provide users with the ability to reveal the underlying structural connections between the water components and to manipulate adjustable parameters to see resulting changes in the system behavior.

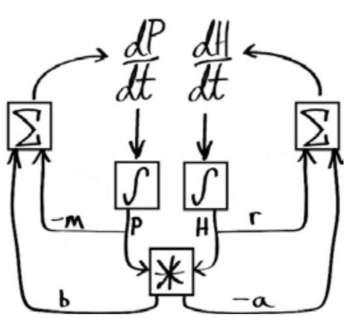


Figure 4: Block Diagram

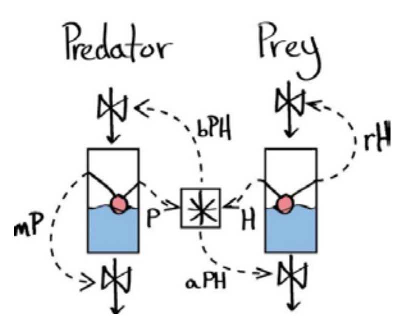
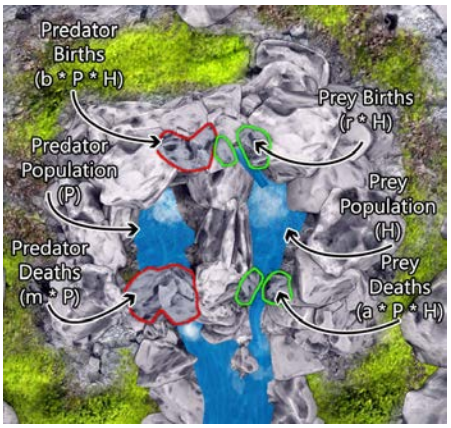


Figure 5: System Dynamics Diagram

In the VE, the left branch of the river represents the predator population's lifecycle, the head of the river is a spring and is marked in Figure 6(a). Initial conditions we predetermined to show off the relationship as clearly as possible. The birth flow for each population is visually indicated by large stones covering the head of the spring which influences the size of the waterfall flowing off of the rocks. The two rocks close together as the birth flow decreases and eventually close the spring entirely.



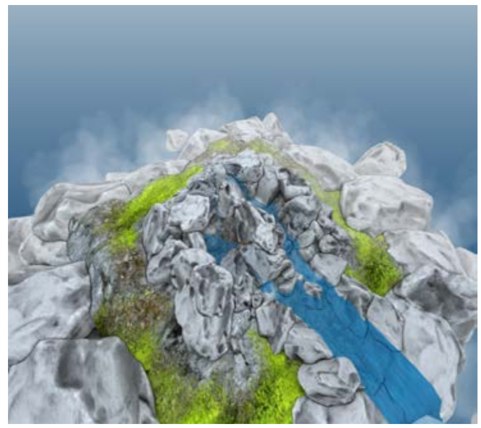


Figure 6: (a) Identifies how the LV model features are represented in the virtual environment. (b) Shows an overview of the virtual environment.

The levels of both ponds are interpolated between a prescribed low point and high point to properly indicate the level of the pond. The height of the water is an accumulation of the integral of the respective populations. The same approach used for indicating the birth rate was used to visually show the death rate. Both flows merge together and flow off the edge of environment into an undulating group of clouds, which presumably recycle the water to the top of the spring. Figure 6(b) shows a screen capture of the V.

Due to the instability of the model, strict limits were put on the variables so accumulated errors did not cause the model to behave incorrectly. The LV equation is modeled as a block diagram in Figure 4. This breaks down the function into discrete steps, but the movements of the objects in the environment are smoothly interpolated for visual continuity. In terms of the water analogy, time-dependent models would be continuous. But since we are simulating animals in nature with a computer, approximating by discrete quantities is acceptable.

7 FUTURE WORK

We want to show the control mechanisms that drives the dynamic behavior in the VE. This mechanism will provide users insight into the underlying structural connections between the water. We also recognize that there are two issues: scaling (Liu et al. 2010) and behavior reuse (Liu et al. 2012) that we need to consider in further detail. Schneider et al. (2011) states that "the main impact of tangible interfaces is to promote constructive behavior (exploration, collaboration, and playfulness of the task)" and this reflects our experience. We will continue to explore where tangibility works and where it is not effective. At the moment in our work, this difference is unclear.

By developing the model we learned it is understandable for high-level students already familiar with the equations, but the abstractness of the LV system demands a clearer representation of the inner mechanisms of the model and how they are linked to each other in the tangible user interface. The system needs to be more intuitive so the viewer can relate what's happening with the mathematical concepts we need a way to represent the multiplication occurring with the current population levels of the predator and prey. We plan to consider ways in which both the block model (Figure 7) and the waterfall representation can become isomorphic. This will require outfitting the waterfall interaction with feedback possibly in the form of pipes or power conduits that line the landscape.

Regarding the tangible model, although we represent the flow of data in the model's LCD screen, to correctly implement our vision of SD we require the use of physical water to simulate data flow. The next prototype will include water beakers that represent the level of the predator and prey populations and how they interact. Also we will include a graph-based representation in the LCD screen so the students can relate both representations and understand what is actually occurring.

CONCLUSIONS

We began our research noting that Forrester's SD representations are typically static. There is no default animation or interaction. Our purpose was to introduce new interactive representations that added immersion into the representation. Two types of immersion were implemented: immersion through a VE, and immersion through interacting with a tangible device. We hypothesize that each of these representations will have different purposes, and our future plans are to analyze the contributing attributes of each model.

We demonstrated our models during the University's Engineering Week and allowed visitors to interact with them. Although a conclusive result cannot be deducted by these observations, both models appeared to be well received. The virtual implementation drew in younger visitors and held their attention while we demonstrated the functions, and older visitors seemed to enjoy interacting with the tangible model. This should encourage further investigation, as the opportunity areas related to tangible models and SD are broad.

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