AIR WAR COLLEGE

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CONCEPTUAL MODELING TECHNIQUES

FOR

USE WITHIN THE DoD ACQUISITION COMMUNITY

by

Edward H. Crews, Lt Col, USAF/ANG

A Research Report Submitted to the Faculty

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Advisor: Colonel Mark S. Sullivan, U.S. Army

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Biography

Lieutenant Colonel Edward H. Crews is a member of the 138th Fighter Wing, Oklahoma Air National Guard, Tulsa, Oklahoma where he serves as the Mission Support Group Vice Commander and full-time GS-14 Support Officer. He is currently on assignment to the Air War College, Air University, Maxwell AFB, AL for the 2013 academic year. He graduated from the University of North Florida in 1993 with a Bachelor of Technology degree in Industrial Technology and in 1996 from Northeastern State University with a Master of Science degree in Industrial Management. He is working toward a Doctorate of Philosophy in Education at Oklahoma State University where his interest in conceptual modeling is connected to his work in using virtual environments for work force education. During his career, he has performed duties as an Aircraft Maintenance Officer, Military Personnel Flight commander and Comptroller Flight Commander.

Abstract

Conceptual modeling is a representation of a real-world system which communicates how the system works based on the interactions and relationships of the smaller subsystems. Conceptual modeling is the first step in the modeling and simulation process critical to creating an effective computer simulation. The Department of Defense has identified modeling and simulation as a vital part of the acquisition process of current and future military equipment procurement. Through modeling and simulation, complex and technologically advanced systems can be simulated using computer simulation which results in cost savings and the highest quality of equipment procured to meet the mission. The conceptual model is the guiding tool of the modeling and simulation process. This paper follows a building process from understanding some philosophical and cognitive foundations of thinking conceptually, to what it means to be considered more art than science, and on to techniques of building models. The techniques of visual, spatial, and abstract are shown as well as how establishing which environment the model is operating in whether physical, informational, or virtual is important. The objective of this overall examination of conceptual modeling is intended to provide foundational concepts for anyone interested in creating conceptual models for use in the modeling and simulation process.

Introduction

Conceptual modeling may be the most critical step in the simulation and modeling process although probably the least understood[1]. This early step in the simulation and modeling process may be overlooked by designers choosing to go straight to the model coding phase instead of ensuring the conceptual model fully communicates the intent and interrelationships of the project at hand. Chen (1999) describes conceptual modeling as helping us understand a specific real-world domain, enhancing communication among ourselves, and setting the stage for global understanding and communications[2]. A better understanding of the purpose, creation, and value of a conceptual model may help place the needed emphasis on developing solid conceptual models to create effective simulations and models. Simulation and modeling as a whole presents the ability to examine highly variable, real-world systems using computer simulations. This capability allows designers to examine multiple scenarios to find optimal solutions to real-world problems at a much lower investment cost than physical testing. Conceptual modeling is the strategic level planning aspect of the overall simulation and modeling process. In its final form, the conceptual model is, as defined by the Distributed Interactive Simulation (DIS) community, the agreement between the simulation developer and user about what the simulation will do[3]. This paper will examine the purpose, creation, and value of conceptual models in the simulation and modeling process and its role within the physical, informational, and virtual environments.

Background

The acquisition process of the United States government in particular within the Department of Defense (DoD) is essential to providing the best training and equipment available to the warfighter and supporting personnel under the constraint of finite resources. It has been recognized that modeling and simulation as part of a simulation based acquisition (SBA) program can be instrumental in achieving the DoD initiative of reducing cost, time, and risk in major defense acquisition programs[4]. The DoD Acquisition Modeling and Simulation Working Group proposed adopting the perspective of model-based systems acquisition (MBSA) across all phases of the defense acquisition life cycle[5]. Recognizing the importance of conceptual modeling to the modeling and simulation process, the Simulation Interoperability Standards Organization (SISO) in an attempt to formalize the process has formed a study group and internet site (http://www.sisostds.org/DigitalLibrary.aspx) which investigates and captures the best practices of conceptual modeling among the global community[6].

Theoretical Framework

To conceptualize in the context of this research means to be able to use mental imagery to construct a larger idea from the smaller characteristics of a real-world system. Some theoretical foundation is necessary before proceeding with how to build conceptual models in reference to human cognitive abilities for mental imagery and its relationship to conceptualizing. Well known Greek philosophers, Plato and Aristotle, debated contrasting views on how sensory imagery resulted in human ideas and memory. Plato believed knowledge was not derived by sensory perceptions, but that ideas were the objects of pure reasoning, whereas Aristotle believed knowledge came from sensory information and thoughts were a product of mental images.[7] For the purpose of building conceptual models, the philosophical views of Aristotle will be used as part of the theoretical framework. Since mental imagery is such an important part of the conceptual process, it is useful to understand Paivio's dual coding theory referring to the cognitive process of how the human mind separately codes verbal and visual information and can use the information individually or in combination. Within this theory, it is recognized that mental images are more likely to be evoked by pictures over concrete language and concrete language over abstract language [8].

Creating an abstract of a real-world system requires a representational code or symbol system. Salomon (1985) links the symbol systems of a particular media such as pictures, words, or graphs to the acquisition of knowledge[9]. The symbols and symbol structures used to develop the conceptual model are the means of capturing the knowledge of the external world. Therefore, to effectively transfer the knowledge intended from sender to receiver of the external world there must be a common internal understanding of the symbol systems used. The model in this case will only be an approximate representation to the level the symbol system can adequately realize the knowledge system[10]. To summarize the theoretical framework supporting this research into one sentence, mental images are a product of sensory information and thoughts coded cognitively either verbally or visually which require a common internally understood symbol system to transfer knowledge of the external world using a model.

Conceptual Modeling

Conceptual models have a purpose, creative process, and value within the modeling and simulation process. Firstly, their purpose is to provide an abstract representation of a real-world system which describes the characteristics to be encoded into a computer simulation model. Secondly, in the creation process, these characteristics will include identifying the important factors to the model to meet the established requirements, the interrelationships of these factors within the system, and how best to communicate clearly the design intent to the encoding function. Creation of conceptual models includes not only determining the objectives, inputs, outputs, and content, but also, identifying the assumptions and simplifications of the model[11]. In reviewing the literature on conceptual modeling, it is important to note the environment which the modeling and simulation process is being directed. Many of the foundational concepts are the same, but the context of the simulation environment being discussed has varying nuances. The three primary areas discussed in this research are models and simulations which are created (a) in lieu of what may have exclusively required physical testing or a physical prototype in the past; (b) in the informational environment consisting of completely software design for software application such as databases and user interfaces; and (c) in the virtual environment encompassing the abstraction of the real-world created with transfer of knowledge in individual training as the primary objective. Thirdly, the value of conceptual modeling can be seen in how it sets the strategic objectives for the simulation and provides a comprehensive map of the functional relationships needed to encode an effective simulation. Conceptual modeling performed well will make model coding more effective and will meet the objectives. However, performed poorly will lack accurate direction resulting in wasted time, effort, and resources with little tangible results.

Figure 1 shows the position and interrelationship of conceptual modeling within the modeling and simulation process. Conceptual models are the transforming link between the real-world system requirements and the computer simulation world. Conceptual models are also the initial vectoring of the final product where errors at this stage even if small will be magnified and may not show up until the final stages. Figure 1 presents modeling as an iterative process with adjustments to the conceptual model expected due to data obtained in subsequent processes. The conceptual model should be dynamic enough to be strengthened through feedback, but should not require too many iterations to obtain a high level of accuracy or else it may be a bad conceptual model. It is important to remember that each iteration equals time, effort, and resources expended.

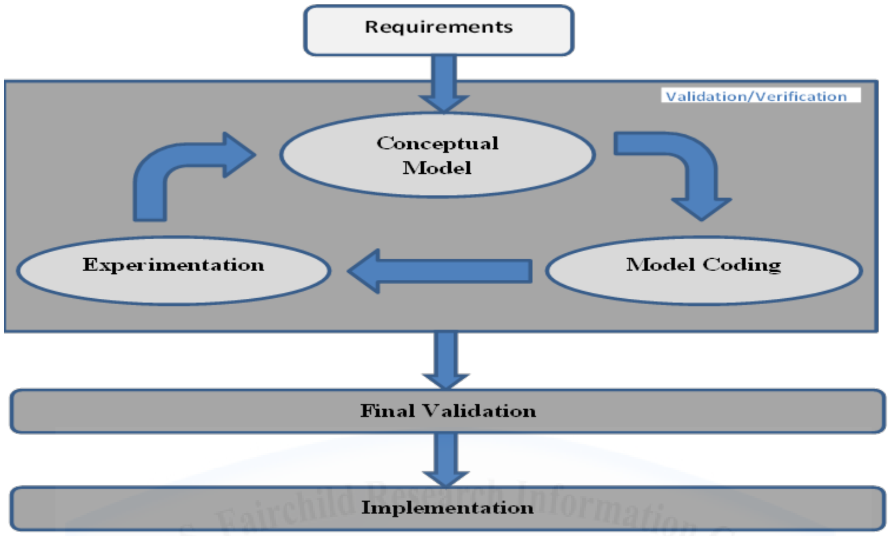


Figure 1 - Modeling and Simulation Process Flow

It is important to note in Figure 1 validation and verification takes place within the modeling process continuously between each of the functions i.e. conceptual model to model coding, model coding to experimentation, and experimentation to conceptual model. Robinson (2004) asserts diagrams which show validation and verification as a single step within the modeling process are misleading[12]. This form of validation and verification determines the accuracy of the model creation. The final validation determines the accuracy of the completed model in meeting the initial requirements of the real system to be simulated prior to implementation. DoDI 5000.61, DoD Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A) establishes policy that all models, simulations, and associated data used to support DoD processes, products, and decisions shall undergo verification and validation throughout their lifecycles[13]. The DoD defines validation as the process of determining the degree the model accurately represents the real world from the perspective of the intended use of the model and verification as the process of determining that the model accurately represents the conceptual specifications.[14]

Conceptual modeling as art

When discussing the importance of conceptual models, many authors will at some point concede the thought that conceptual models are more art than science. Examining this question of why more art than science may provide a better understanding of how to approach creating conceptual models, how to educate people in the art of conceptual modeling, and why it is the least understood portion of the modeling process. Viewing conceptual modeling as an art relates, at a minimum, to the fact there is not a scientific method or checklist to follow in the creating a conceptual model. In building an abstraction of a real-world system which contains a high level of variability, the success relies heavily on the modeler's experience and talent in discerning the important from the trivial, identifying the interrelationships of the important factors, and presenting in a form which allows for effective communication to a variety of users. Developing a conceptual model is a form of non-linear problem solving which requires the abilities in decision making such as intuition, mental simulations, spotting leverage points, recognizing patterns and anomalies, and understanding intent which is not a matter of intelligence, but a matter of experience[15].

Carl von Clausewitz, famous Prussian military theorists, viewed strategy in war as more art than science. Certainly, war has the high level of variability and complex interrelationships which lends itself to non-linear problem solving. In Clausewitz's conceptual model of war, he described effective strategy as if it were an object balanced between three magnets individually representing the people, the military, and the government[16]. This is a useful analogy in developing conceptual models. The developer of the conceptual model has to contemplate what entities are the magnets exerting influence in a real-world system, how strong of an influence does that entity exert, what is the equation of the force field in a sense of an entity which will take into account the influence of supporting categories, and what is the interrelated influence on the other magnets. Accuracy of the conceptual model will be dependent on the proper balance obtained and correct representation of the "magnets" or entities of influence of the real-world system.

In exploring the concept of art over science further, Otto Scharmer in *Theory U* presents a parallel to innovation and painting. To study the art of painting, one approach is to study paintings or the result while another is to study the mechanics of painting or the process. The next approach which Scharmer presents to be critical to innovation is studying the mindset of the artist as he stands in front of the blank canvas. Scharmer describes the challenge is in helping people access their sources of inspiration, intuition, and imagination[17]. All three attributes are essential to conceptual model creation. Scharmer provides a comprehensive study of how to obtain what he calls presencing and its importance to innovation. Further connecting the two, developing the abilities required in the art of creating conceptual models and innovation requires more than just studying results and process, but must include the study of the sources of innovation and what it means to think conceptually.

Mechanics of creating a conceptual model

It has been estimated fifty percent of the benefit of modeling and simulation comes from building the conceptual model alone[18]. This may be a generalized statement, but points to the importance of working through the process of building the conceptual model and the significance of what is revealed in the way of relevant characteristics, interrelationships, and easily communicated functioning of a system. A conceptual modeler may choose from three primary graphical tools which include (a) visual diagrams offering apparent resemblance to the object; (b) spatial diagrams using classical mechanical drawing techniques to indicate relationships; and (c) abstract diagrams similar to organizational charts or Unified Modeling Language (UML) which do not necessarily communicate real spatial relationship[19]. Each of these graphical tools is presented below in Figures 1 through 4 shown as they apply to a hypothetical example of an aircraft wing.

Within the mechanics of building conceptual models, the methods of simplification should be continually applied. Simplification is accomplished by removing or reducing components while at the same time having little effect on model accuracy[20]. This will allow for models with greater utility, faster run-times, and more efficient encoding efforts. The best models will be the ones which can accomplish the objectives in the simplest manner possible.

Conceptual Models in Use

The mechanics of building a conceptual model can best be examined through the use of a hypothetical situation. Imagine the real-world system of a military aircraft wing which is to be loaded with munitions. In designing the wing for a new production aircraft, it is determined a computer model needs to be created to simulate the functioning of the wing under load in relation to the structural stress experienced by the aircraft. This is in the environment described previously as simulation and modeling in lieu of what may have required exclusively physical testing or a physical prototype in the past. The conceptual model could be designed using any of the three graphical tools of visual, spatial, or abstract. To gain an understanding of the style of these tools, refer to the figures below. Figure 2 is a visual representation of an aircraft wing. Using this style, a modeler could add visual representations of the munitions to be loaded, attachment of the wing to the fuselage, and label with necessary information. The advantage in this style of detailed visual effects is in its ability to easily communicate the real-world system because it is less abstract than other methods.

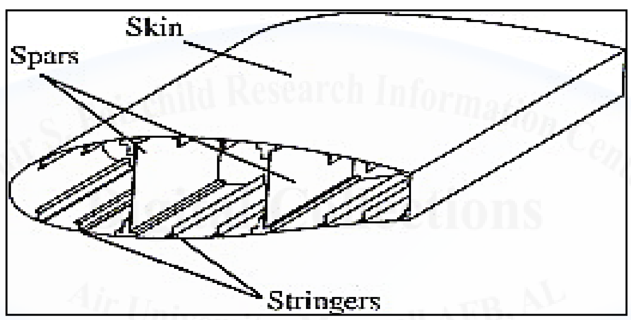


Figure 2. Visual diagram of an aircraft wing.[21]

The spatial diagram in figure 3 is effective in communicating directional force, relative positional relationships of objects in the system, and a holistic view of the system. In figure 4, an abstract diagram of an aircraft wing system is displayed with hierarchy, entity, and relational information, but in a more abstract form. This can be useful as it presents the conceptual model in a vocabulary closer to model coding allowing the use of linguistic labels for entities and relationships[22].

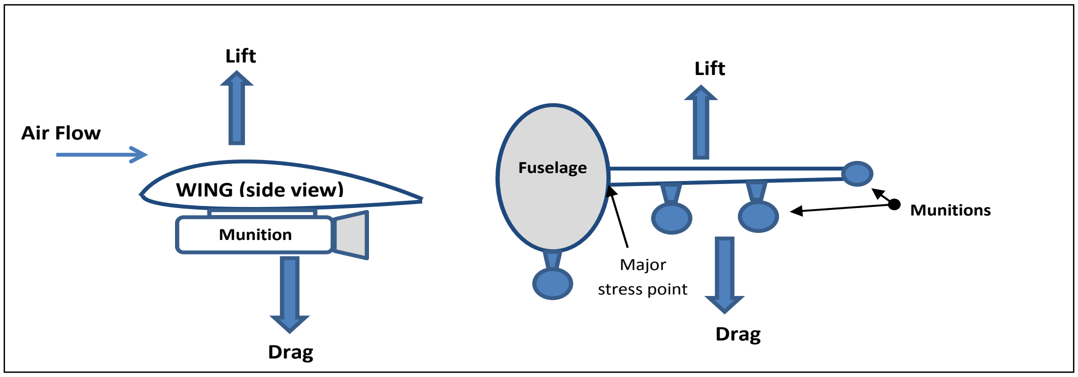


Figure 3 – Spatial diagram of an aircraft wing with munitions

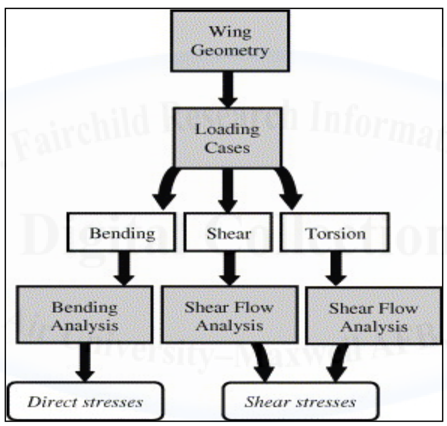
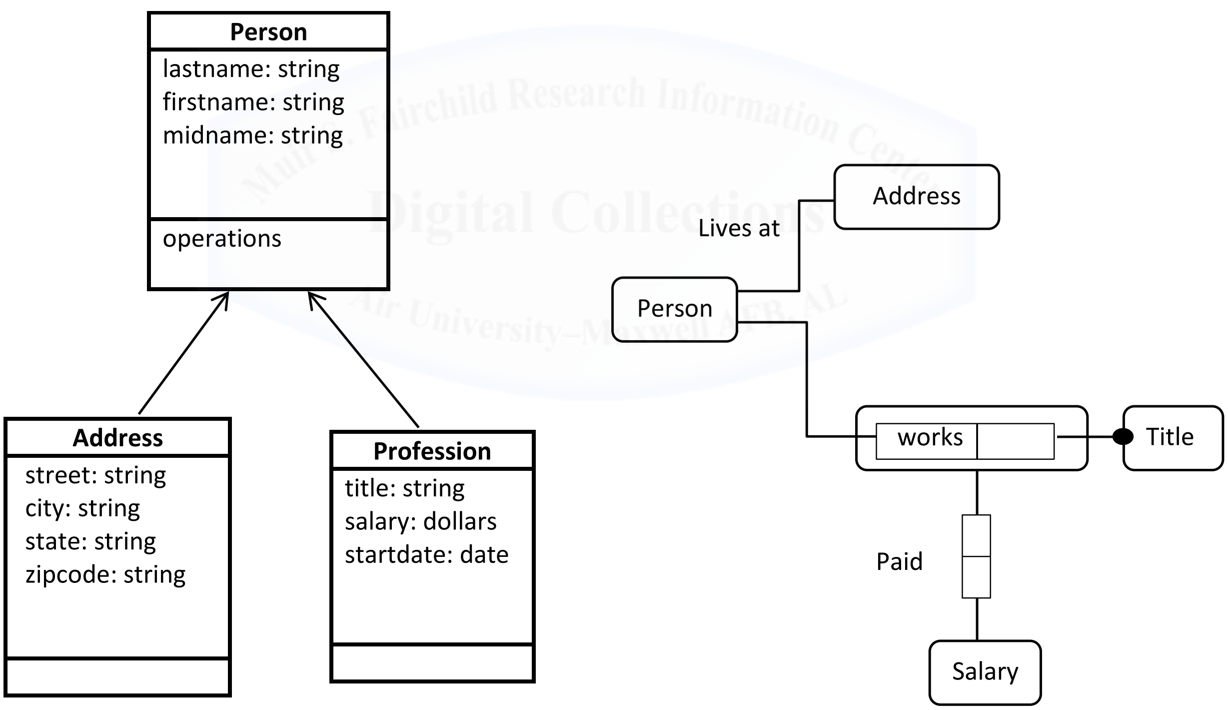


Figure 4 – Abstract diagram of an aircraft wing [23]

None of the examples above are complete in providing the full conceptual model to meet the requirements of the model and simulation objectives. The focus is on the different methods of graphical diagrams and possible strengths of each available to the conceptual modeler. Before moving from this example to examining informational and virtual environments, it is important to look at what is taking place from a macro level. The conceptual model is setting the constraints of the real system to be encoded into a computer model. If done correctly, the encoding should allow for a computer simulation which will make designing the new production aircraft wing better, cheaper, and faster than was achievable in the past through physical testing. Multiple “what-if” questions can be answered in a fraction of the time and cost. For example, what if the munitions loading stations on wing were one inch further apart? What would be the impact on the stress point where the wing and fuselage connect? What is the optimal distance to achieve the least amount of stress? What if a different metal alloy was used? How would the flight characteristics change? With a good computer model, these questions can be answered quickly and accurately. Otherwise, under a physical testing scenario, a test flight or wind tunnel test would need to be conducted for each scenario. One caveat, it is not to be implied that there will be a complete absence of physical testing or physical prototypes, but primarily for initial measurements which can then be simulated in testing multiple scenarios.

Concerns of simplification should be continually addressed during the process of the creating the conceptual model. This is especially important to computer simulations because each calculation leads to longer run-times and the need for more computing power. In this case, more is not better adhering to the law of diminishing returns. For example, adding equations to account for operating the wing in varying temperature conditions may be fully warranted due to its effect on the metal and the probability of experiencing a wide range of temperatures, but adding in an equation to account for the type of paint used on the wing may be unwarranted assuming the differences between types of paint is negligible in factors such as weight or temperature.

Conceptual models in the informational environment are well suited to abstract diagrams especially using the Unified Modeling Language (UML) and Object Role Model (ORM) techniques. In this informational world, conceptual modeling in focused on data, information, or knowledge in a certain universe of discourse (UoD) that will be encoded into a database or other software application. The design of the conceptual model will be based on the ontological approach of viewing the world as made of things (entity-type construct used in UML) or made of facts (fact-type construct used in ORM)[24]. In the entity-type construct, the system is represented in terms of the objects present, their attributes, the operations performed on the objects, and the relationships between objects[25]. In the fact-type construct, the system is represented in terms of the objects present and the roles each plays whether unary, binary, or longer with the attributes being derived from the role instead of a base construct[26]. Refer to figure 5 to compare UML and ORM formats.



UML Class diagram – Entity-Type relationship

ORM diagram – Fact-Type relationship

Figure 5 – UML and ORM style diagrams

When watching Olympic high diving, it is easy to see all diving is difficult, but the dives are differentiated by the judges in levels of degree of difficulty. Conceptual modeling is analogous in that all modeling has complexities, but when modeling in the virtual environment or artificial intelligence arena the degree of complexity rises. In conceptual modeling of a virtual environment (VE), additional elements such as the structural representation of the domain, virtual objects presentation, virtual objects behavior, navigation through the VE, factors influencing sense of immersion in the VE, and accessibility must be considered.[27] Some of the same concepts of entity-type relationships are useful, but applied in a more dynamic environment. An approach termed active conceptual modeling is vital to the artificial intelligence environments as it attempts to conceptualize such events as (a) learning through the perception of the five senses, (b) creating meaning from experience through direct and indirect involvement, (c) associating knowledge from past and differing perspectives, and (d) using episodic, one-time exposures and semantic, multi-exposures to a referent[28]. Modeling and simulations in the virtual and artificial intelligence environments build probably the best case for the importance of conceptual modeling as it would be extremely difficult to start computer modeling coding of such a complex environment without a conceptual map of the interrelationships and objective of the model. In other words, building a database without a conceptual design would take extra time, but would likely still work whereas trying the build a virtual environment without a conceptual design would take much longer and may never work correctly.

Importance and limitations

The value of conceptual modeling to the DoD is presented here from the perspective of the benefits the DoD receives as a whole from the modeling and simulations process as their benefits are mutually inclusive. The higher the quality of the conceptual model the higher the quality of the modeling and simulation which produces the benefits associated with a higher return on investment (ROI). In the modeling and simulation context, ROI is viewed in terms of such important aspects as improving performance, saving lives, cost avoidance, time savings, reliability, and quality assurance[29]. ROI for the DoD has some similarities to the traditional business use of the term, but the DoD does not deal with profit margins or tax implications. However, considerations unique to DoD of rapidly changing threat environments, weapons technology advancements, and risk of human life make the increased performance, ability to adapt quickly, and cost avoidance that modeling and simulation provides even more important. In addition to direct ROI, modeling and simulation provides a high level of decision support to the key decision makers. Modeling and simulation provides the anticipated behavior of a current or future system which gives decision makers insight to improve design, construction, training or operations.[30] This aids decision makers in choosing one project over another based on a reliable set of data of anticipated performance.

Modeling and simulations are not without limitations. The depth of knowledge of the phenomena being modeled sets the parameters for what can be accomplished.[31] The ability to re-use portions of models in multiple applications is desired for its monetary and time savings, but with many models being highly specialized and technologically complex, arbitrary plug-and-play approaches have been shown to be fatally flawed.[32] Trying to capture metrics for actual monetary savings is difficult to unrealistic within the DoD since it deals with categories such as lives saved, readiness improved, and better training.[33] The limits described above are natural to the modeling and simulation process and can be minimized by understanding they exist and viewed in context. Two additional limitations highlighted here which are not due to the nature of the modeling and simulation process itself, but are barriers due to lack of support for more widespread simulation based acquisition (SBA) within the DoD include inadequate allocation of resources to support SBA and the need for standardized education for modeling and simulation professionals.[34] It is always tough to make the argument that in order to save money, you must first spend money especially when as noted modeling and simulation can be difficult to monetize the benefits. Constrained resources limit the amount which can be invested in standardized education for the modeling and simulation professional. To overcome these barriers requires a strong belief in the long term benefits which will come from investments made in supporting simulation based acquisition. Experience over time and proven track records using SBA will help overcome these barriers as well.

Recommendations

Educating or training people in the art of conceptual modeling will present its own set of challenges to consider. This research suggests starting with understanding the purpose and role of conceptual modeling within the modeling and simulation process. This will include the larger scope of objectives, iterations, and validations. Then, explore the graphical tools used in the creation of conceptual models from visual to spatial to abstract. A student would need to gain an understanding early in the learning process of how the environment of the conceptual modeling effort drastically influences the approach, discussion, and literature available on the topic. All conceptual models are an abstract representation, but is it an abstract of a physical, purely informational, or virtual world? Throughout the learning process, a common theme of why conceptual modeling is more art than science would be useful. For students, connections should be made between the ways of studying conceptual modeling from the perspectives of results, process, and sources of innovation and how it relates to experience, intuition, non-linear problem solving, and pattern recognition capabilities.

Further research

This research describes the fundamental concepts of the purpose, creation, and value of conceptual models, but primarily sets the stage for higher level research. Diving deeper into answering the question of what does it mean to think conceptually in relation to the cognitive processes would provide greater insight in how to educate people in the art of conceptual modeling. Measurement instruments have been developed to measure whether a person in more naturally adept at thinking using visual, auditory, or kinesthetic information, but are there people more naturally adept at thinking conceptually? For those who showed greater conceptually thinking ability, does being a visual, auditory, or kinesthetic learner correlate to this in any statistically significant manner? Does field dependency influence conceptual thinking in any way? Finally, understanding the complexity of conceptual thinking is expected to be the subject of many studies as the search for creating more sophisticated artificial intelligence evolves.

Conclusion

The intent of this research was to investigate what is meant by the term conceptual modeling and what value does it provide. In answering these questions, the approach was continually in the perspective of what someone new to the field would need to fundamentally understand and further develop the ability to envision potential applications. Creating conceptual models is a basic path of taking a real-world system, developing mental imagery, translating to a conceptualized image using graphical tools, and ensuring the conceptualized image will allow for coding which meets the initial requirement of the overall simulation and modeling effort. Well defined requirements of the project is an absolute, but was viewed in many respects as an assumption in this research to be able to move forward to the main task of creating conceptual models. The philosophical approach selected was of the Aristotelian view of the importance of sensory information and thought to the creation of mental images. The theories related to dual coding and symbol systems support the understanding of how mental imagery forms on the cognitive level which links to the translation to a conceptual model. The prominent graphical tools used to capture the conceptual model as discussed were the visual, spatial, and abstract. Each tool can be used independently or in conjunction to best fit the environment or level of detail necessary for model coding. The reader was cautioned that when studying conceptual modeling to focus on the context of the environment of the discussion to distinguish between the physical, informational, or virtual environment. Each of these environments makes a slightly unique use of the tools and terminology. As more art than science becoming proficient at conceptual modeling will require experience and a measure of creativity, but educating those new to the process in the fundamentals will set them on the right course to being able to use conceptual models for better simulation and modeling results.

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[3] Pace,"Ideas About Simulation Conceptual Model Development," 329.

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[8] Ibid., 59.
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[10] Newell, “Precis of Unified Theories of Cognition,” 1236.
[11] Robinson, *Simulation the Practice of Model Development and Use,* 65.
[12] Ibid., 55.
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[14] Ibid., 10.
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