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The Ability of Engineers to Extract Requirements from Models

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***Abstract*—The Department of Defense is adopting model-based systems engineering in which models will replace the extensive amounts of documentation generated in developing a new system. This research examines how this shift from textual description of requirements to a model-based description will effect the requirements engineering process. Specifically, we ask whether engineers will be able to extract the same understanding of the system requirements from the models as they can from the traditional textual requirements specifications. This paper describes the theory and related work on the understandability of models and the performance of cognitive tasks such as requirements engineering. Our research into model representation is part of a larger effort on a theory of model relativity postulating that models affect how we think about the system of interest. In this paper, we present our exploratory research studies, discuss our research protocol, describe the research plan, and present the current status of our study.**

I. Introduction

In a typical acquisition program for a new major system (e.g., weapon, ship, aircraft, etc.), the Department of Defense (DoD) specifies the operational architecture and the functional requirements for the system. The operational architecture includes: (i) the concept of operations, (ii) the mission threads, and (iii) a description of how the system will complete its mission in terms of operational activities. The program creates the operational requirements documents from these sources. The program will complete a system requirements review involving most all the stakeholders to verify the requirements are correct and complete, and to validate that the requirements capture the operational need of the sponsor.

The requirements engineering process is notoriously document intensive since all the requirements are written down in a traditional textual format with lengthy descriptions of each component and subcomponents of the operational architecture. These textual-based materials are lengthy and burdensome to read, they may also not be the preferred way for individuals to acquire information [1]. With this in mind, the DoD acquisition community is moving to a model-based systems engineering (MBSE) or sometimes referred to as digital engineering process in which all program data is captured in computer-readable models [2]. In the MBSE paradigm, the information is represented and conveyed through models, and the engineers and other stakeholders interact with the program data via models to support all the activities for specifying, analyzing, designing, and verifying systems. The models will populate important acquisition deliverables including the many requirements documents such as the initial capabilities document, capabilities development document, system specification document and others. Multiple modeling languages can be used to create these models, including the Systems Modeling Language (SysML), Unified Modeling Language (UML), Integrated Definition Methods (IDEF), and Business Process Model and Notation (BPMN). All of these languages can be used to create DoD Architectural Framework (DoDAF) views [3].

The anticipated benefits of MBSE are improvements in communications, quality through early identification of requirements issues, improvements in specification of allocated requirements, better traceability, reduced program risk, increased productivity, better impact analysis of requirements changes, early and ongoing requirements validation and design verification. Studies reveal these benefits in the quality of the process outputs. For example, Saunders [4] reports significant reductions in specification defects after adopting MBSE.

Engineers have always used models. What differentiates MBSE is the use of conceptual and descriptive models to represent what has traditionally been documented in traditional textual format. Systems engineering models represent requirements, activities, and states of the problem space, as well as the functions, behavior, and structure of the system. Unlike the majority of engineering models, these models are not based on the underlying physics thus we refer to them as conceptual models. Requirements models are conceptual models because they do not correspond to actual physical components or phenomena.

The shift from a document intensive process to a MBSE process is exposing many unaddressed issues in the acquisition community. One of these issues is whether the models capture all the required program data. Another issue is whether the various members of the project team (program manager, system engineer, specialty engineer, logistician, test engineer, etc.) can correctly and reliably understand and interpret the models. Some studies have addressed the adequacy of the models and identified data that must be supplemented to the models in order to satisfy current acquisition processes

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[5]. The proponents of MBSE assume the answer is yes to the second issue of whether engineers correctly understand and interpret the models. Beyond basic comprehension of the model, it is also of interest to the present study to investigate how a model-based versus traditional textual representation of information might alter the perception and reasoning of the information, and therefore decisions relevant to the acquisition program's objectives.

This research proposes a theory called Model Relativism Theory claiming that modeling languages shape how engineers reason about the system being modeled. The theory is motivated by linguistic relativity, popularly known as Sapir-Whorf's theory, that human language affects how people think [6]. Models are created using a modeling language, and it is through the models that engineers communicate about a system. Studies on linguistic relativity support a weak version of Sapir-Whorfs theory (i.e., language influences though as opposed to determining thought [7]). Additionally, the way information is presented (e.g., in a model vs textually based) conveys different inferences that then can lead to a construction of different mental models, which are argued to be the foundation for reasoning [8]. Looking at systems engineering as a cognitive process, it is plausible that information presented using different modeling languages would influence thought processes. The experiments proposed by this research project will be the first set of evidence about cognition with respect to models in systems engineering. Consequently, the results are of value to the larger systems engineering community and industry, which is also adopting a model-centric approach. Lastly, the research may be of interest to cognitive scientists and linguistics as yet more evidence of language relativity being demonstrated in a more limited domain of discourse.

We are conducting a series of studies to investigate the relationship of MBSE and human cognition in general, and more specifically how MBSE effects the systems engineering activities in the DoD acquisition process. The paper first presents background information on MBSE and linguistic relativity theory, which motivates the research. The paper then presents the research model including the independent and dependent variables. The paper next describes the research plan for three separate experiments each addressing a separate research question. The paper then briefly reviews related work, and concludes by summarizing our work to date and future work.

II. Background

This section presents the background on requirements engineering, MBSE, the System Modeling Language (SysML), and linguistic relativity theory.

A. Requirements Engineering Process in Systems Engineering

In a typical SE process, stakeholder and system capability requirements are captured, then translated into system, subsystem and component performance requirements. The person(s) responsible for capturing these requirements iteratively goes through tasks such as discovering, qualifying, communicating, organizing layers of abstraction between requirements in order to trace requirement relationships in order to define the problem domain and the solution domain [6]. These requirements are the "measuring stick" to identify and decide upon hardware, software and people configurations to bring the system to life. This is done through an iterative and recursive design/build/test/integrate cycle. Any representation of these requirements, either textual or visual, must enable the completion of these tasks.

From a human factors standpoint, the individuals responsible for the requirements engineering perform very specific information processing and decision making tasks. These include, but are not limited to, analyzing design goals, determining design parameters, analyzing functional behaviors [7].

B. MBSE and SysML

MBSE is the formalized application of modeling to support systems design and analysis throughout all phases of the system lifecycle. The models must be in computer readable format in order to be useful to the program. Typically, this means the models are views on top of an underlying database containing all the program data. The success of MBSE rests on the modeling processes, modeling languages, modeling tools, and presentation framework. The modeling language is only one of the four components, but an important one. The emerging standard seems to be the Systems Modeling Language (SysML). SysML was derived from the Unified Modeling Language (UML) in software engineering, and SysML reuses seven of the fourteen UML diagrams plus two new ones to address specific needs of the systems engineering community.

C. Cognition and Visual Formats

Comprehension of information depends on factors such as experience, relevant knowledge, and expectations. A mental model is then constructed based on the information presented and the inferences drawn from other factors, such as implicit information conveyed through how it is presented.. Replacing text with a visual representation of the same information must be able to convey the same information as textual presentation, however, visual representations will carry with it implicit information (e.g., spatial properties). Information displayed in visual formats can aid decision making and performance by conveying a more complete representation when constructing a mental model [8]. Whether visual formats aid cognition depends on whether the graphics help the user search the data structure, recognize relevant information, and for draw inferences [9]. If information is difficult to extract from the graphics, it becomes more burdensome to an individuals working memory capacity and can then be a hindrance to cognition. As stated by North [10], engineers must decode the information presented in the models in order to achieve simple insights like finding and summarizing information, as well as complex insights such as finding patterns, making comparisons, identifying outliers and anomalies. Kim et al.

[11] studied how subjects integrate information from multiple diagrams and found better integration of contextual and perceptual information, and therefore better comprehension of the system when visual cues were in the diagrams to facilitate integration of the multiple views, which is relevant to modelling languages that use multiple diagrams. It appears for simple tasks visual and textual formats lead to equivalent performance; it is only for complex tasks when visual formats lead to superior performance [6]

The business process modeling literature has examined the understandability of business process models, which are just one type of requirements model (see [12] [13]). This stream of research has mainly presented the subjects with business process models followed by questions about the understanding of the model, and as such, they have mostly tested perceptual processes. Gemino and Wand [14] present a framework to identify relevant factors for the empirical evaluation of conceptual modeling techniques, and show how to also include measures of effectiveness to address the analytical processes.

Moreover, the type of visual presentation of the information needs to be suitable for the task, which the researchers call cognitive fit [15]. Cognitive fit is when the cognitive processes to perform a task match the external representation of the problem. Various studies have confirmed cognitive fit leads to impoved performance by comparing tables versus graphs [16], object-oriented methods versus process-oriented methods [17].

Related to our comparison of model types is the work comparing process versus object-oriented tools, which found partial support for the cognitive fit theory [18]. Other similar research has investigated the interpretation of different diagram types [19], [20]. However, the majority of these studies used novice subjects, often undergraduates.

A related stream of research examines what makes a good conceptual model and has led to many researchers specifying quality metrics for conceptual models. While some of the proposed quality metrics are grounded in semiotic theory [21] or process modeling [22], many are better described as a collection of well-argued list of attributes one would want in a modeling language [23] [24].

The understanding of MBSE and how it affects comprehension and reasoning should be guided by theories with explanatory power of the cognitive processes. We propose a theory to allow us to investigate modeling and model understanding from a cognitive perspective, not yet discussed in the MBSE literature, thereby allowing for the possibility of extending our knowledge in this area.

The theories of how language influences cognition has not been explored in the realm of modeling and requirements engineering and may prove to be a rich area for furthering our knowledge of human cognition and the requirements engineering process.

D. Linguistic Relativity Theory

A long history of research has sought to better understand the connection between human cognition and language. One theory called linguistic relativity observes the diversity of human languages and claims a persons language influences how they think about phenomenon, and therefore how they perceive the world [25]. The theory is now associated with Sapir and Whorf who were early proponents of the idea (see [6]). The strong idea that language determines thought has mostly been dismissed by the research community, while the weaker version of how language may limit thought and influence thinking has gained wide acceptance substantiated with empirical data and results [26]. Evidence now supports that language affects how people think about spatial arrangements, time events, and it seems also how we think about physical objects ([7] [27]). The aforementioned research examined differences between languages. In addition research suggests the way we describe a phenomenon also shapes the way we think [28]. This later observation may be more relevant to our investigation into modeling languages because all our subjects will speak English and the differentiating factor will be the modeling language, which is a second and auxiliary domain-specific language to the person.

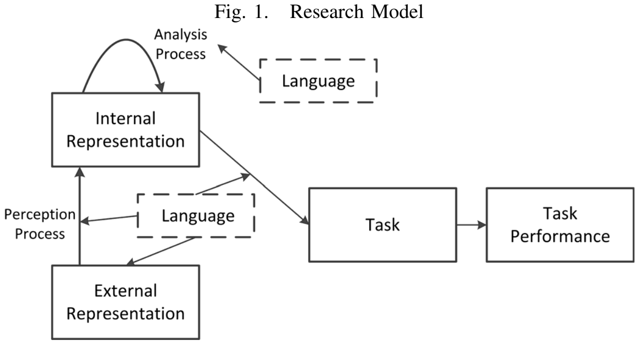
Many of the concepts surrounding linguistics apply equally to modeling languages since in both cases a person uses the language to make and communicate statements about a phenomenon of interest. While researchers in modeling languages have for the most part not investigated language relativity theory, many engineering research streams do suggest the idea of modeling languages influencing how we think about systems. The Soft Systems Methodology uses the term *Weltanschuuang* to describe a worldview influencing how engineers define the problem and develop a system solution [29]. Bucciarelli [30] and Ferguson [31] both make a strong case that engineers think nonverbally as evidenced by the use of drawings ranging from sketches to more formal blueprints and these authors then discuss how drawings shape our thinking about systems. Dori [32] developed the object-process methodology for modeling systems based on an assumption that humans need to simultaneously process images and words to convert data into understanding and knowledge about the system. His emphasis is on a modeling approach that acknowledges and accommodates human cognitive limits. Giachetti [33] conducted a concordance analysis of DoDAFs underlying language with respect to systems engineering manuals and found many instances of poor support by DoDAF for some systems engineering activities and suggested it might cause problems in completing the activity. So while the concept has been out there, nobody has conducted research to examine the link between modeling and engineering thought.

In summary, language relativity has been tested extensively and evidence strongly suggests language does influence how people think. In the domain of modeling languages very little research efforts have investigated the relationship between modeling and human cognition.

III. Research Model

This section describes the research model in terms of the independent and dependent variables and the hypothesized relationships between them. Figure III shows the structure of the research model. Problem solving involves perceiving external representations to extract information and converting it to an internal representation upon which production processes are used [34]. The external representation is the how the information is encoded and can be textual requirement documents or requirement models. The internal representation is how the information and knowledge is encoded in our brains. System engineers document the requirements in some external representation and the engineers and other stakeholders use the requirement documents to complete tasks requiring information input. Tasks requiring information input involve a perception process to understand the information and an analysis process to reason, make inferences, and make decisions to complete the task [9]. The perception process connects the external and internal representations. People perform the analysis process or reasoning based on mental models constructed from the information presented as well as relevant prior knowledge and expectations [35]. A mental model is an iconic representation corresponding to actual objects and relationships in the world upon which supporting our explanation, deduction, and induction. Perception of reality varies among individuals, and is shaped in part by language among other factors. Our interest is in how modelling languages might shape our perception of the information presented, which will affect reasoning processes.

Fig. 1. Research Model



The primary factor for the external representation is expressiveness. We define the expressiveness of a language according to the breadth of ideas the language can represent and communicate about the system. The expressiveness of a modeling language is its ability to generate scripts that capture information about a modeled domain. Expressiveness is related to the number of constructs in a language. Consequently, natural language has many more available constructs, i.e., words to express a concept than a graphical modeling language such as SysML.

In addition to factors related to the external representation of the information, personal factors concerning the knowledge and experience of the person influences the ability of a person to perceive a model and do the analysis to complete a task [12]. Domain knowledge and process knowledge are likely two personal factors affecting the performance of tasks. We are not interested in these effects and in all experiments the subjects will be drawn from similar backgrounds and experience to eliminate both domain and process knowledge as factors.

Task performance depends on both perceptual processes and analysis processes. Perception indicates the subject is able to understand the information. Aranda et al. [36] proposes the correctness or accuracy of the understanding, the time required to answer questions about the information, and the perceived difficulty of understanding the information. The latter is a subjective measure of understanding. These three measures are dependent variables of task performance in the model: accuracy, task time, and perceived difficulty. To test for understanding we will follow Mayer [37] who argues the application of knowledge in a meaningful way is a better indication of understanding and learning than questions focused primarily on recall.

Other research has found task complexity to be important because they only observe differences in performance between external representations when the task complexity is high. For this reason we will define complex tasks requiring more than information retrieval so that if there is a difference in performance, then it is more likely to be evident.

The hypothesis is:

Hypothesis: The modeling language effects a person's perception and analysis, and ultimately how they think about a system.

A modeling language is unlike natural language because it is intentionally developed for narrow, specific goals and it carries the perspective of its developers. Experienced users of the model adopt and become proficient in the modeling language, which we hypothesize influences how they perceive and analyze the model data.

From the hypothesis we identify four research questions:

RQ1: Can engineers extract the system requirements from the models?

RQ2: Does MBSE increase the accuracy and efficiency of system engineering activities?

RQ3: Are some models and/or modeling languages better at supporting certain tasks than others?

RQ4: Do users of one modeling language exhibit differences in understanding and modeling of a system compared to users of another modeling language?

The first three research questions do not directly address the model language relativity theory we propose. They address task performance differences between documenting requirements in text versus models. The last research question directly addresses the model relativity theory and focuses on how the subjects think about the system based on the modeling language they use.

We did a pilot study for RQ1 in which eight subjects were presented with an activity diagram for a system and asked to write down the set of equivalent requirement statements for the functional requirements. The subjects were also asked what requirements, if any, the model did not show but which they thought the system should have. All the subjects are practicing system engineers in the DoD acquisition workforce and are part way through a graduate program that includes modeling. The results were that most subjects were able to accurately extract most all of the requirements. The lessons learned from this pilot study will inform our experimental design. RQ2 will be investigated by comparing textual versus model documentation of a system. RQ3 will be investigated by comparing two different modeling languages.

IV. Research Plan

The research plan calls for different experiments addressing each of the research questions. We will control for several factors across all experiments. First, we will ensure the information equivalence between the modeling and/or language representations being compared. Two representations are informationally equivalence "if all of the information in one is also inferable from the other and vice versa." [9] p67. Second, we will select subjects with similar domain and process knowledge to eliminate these factors as causes for any observed effects. We want to eliminate these factors because the literature indicates they are factors in task performance. Third, we will design the tasks so they are moderate and higher complexity because the literature shows subjects can often perform well on simple tasks regardless of the external representation.

A. Experiments on Extracting Requirements from Models

We are in the process of conducting an experiment to test subjects' understanding of the system requirements documented in a set of SysML models. We have developed use case diagrams, activity diagrams, and block diagrams of a tactical sling for which we have the requirements documentation. The tactical sling is a relatively simple piece of equipment that the majority of our subject population will be familiar with. The pilot study is asking the subjects to document the requirements in the traditional textual manner based on their understanding of the models. Additionally, each subject will respond to a series of questions about their understanding of the models, the perceived usefulness of the models, and the usability of models [38]. The subjects will then be asked to consider how a requirements change affects the set of requirements. Specifically, the specification is for the Army's needs and the Marine Corp has additional needs that will be introduced. The pilot study will help us evaluate the operationalization of the measures in our questions, the feasibility of the study design, and further development of the research protocol for the full-scale experiments.

B. Experiments on Requirements Understanding between Models and Documents

We are planning a series of experiments with experienced engineers in the acquisition workforce to test RQ2. The subjects will be engineers drawn from the DoD acquisition community. They are enrolled in a graduate systems engineering program and typically have about five years of work experience beyond their undergraduate degree. The experiments will have a control group and an experimental group. The control group will be presented with the standard requirements documentation now used in the acquisition process. The experimental group will be presented with the modeling equivalent, which we anticipate to be approximately five different SysML models including use cases, activity diagrams, internal block diagrams, state transition diagrams, and requirements diagrams.

The scenarios will be to present each subject with either the documentation (for control group) or models (for the experimental group) of a system. The subjects will be asked comprehension questions about the model to test their perception. The subjects will be asked to address a requirements change and determine how the requirements documentation or models much be revised to accommodate the requirements change. As an example, we are working on a scenario of a military ground vehicle. The requirements change will be to add functional redundancy of the navigation function through an inertia navigation system. The tasks we will ask the subjects to perform are of moderate task complexity because they go beyond simple recall and trivial task completion. Consequently, the task requires analysis using the models beyond simple perception. We are designing the scenarios and requirements change so there is a correct solution to each task. To define the correct solution, we will have three subject matter experts review each scenario for correctness of the documentation, models, and the agreement between the documentation and models. It is important they are equivalent. The subject matter experts will also identify the correct solution.

The dependent variables are perception time, analysis time, and accuracy. Perception time is a measure of how long for a subject to understand the model. Analysis time is how long for the subject to complete the task. Accuracy of perception will be measured by the subject answering a series of questions about the system. Accuracy of the task will be measured by how far the subject's response is from the correct solution.

To support generalizability of the findings we plan to have more than one scenario. We estimate we need between 100 and 150 participants to have sufficient statistical power according to GPower 3.0. The results will be analyzed using appropriate statistical models, likely ANOVA.

C. Experiments on Model Relativity

The previous examples focused on the comprehension of requirements from models vice textual documentation. The results of the experiments will inform us whether engineers can understand and derive the same set of requirements when using models. However, the experiments do not test the central tenet of model relativity theory that says the modeling language affects how engineers think about the system. Psychologists have long considered the language relativity theory essentially untestable until recently. We examined the linguistic relativity theory research and learned the successful experiments identify aspects of a language with stark differences and then test of speakers of those languages think differently about the phenomenon. The studies included gender, direction, colors, and time as some language aspects that differ considerably between languages. We will adopt this general approach and are identifying differences among various modeling languages. Two areas of significant differences are emerging. The first is how the systems engineering community in Department of Defense distinguishes between operational activities and functions. Other industries do not make the same distinction and instead use function modeling for both operational activities and functions. We also identified how the lifecycle modeling language (LML) uses the term Action to define capabilities, functions, events, and operational activities. We see this as another opportunity to see if modelers of LML think about capabilities differently, such as not including or deemphasizing non-functional capabilities? To test this aspect of the theory we plan to conduct experiments in which we model a system using two different modeling languages and ask the subjects questions to try to reveal how they think about the system.

V. Conclusion

This paper presents our research plans for a broad investigation into how the adoption of MBSE will effect the requirements engineering process in the DoD acquisition process. The paper describes our theory called model relativity theory suggesting the models effect human cognition. The theory is motivated by findings in natural language and cognition. We presented our plans for three experiments to investigate whether engineers can extract requirements from models, whether MBSE increases the accuracy and efficiency of the requirements engineering process, and whether some models are better suited than others for requirements engineering tasks. The results of our research will inform the implementation of MBSE and also contribute to the literature a greater understanding of modeling and human cognition.

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