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Attached is my completed paper submission. This was originally written as an independent study paper for credit towards a Master's degree in Modeling & Simulation at Old Dominion University, Norfolk, VA.

FIDELITY VERSUS COST
AND ITS EFFECT ON MODELING & SIMULATION

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Abstract:

Fidelity and cost are intertwined in any model or simulation but how does one affect the other? As with most simulations, human factors are present from development through acquisition to the end users perception of the simulation fidelity. This paper begins to examine the relationship between cost and fidelity and how the human perception affects the two. In addition to fidelity and the cost thereof, the author begins the exploration of the concept of a theoretical 100% fidelity and its relationship to the perceived fidelity of the end user.

Introduction:

In both the private sector and government organizations, pressure is continuously applied to the work force to produce “better, faster, and cheaper.” “Cheaper,” or more professionally stated as reduction of expenditures, is my focus and its effect of the end product and its customers, or users.

The Modeling & Simulation world is not immune to rising costs and reduced budgets. Included in the applications of Models and Simulations are training, analysis, experimentation, and acquisition. Each of these applications can be adversely affected by poor fidelity. In some cases, cost may be either the culprit or contribute to the problem. Questions we must answer are: “Is the resultant simulation ‘good enough’ to meet the end user’s/customer’s need?” Assuming that the simulation is “good enough,” the following need to be considered: “Is the customer satisfied with the simulation?” “Even if the simulation is accurate but some features are missing, will the end user trust the simulation?”

Another area of concern is safety. The fidelity of an aircraft simulator comes to mind. If the fidelity is poor, will the pilot, air crew, and their families suffer due to poor training? We may be forced to reduce fidelity in order to save money or meet a budget. In some cases the trade-off is insignificant, while in others the result cannot be conveyed in currency.

Take for instance the following comparison:

The fidelity of a model or simulation can affect the intended end user’s understanding of the real world entity being simulated. In turn, this understanding can affect the end user’s performance when taking the controls of the real world entity for which he/she were training. Consequences of poor fidelity can range from insignificant to catastrophic. Using the example between an ejection seat simulator and an aircraft simulator can help to display the difference. From experience, an ejection seat simulator teaches the trainee the ejection procedure which is the same for nearly all ejection seat aircraft. Differences do exist between ejection seats; however, one trainer can be used for nearly all types of ejection seats. Next, let’s consider the case of an aircraft simulator. A similar scenario as the one above can be considered, this time referencing the internal turbine temperature of a turbo-prop engine. Once airborne, if the indications are not the same as the flight simulator, the pilot cannot simply stop the aircraft and exit as in an automobile. The pilot is faced with a potential life threatening situation for themselves and their crew. While both scenarios face safety risks, the latter has the potential for a more catastrophic outcome.

This paper will explore the sacrifices in fidelity of simulations due to cost restrictions and their potential impact upon the end user.

Fidelity:

Numerous definitions abound for the term Fidelity. The American Heritage® Dictionary of the English Language: Fourth Edition, 2000, lists as a definition of fidelity as **2.** *"Exact correspondence with fact or with a given quality, condition, or event; accuracy" [9]*. This is a very generic definition of fidelity, but it does correspond to the various definitions offered by the M&S community [1] [3] [4] [6]. In his 1980 concept paper [12], Hays compiled an extensive list of fidelity definitions and compared their differences and overlaps in order to help him define training requirements of fidelity for the US Army. Fidelity, as defined by the Simulation Interoperability Workshop (SIW) Integration Study Group (ISG), is "The degree to which a model or simulation reproduces the state and behavior of a real world object or the perception of a real world object, feature, condition, or chosen standard in a measurable or perceivable manner." [1] Fidelity is also considered to be an absolute measure of M&S representational closeness to reality as compared to validity, which is considered to be a judgment. [1]

In addition to the numerous definitions of fidelity, dissecting different types of fidelity exist as well. The UK Royal Navy [7] [10] dissects fidelity into the 3 categories:

1. Physical – Spatial, tactile, and appearance
2. Functional – Format, content, and response
3. Environmental - Sound, motion, and ambience

Pongracic, Marlow, and Triggs dissect fidelity into numerous categories: physical (visual, auditory, sensory, and motion), functional, psychological, content, motivational, workload, selective, dynamic, database, and temporal. [3] As with the definition(s) of fidelity, multiple viewpoints as to the dissection and classification of the various types of fidelity exist further complicating how to measure fidelity, and how to accurately determine the cost of fidelity.

The following quote has a great deal of insight:

"all models are wrong, but some models are useful" [8]

With the above quote in mind, we can deduce that a perfect simulation is impossible to achieve, therefore measuring fidelity is essential as a metric in determining the usefulness of a model or simulation. A multitude of methods to measure fidelity exist; some are quantitative while others are qualitative.

Qualitative descriptions are inevitable to human nature and unavoidable. In fact, they do have usefulness because perception to the target audience is reality unless proven otherwise. And then, human nature may still not be convinced. Qualitative descriptions include: high, medium, and low. What do these terms really mean? Below is a diagram developed by Hays [12] to help define these terms with the intention of determining the best combination of fidelity for a given task. See figure 1:

		Physical fidelity		
		Low (control absent)	Medium (drawing)	High (3-D)
Functional fidelity	Low (doesn't work mechanically)			
	Medium (works with no effect)			
	High (works with effect)			

Figure 1: Hays Sample Design for a pilot study to determine the "best" combination of fidelity levels for a given task. [12]

These qualitative measures may mean different thing to different end users, thus they are primarily human perceptions. Another aspect to human behavior to consider is the physical effects on the human body. Undesirable effects include simulator sickness and unreal physiological sensoring. These effects can also have yet another influence on the user's perception of fidelity [3]. Because the human factor is part of the equation, randomly chosen individuals will most likely exhibit differing perceptions as to the degree of fidelity. This significantly complicates any metrics which may be used to determine a degree of fidelity.

Quantitative descriptions and metrics are normally ignored because they are difficult to determine. Difficult questions to resolve include: What is most important to the simulation? Do all aspects need to be of equal fidelity? Will less fidelity in some areas affect the end user's perception of the simulation? For example, over the past 30 years Computer Generated Imaging has improved to the point that flight simulators can have the capability to create images that are nearly real world [5]. Is this necessary to all simulators and is the increased cost associated with these enhanced images worth the increased expense? All are difficult to answer without extensive studies and data collection.

Exacerbating the issue of fidelity versus costs emanate from the perception of the end users being translated to those in charge of purchasing the simulations. The end users have a natural tendency to seek a very high level of fidelity and may tend to over-specify their fidelity requirements. Buyers may not fully understand the needs of the end user, thus leading to inadequate specifications. This will then compound the problem for the supplier who may be receiving poorly defined fidelity requirements [4].

While we are not focusing upon all these questions in this paper, actions taken in response to these questions when creating a simulation can affect the cost of the simulation, thus a relationship between cost and fidelity is real.

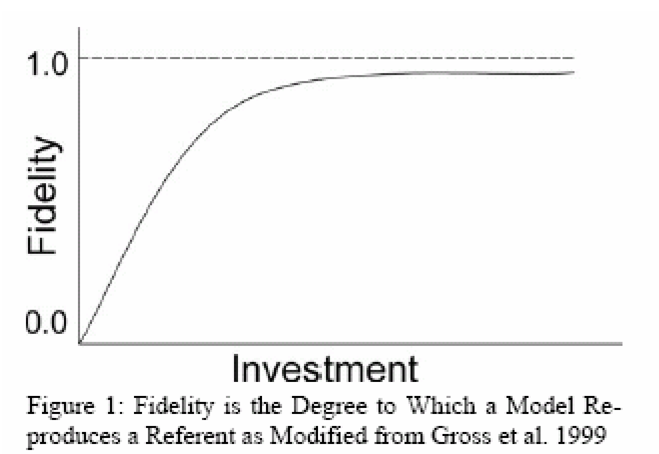
Cost:

When discussing cost, one normally thinks of a monetary value. Cost can also come in the form of human life especially when the model and simulation affects the safety aspects of the simuland. Especially in the training environment, cost of simulation is generally viewed as a factor in the total cost of training. More time spent training in simulators in the aviation environment normally means reduced time needed in the actual aircraft. While there is a cost associated with maintenance, upkeep, and upgrading a simulator, the reduction in fuel costs, maintenance and upkeep of the actual aircraft can potentially be greatly reduced, thus making the flight simulator a cost-effective tool for training.

It is generally accepted that an increase is fidelity will result in an increase in cost and, in fact, and exponential relationship as the fidelity approaches reality. [1] [4] [5] [11] [12] [13] [14] While publications and papers state the previous statement as fact, very few address the actual monetary data to support this statement. Collecting data on costs has proved very difficult. Some of the difficulties arise from proprietary information, financial disclosure, and competitive advantage. For this reason, costs in this paper are described in a somewhat abstract and possibly ambiguous manner. While considering the degree to which fidelity is “good enough” for the end user, the modeling and simulation team must consider the cost of this increased fidelity and the risk associated with the end user with a reduction in the degree of fidelity [2].

Much of the cost of state-of-the-art flight simulators are driven by capabilities such as the fidelity of the graphics, the availability of motion-sensors, networking options as well as other features available [2]. This prevents most organizations, including flight schools, other than government organizations from purchasing high fidelity simulators[2].

A graphical representation of the fidelity versus cost dilemma is seen in figure 2:



[2]

Figure 2: [2]

Most likely one can expect diminishing returns at some point in the model and/or simulation development. Deciding where this point exists is determined by the modeler and/or the M&S team.

Case Studies:

Landing Craft Air Cushioned:

A Landing Craft Air Cushioned (LCAC) vehicle simulator in San Diego cost the Navy $29 million. Mike Coligny, chief executive officer of Flyit Simulators in San Diego felt that 70% of the $29 million simulator could be provided for approximately $200,000 [2]. Hypothetically, let us assume the $29 million simulator realized 95% fidelity. The alternative simulator would have represented 66.5% fidelity. Thus the additional 28.5% cost $28.8 million. This translates to an average of over $1 million per percent of increased fidelity as compared to an average of $3007 per percent fidelity of the less expensive simulation. This assumption supports the general shape of the graph in figure 1. While the above is not supported by raw data in the article, it does introduce the question, "How much fidelity is enough?" and the notion that there exists a trade-off between fidelity and costs associated with increased fidelity.

Flight Simulation:

"It could be argued that Flight Simulation is perhaps the most persuasive and successful area within the simulation arena." [15] Based upon assumption of this perspective, it makes sense to explore the realm of aircraft simulation. The following is from Robinson, Mania, and Perey, 2004 [15] and begins by examining a low fidelity aircraft simulation progressing to a full motion, full imagining with environmental features. The four progressive categories examined are: avionics & instrumentation, motion base, visual system, and environmental. Because a visual system is already under consideration for the other three increments, I will not explore it as a separate entity. For purposes of this exploration, I will consider three increments of fidelity: avionics & instrumentation (1), motion base (2), and environmental (3).

The initial step or baseline was to consider a low cost simulation that was designed to approximate the appearance and layout of a flight deck (for the purposes of this paper, flight deck refers to the aircraft, not the flight deck of an aircraft carrier.) spread across multiple screens. This type of simulation also possesses the possibility to be run on a laptop or PC with a single display. Obviously this type of simulation could be treated at a baseline, for cost as well as fidelity, in future research and have a great deal of flexibility/mobility for its use. While this is not the primary topic of this paper, it is worth noting that a low cost simulation will most likely be more mobile with the potential of being deployed to "the field." Most notable to this low fidelity simulation is the fact that actual avionic devices are not needed, thus reducing the overall cost of the simulation and fidelity. The nature of the display will appear synthetic and unnatural. See figure 3.

Figure 3: Airbus A320 'simfinity' Flight Training Device (Courtesy of CAE) [15]

Increment 1.5 in fidelity involves recreating the flight deck avionics. This will offer a more accurate representation of the flight deck and most likely be coupled with a virtual display depicting what the pilot would normally see. As with our low fidelity model, the display will be synthetic and unnatural; however the flight deck will be an accurate depiction and allow for natural pilot responses typical to those in the actual aircraft. Those responses include internal and external communications, power control, emergency procedural play, and visual cockpit scanning. All combined allow the pilot to enhance his/her training. Normally this will require that the simulator remain in a fixed position loosing portability. Hardware costs will most likely increase with this increment in fidelity and the sensory device for each instrument will need to be accurately modeled adding to the cost of the simulation and fidelity. See figure 4.

Figure 4: A simulated Boeing 737 flight deck level D visual (Courtesy of Boeing) [15]

The second increment in fidelity takes our result of increment 1.5 and adds a motion base which will add the sensation of motion to the simulator. Two basic types of motion bases exist, hydraulic and electric. Hydraulic operated motion bases are the most widely used due to their increased fidelity as compared to electric systems. The addition of the motion base allows the simulator to move through six degrees of freedom: pitch, roll, yaw, acceleration, deceleration, and turbulence. Significant costs are associated with the motors, servo-valves, electrical power, pumps, cylinders, and the building space. This alone increases costs, however in addition, significant costs exist to allow for synchronization between the visual scene with the changes in simulator attitude. This appears to be a greater increase in cost as compared to the increment from 1 to 1.5. See figure 5.

Figure 5: A full flight simulator (Courtesy of CAE) [15]

The final increment in fidelity discussed is the environmental portion of the simulation. The environment aspect is very closely tied to the visual imaging but is being treated separately due to the uniqueness of this aspect. For the purposes of this paper environmental simulation refers to all aspects external to the aircraft. These aspects include weather conditions, terrain, airfield layout, and other air traffic. Weather conditions include severe conditions such as wind shear and thunder storms. Take for instance the case of wind shear. Wind shear can be predicted with a visual of a temperature inversion. It is important to recreate the visual conditions as accurately as in the real world in order to facilitate adequate training. Terrain can be mapped accurately from satellite technology with the potential to recreate it in a simulator image. Creating these accurate effects takes significant amounts of time to model which in turn can significantly increase the cost of the simulation. See figure 6.

Figure 6: Cloud Layer indicating a possible inversion (Courtesy of CAE) [15]

Measuring Cost:

The Hays perspective:

Robert Hays developed conceptual ideas on training simulator fidelity which were published in 1980 [6] [12] and formalized in his book, "Simulation Fidelity in Training System Design: Bridging the Gap between Reality and Training."[6] [12] His definition for fidelity of a training simulation is: "the degree of similarity between the training situation and the operational situation, which is simulated." He further developed a formal equation to calculate fidelity:

$$TSF_x = f[a(PhyF)_x + b(FuncF)_x]$$

where:

TSF_x is the training situation fidelity for task x,

$a(PhyF)_x$ is the weighted physical fidelity requirements function,

$b(FuncF)_x$ is the weighted functional fidelity requirements function.

Hayes further breaks $a(PhyF)_x$ and $b(FuncF)_x$ into the following two equations:

$$a(PhyF)_x = f[a(\text{task chars})_x + a(\text{trainee chars})_x + a(\text{instructor chars})_x + a(\text{instructional strategies})_x + a(\text{resources})_x + a(\text{ N other variables})_x]$$

and

$$b(FuncF)_x = f[b(inf)_x + b(equip)_x].$$

The $a(PhyF)_x$ break down deals with the human factors involved in a simulation. These are difficult to formulate and while they have no bearing on the theoretical true fidelity of the simulation, they can have a significant effect on the perceived fidelity of the simulation. This perception, while not affecting the theoretical, will have significant affect upon the total overall cost of the simulation. The following does not address the true cost of fidelity versus cost but it does establish a potential framework for comparison provided we were able to attain at least two different groups such that their weighting variables were significantly different.

The $b(FuncF)_x$ breakdown is into informational, $b(inf)_x$, and equipment, $b(equip)_{x.}$ According to Roza [6], Hayes does not further break these values. One can assume that the informational aspect is the information the simulation can pass to the trainee or end user and vice-versa. There is a cost associated with this information which include labor, computer hardware, and software. The equipment aspect will focus upon how close to reality the simulator appears and how well the motion, or physiological affects are incorporated into the simulation.

I suggest that total overall cost of fidelity for a given group can be viewed as follows:

$$\text{Cost(TSF)} = \text{Costf}_{a}\text{(FuncF)},$$

where the cost of fidelity, Cost(TSF), is equal to the cost of functional fidelity based upon the cost functioning of the perceived fidelity, 'a,' or in essence the weighting of the Physical fidelity. Furthermore, this can be further expanded:

$$\text{Cost(TSF)} = \text{Costf}_{a\text{-}inf}\text{(inf)} + \text{Costf}_{a\text{-}equip}\text{(equip)},$$

where

$\text{Costf}_{a\text{-}inf}$(inf) is the cost function of the informational portion of the functional fidelity required based upon the perceived fidelity and

$\text{Costf}_{a\text{-}equip}$(equip) is the cost function of the equipment portion of the functional fidelity required based upon the perceived fidelity.

The above equations leave much to be determined. They do allow for further discussion and exploration into actual measurements to determine "good enough" fidelity and determine the true cost of that fidelity. Further research is required and actual data; monetary, labor, software, material, et al; is required to adequately test this suggested equation.

Summary and Conclusions

The use of the term fidelity, while being formally defined in the Modeling & Simulation community, will continue to mean different things to different people and "good enough" fidelity will, most likely, require a qualitative measure from the end user or customer. This being stated, the human perception will continue to be part of the equation to measure the "good enough" fidelity and thus the cost of fidelity. The above mentioned equation for cost of fidelity is in a very early stage of development and I am unsure at this point whether a quantitative measure can be accurately deduced. Primarily the equation is meant to show the importance of the human perception factor is related to the fidelity required for a given simulation. Fidelity in the paper deals with involvement of the human factor. Not all simulations require as significant a human point of view and thus for those simulations the 'a' factor may not be nearly as significant, however the information and physical inputs to cost will remain.

Having a formal definition for fidelity is important as a guideline, however, in the end, the definition one uses to define fidelity is not of great importance provided the end user's needs are being met in a cost-effective manner. The cost factor will continue to be an issue when creating simulations. The human factor will also continue to affect the simulation costs and thus will be a significant factor in the comparisons of fidelity to cost. When designing and constructing a simulation to fit a group of individuals who have different perspectives, it may be useful to develop a statistical analysis tool directed at determining a least risk factor of the simulation's targeted audience to determine the 'a' factor for the given simulation.

Future Research

In order to test the equations, data from actual projects will be required. In order to enhance the validation of my proposed equation, groups of end users, possibly trainees, coupled with their instructors, instructional approach, and other 'a' factors should be researched. I propose examining several simulations from inception to fruition charting costs, fidelity, and perceived fidelity in order to help develop a metric or set of metrics that would facilitate the determination of "good enough" fidelity. Comparing simulations requiring a high level of human perception with those requiring minimal human perception may prove useful to help determine the 'a' factor for the cost equation and the relationship of the 'a' factor versus the degree of human involvement (linear, exponential, other) required to operate the simulation. Further research subsequent to the two previously mentioned might include a tool that could be used to interpret end user perceptions into a minimal risk equation to help determine the 'a' factor and its influence on cost.

References:

[1] Hughes, Tom and Rolek, Evan, "Fidelity and Validity: Issues of Human Behavior Representation Requirements Development,"2003 Winter Simulation Conference

[2] Erwin, Sandra I., "$65K Flight Simulator Draws Skepticism From Military Byers," November 2000, NDIA's Business & Technology Magazine

[3] Pongracie, Helen and Marlow, David, Triggs, Tom, "Issues in cost-effectiveness and fidelity of simulation."

[4] Northam, Geoff, "Simulation Fidelity – Getting in Touch with Reality."

[5] Bastow, John M., "The Price of Reality."

[6] Roza, Zwerus C, "Simulation Fidelity Theory and Practice." Doctoral Thesis.

[7] Lever, Alex, "Fidelity and Negative Training in System Simulation."

[8] Launer, R.L., Wilkinson, G.N., quote from Box, G.E.P., "Robustness in the strategy of scientific model building, in Robustnest in Statistics," 1979, Academic Press: NewYork.

[9] The American Heritage® Dictionary of the English Language: Fourth Edition, 2000.

[10] Training Guide 1 – The Royal Navy Instruction For The Conduct Of Training Needs Analysis (TNA)

[11] Haddix, F., "Prescribing Fidelity and Resolution for CMMS," 98 Spring Simulation Interoperability Workshop, March 1998, Paper 085.

[12] Hays, R.T., "Simulation Fidelity: A Concept Paper," Technical Report, US Army Research Institute for Behavioral and Social Sciences: Alexandria, Virginia, November 1980.

[13] McDonald B., "A Proposed Process for Defining Required Fidelity of Simulations," 98 Spring Simulation Interoperability Workshop, March 1998, Paper 234.

[14] Roza, M., et al, "Fidelity Requirements Specification: A Process Oriented View," 99 Fall Simulation Interoperability Workshop, September 1999, Paper 032.

[15] Robinson, R., Mania, Katerina, M., Perey, P., "Flight Simulation: Research Challenges and User Assessments of Fidelity," Association for Computing Machinery, Inc, 2004.

[16] Kass, Richard A., USJFCOM/JI&E, discussions concerning viewpoints on modeling & simulation and the uses in the experimentation environment