A PHILOSOPHY OF MODELLING AND SIMULATION AS APPLIED TO DYNAMIC SYSTEMS

Richard N. Zobel
Department of Computer Engineering
Faculty of Engineering
Prince of Songkla University, Phuket Campus
80 Vichit Songkram Road, Kathu
Phuket, Thailand 83210
Email: rzobel@phuket.psu.ac.th
r.zobel@ntlworld.com

KEYWORDS

Modelling, level of modelling, simulation, simulation studies, parametric and statistical studies, V,V & C, testing, results, analysis, reports

ABSTRACT

Undertaking a simulation study, except when trivial, is always a complex process. It is viewed in very different ways by the various parties involved. This paper looks at the processes, stages and sequences from several different perspectives, in order to expose the philosophy and arguments involved in the decision making leading to the successful and profitable use of simulation or to its rejection.

INTRODUCTION

Simulation can be a very powerful tool for system design support and validation, for providing performance data, for investigating operational regions beyond the anticipated safety limits, and provide a valuable aid for training. Although many complex systems may be amenable to analytical techniques, simulation is required to ascertain characteristics and performance for systems represented by many equations, which are also non-linear and time-varying.

In the following discussion the author uses his own experience and knowledge of simulation gained over the past 45 years in industry and academia to expose some of the problems, dilemmas, views and solutions for a variety of different simulated systems.

AIMS AND OBJECTIVES OF A SIMULATION STUDY

Simulations and simulation studies should be developed in a similar way to a piece of software or a product, that is, through a sequence of cycles of requirements, specification and outline design, until the aims and objectives are reasonably clear. At this stage it is essential to involve the management team, project engineers and others, in order to provide a properly argued case for the need of such a simulation study on a need and cost/benefit basis (Korn and Korn 2000**,** Melsa and D. Cohn 1978).

Costs should include items for modelling, development of simulation including verification and validation of the models and simulation, modelling and simulation tools, computers and software, and suitably qualified staff, all associated with time estimates for each task. These and the benefits must be achievable and clear to the management. The benefits should include the verification and validation of product or service design decisions at all stages. Where persons are included in the loop, appropriate human factors must be considered. Where there is hardware-in-the-loop to be considered and/or humans, the real-time and interface aspects must be included in the evaluation. For the situation where there are both person(s) and hardware-in-the-loop all of these factors must be considered.

The principles of concurrent engineering should be used in the product design and manufacturing processes, and also used for parallel modelling and simulation developments, see figure 1 (Habibi and Zobel 1996).

The level of modelling employed overall and for each of the sub models should reflect the aims and objectives of the study in relation to the requirements for sufficient accuracy, resolution and validity. Higher levels cost money and time and should be seriously questioned by the management. Of course, re-use of existing models is highly desirable, even if they are more complex then required for the new study. However, this must be subject to adequate documentation including a complete specification, interface definitions, evidence of verification and validation, and a complete list and specification of modelling assumptions and limitations (Gass 1978, Han 2000). A simulation model library is desirable, but this must be used with care (Lee and Zobel 1997).

After sufficient iterations, the final aims and objectives must be completely specified, documented and agreed by all interested parties. These should include the customer, whether internal or external to the organisation proposing the simulation study.

Proceedings 19th European Conference on Modelling and Simulation
Yuri Merkuryev, Richard Zobel, Eugène Kerckhoffs © ECMS, 2005
ISBN 1-84233-112-4 (Set) / ISBN 1-84233-113-2 (CD)

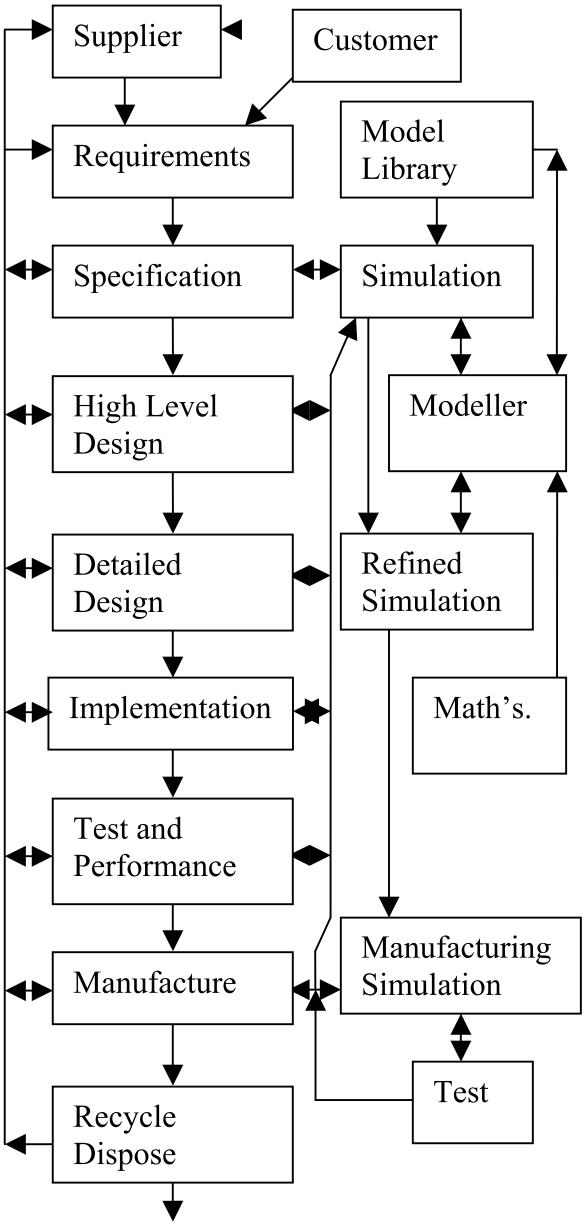

Figure 1: Parallel Concurrent Engineering and Simulation for Manufacturing

STRUCTURE OF A SIMULATION STUDY

There are many aspects, facets and views of a simulation study which must be considered, implemented and documented, before such a study can be justified and carried out.

System Block Diagram

The first requirement is a for a top level system block diagram, with details of each block (figure 2). Lower level block diagrams are also needed, subject to the need for restricting the level of detail to those required by the aims and objectives of the study, and other technical details (figure 3). The latter may involve the need for the real-time solution to a partial differential equation, for which the available hardware does not have the performance. Alternative methods may have to be sought. It may be necessary to look at the assumptions, justification, and limitations of proposed methods and the acceptability of alternatives.

Some systems are purely discrete event and others are continuous systems. In this day and age, many systems are mixed continuous and discrete event. This aspect will have a strong influence on the simulation package choice.

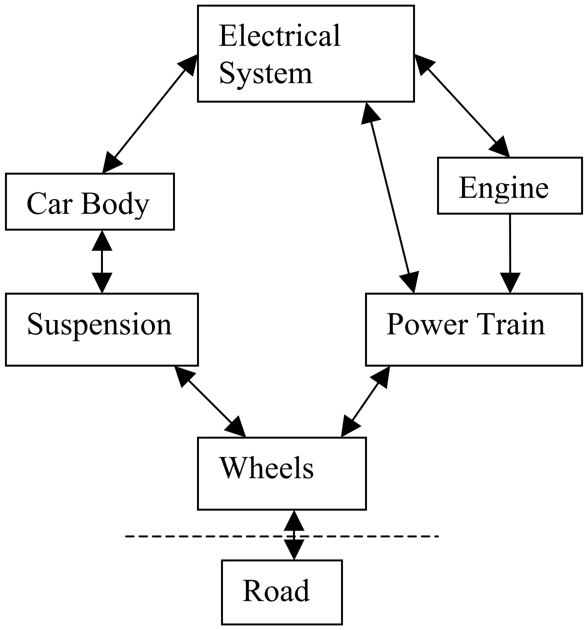

Figure 2: Car Top Level System Block Diagram

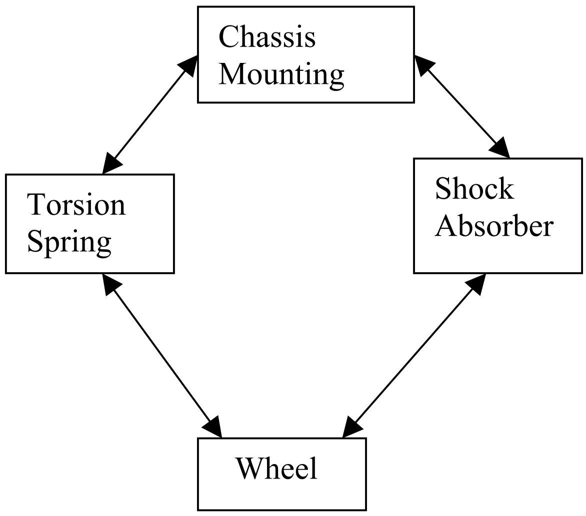

Figure 3: Lower Level Suspension Sub-System Block Diagram

Mathematical Modelling

Second, the mathematical modelling is required (Korn and Korn 2000), if not already completely or partly already available from previous studies, or is partly available through adaptation of earlier models. However, all of this may be suspect, due to incomplete model specification or lack of detail, especially of assumptions and limitations associated with the model to be re-used. On completion, the mathematical models must be verified to determine if they are complete and correct, otherwise there is no point in proceeding to build a simulation from the models (Balci and Saadi 2002, Balci 2003).

Simulation Construction

The simulation is then constructed, preferably by using a standard simulation package. This is often one that the organisation already has, but may not be the most suitable or appropriate. However, the simulationist may well already be familiar with the package, thus speeding up development of the simulation. A better or more suitable package may well require much learning before it can be used efficiently, properly or even reliably, and its cost and delivery time may be prohibitive, even if the package is desirable. It is important, if not essential, that the simulation package has a good graphical user interface and has, or is linked to, an animation package for visualisation of the simulation results. Such results may be in tabular, graphical or full 3D animation as in DIS/HLA simulations [Tandayya and Zobel 1998)].

Simulation Testing and Verification

After a simulation is built, it must be tested and its operation verified. The process is, of course, complex. It is similar to the testing of any complex piece of software (and hardware). This is best carried out by testing modules and then the interaction between modules, until the entire system has been tested. The process is the verification that the simulation operates as its designer intended. This does not mean that it is correct.

Validation

For reasonably correct operation, the simulation must then be validated against the real world, or as near as possible to the real world as is available or feasible. It is important to remember that for new products or systems, there will be no real system to validate against. In this case the operation and performance of similar, perhaps earlier products or versions, together with the experience of engineers and simulationists has to suffice. The concept of *reasonableness* can be useful here. A degree of fuzziness is also required here. Only experience can be used to judge whether resulting simulation is sufficiently validated. It is useful to introduce the concept of "this can not happen", so do not test for this. Many system failures can be attributed to making this erroneous assumption.

Certification

Certification of the validity of a simulation or simulator is required for systems which can be categorised as safety critical. This particularly applies to training simulators for civil and military aircraft, ships, land vehicles, weapons systems, air traffic control, nuclear power plant, etc. The certification authority in each area requires mandatory compliance and certification before use.

SIMULATION STUDIES

The specification, design and execution of a simulation study is a complex matter. In the discussion below, many of the issues and topics are discussed. The list is not guaranteed to be exhaustive.

Parameters

Parameters, or "constants", of a system need to be specified before any study may be carried out. Although defaults can be useful, one incorrect default can make the result of an entire study useless (if discovered!).

Initial values

A system has to start somewhere, often at time zero. However, all dynamic systems require initial values for all the system variables and for all of their derivatives, except the highest, which are algebraically determined from the relevant differential equation(s).

For example:

$$\text{If} \quad ad^2x/dt^2 + bdx/dt + cx = f(t) \text{ …………....(1)}$$

For equation 1, at $t = 0$, it is necessary to specify $dx/dt(0)$, $x(0)$ and $f(0)$.

Then $d^2x/dt^2(0)$ is automatically specified by the equation after the values of the parameters a, b and c have been set.

Inputs

Inputs to a simulation are driving functions, forcing functions, outside influences, etc. For example, the vehicle block diagram illustrated in figure 2 shows a wheel with an external connection to a road. The deviation of the level of the road surface from a reference value is an input to the tyre on the wheel. The relative speed of the vehicle to the road determines the required rate of generation of the road surface function. This function may also contain a roughness noise element. Other inputs may be weather, including effects of wind, rain, fog, and snow on the road and vehicle, other vehicles, road signals. In general terms, inputs are any external events and/or forces or conditions that, in some way, affect the simulation.

Noise components

Many real systems include noise arising from a variety of sources. Examples are noise in a vehicle from wind arising from the motion of the vehicle and also meteorological wind. There is also tyre noise arising from the granularity of the road surface. There are many other naturally occurring sources of noise which affect the operation of systems designed by humans. Some of these may significantly affect system performance under certain conditions and thus noise signals may need to be included in a simulation.

Noise is generally considered to random with a distribution such Gaussian, Poisson or binomial. Noise occurring in real systems may have different distribution due to additions of specific components such power supply hum, sideband interference, or to modification due to filtering effects, resulting in what is loosely described as pink noise.

Noise frequency components may also vary with system parameters and current variable values. Variations may occur in both amplitude and frequency.

Noise sources include analogue generators of various types. However, digitally generated sources, using a variety of random number generation techniques have the advantage of repeatability, useful for replays and for studies with parameter variation requiring identical noise for each parameter setting.

Mathematicians are deeply suspicious about the use of digitally generated noise and other “random” number generators and their statistical relevance.

Parameter Studies, Statistics and Sensitivity

Parameter studies are commonly carried out using system simulation to gather more information about a system. One of the most useful types of parameter study is optimization. This concerns finding the operational area, in relation to the major system parameters, in which the system operates in the most optimal way. Optimum here can mean many things, but usually it is related to the major performance criteria, such as speed, cost, availability, time, and customer expectations. Adjustment of key parameters can make an important difference to the performance of a system.

Usually and optimisation is carried out using a specific strategy such as hill climbing or steepest descent methods for a specific set of parameters. Of course, complex systems have many parameters, and determining which of these are important is not an easy task. However, using statistical variation of parameters based on random selection can be quite useful.

A more directed approach is to start with a study of parameter sensitivity. This concerns the observation of the performance in terms of variation of each parameter to determine its sensitivity to variation.

An example of this might be a system in which there are two cascaded time constants (equation 2). One is large and the other is small. The system response time is normally dominated by the larger time constant, which implies that the smaller one is not particularly sensitive to variation in terms of the overall response time of the system, but may affect closed loop stability.

$$Vo/Vi(s) = K/(1 + sT_1)(1 + sT_2); \quad T_1 << T_2 \ \ldots\ldots\ldots \quad (2)$$

The result of this may be, that in a parameter optimisation study, it is safe to disregard T_1 as being not relevant for the study. This reduces the size and complexity of the parameter optimisation study.

Tolerance Studies

Another type of parameter study which is commonly used is that concerning tolerances in order to determine the probability that a product will operate correctly with a given set of parameter tolerances. A typical example of this occurs in electronic circuits or in mechanical systems, where components are often used, having a tolerance of ±n%, where n should be as large as possible to minimize cost, but without compromising performance.

Systems with Several Modes of Operation

A further complexity arises where a system has more than one mode of operation. A car, train or plane may have more than one state. For example, a car may be cruising on the autobahn, driven in town, stuck in a jam, stopped at traffic lights, parked or garaged. An aeroplane has other modes, such a taxi, take-off, climb, cruise, change course, descend, land, taxi, engines off with local services, parked, etc.

Such systems require a more complex simulation with manual or automatic sequence of mode changes. A study of the transients associated with mode change can be important.

Model Limitations

Models are rarely fully general purpose. They are usually restricted to specific regions of parameter space, and are further often simplified or linearised to save on memory and/or processor time.

To achieve this, it is necessary to specify the limits of operation and use of such a model. It is essential to document, not only the limits, but also the reasons and assumptions which form the basis for the model simplification and the limits to its use. It is essential that when the limits are exceeded, even by a small amount, the validity of the simulation results must be questioned.

Exceptional Conditions

Some years ago an aeroplane was flying at a height of 10km and at a speed of around 850km/h, i.e. normal cruising conditions. Suddenly, one of the two engines went into reverse thrust, a condition which should not happen. Although there are interlocks to prevent this from happening, it did happen. Pilot instructions offer little if anything to give a procedure to overcome this problem. The result was a tragedy.

Simulation was used to establish if this was a condition that could be recovered from. It is unlikely that the simulation model was valid for this exceptional condition.

Any simulation that is operated outside the anticipated parameter envelope should be re-validated as a minimum requirement.

Research

Research continues into computer simulation as a useful, and in many cases essential tool for understanding and evaluating the complex systems that we design, build and use every day.

However, it is vital that we continue to live in the real world and not in a virtual world. We should remember that computers and simulators are tools. Producing a working simulation is *not* the object of the exercise. It is the verification, validation and intelligent use of the simulation which is its most important aspect.

There is a well known cynical expression “lies, damn lies and statistics”. On might insert “simulation” and/or “virtual reality” into the list. We commonly rely on simulation to add to our knowledge about a system, or to interpolate where we can only afford a few live system tests. A well know UK politician as heard to remark recently about the performance of a certain military system, but then added that this was only a simulation. He was clearly unaware that most complex military systems rely heavily on simulation throughout their design, manufacture, testing and use. The latter item is concerned with training simulators, which are now heavily employed to save, time, money, wear, and environmental damage. This now also applies to many non-military systems as is obvious from even a casual study of the proceedings of simulation conferences.

Understanding the Model Behaviour

Many modern systems are complex or very complex. It is essential for all of those concerned with the engineering of such systems to be able to understand the function and operation of the overall system, its subsystems and the communications between the subsystems and the external world. Whilst the mathematical model is important, it is not always easy for those who have not been involved in the design to fully understand the significance of the details of the mathematical model.

Experience shows that simulationists can gain a lot a of practical feel of the operation of a complex system during a simulation study. This is particularly true of simulationists, such as the author, who have much experience of a variety of different systems and how they operate. It is generally called having a *feel* for the system. It helps to identify faults or faulty operation when the system behaves in an unusual way. It also leads to a better understanding of the system. Of course, some new system advances do lead to unfamiliar behaviour. This is particularly true of digital filters, for example, which can do things that analogue filters cannot do.

Distributed Simulations

Over the last 10 years or so, the linking of simulations and/or simulators together over the network has lead to a whole new set of applications and problems. Not the least of these is the requirement for real-time operation with limited bandwidth and good virtual reality, especially for training simulators. This has resulted in the development of prediction techniques and minimisation or elimination of the effects of the actions of distant objects.

Further, for non-military applications, the requirement for security on the internet has lead to the development and use of more secure systems for authentication and encryption (Roberts and Zobel 2004).

RESULTS

Simulations can produce copious quantities of data in the form of results and the reasons for and conditions under which they have been obtained. It is important to have proper management of this in a usable form.

Recording of Simulation Results

All sets of data from simulation runs and full details of the scenarios in which they were obtained must be recorded in a standard machine readable form. Casual recording of results really is a waste of time and can even be dangerous. Of course it is acceptable to play with a simulation to get a feel for a system, the concept of reasonableness comes into play here. Subsequent simulation studies must be dealt with in a more formal manner if a truly professional approach is used, an essential for all serious simulationists.

Analysis and Report Writing

With large quantities of data available some systematic method must be applied to reduce the important results to graphical and/or tabular form. There are, of course, tools available specifically for this purpose. Consequent upon this, reports need to be written for project meetings, records, management, etc, each in an appropriate style.

CONCLUSIONS

It is clear from the above discussion, that simulation is a serious and complex activity. As with all such activities, experience is highly desirable. However, few people have a career in simulation. Many are involved in simulation only when their current project requires it, and then they move on. Consequently, the simulation community world wide is relatively small. For this reason it is desirable to have regular simulation conferences. This leads one to make contact with others who are working on similar activities in totally different topics or even areas. This in turn results in simulationists acquiring a very wide knowledge base. Long may it last.

REFERENCES

Balci O. and Saadi S.D. 2002, "Proposed Standard Processes for Certification of Modelling and Simulation Applications," In *Proceedings of the 2002 Winter Simulation Conference* (San Diego, CA, Dec. 8-11). IEEE, Piscataway, NJ, pp. 1621-1627.

Balci O. 2003, "Verification, Validation, and Certification of Modelling and Simulation Applications," In *Proceedings of the 2003 Winter Simulation Conference* (New Orleans, LA, Dec. 7-10). IEEE, Piscataway, NJ, pp. 150-158.

Gass, S. L. 1978. "Computer Model Documentation". In *Proceedings of the 1978 Winter Simulation Conference*. (Miami Beach, FL, Dec. 4-6). IEEE, Piscataway, N.J., 281-287.

Habibi J and Zobel R.N. 1996. "Integration of Simulation and CAD Systems for a Virtual Factory within Synthetic Environments for Manufacturing." In *Proceedings of the ESS 96 Multiconference on Computer Simulation in Industry*, (Genoa, Italy, Oct.) SCS, Ghent, Belgium. pp. 86-90. ISBN 1-565-550-99-4

Han. L. 2000. 'Development of Full Generic Verified and Validated Re-Usable Simulation Models'. MSc Thesis, Manchester University, UK.

Korn, G.A., and T.M. Korn: 2000 *Mathematical Handbook for Scientists and Engineers*, 2nd Edition, Dover, New York.

Lee C-H, and Zobel R.N. 1997. "Model Re-Use Through the Use of a Simulation Model Library". In *Proceedings of the ESS 97 Multiconference on Computer Simulation in Industry*, (Passau, Germany, October). SCS, Ghent, Belgium. pp. 91-95. ISBN 1-565-550-99-4

Melsa, J. L, and D. Cohn 1978. *Decision and Estimation Theory*, McGraw-Hill, New York.

Roberts P.H. and Zobel R.N. 2004. "A Discussion of Elliptic Curve Cryptography and Configurable ECC System Design with Application to Distributed Simulation".*Invited paper in International. Journal of Simulation, Systems, Science and Technology, Special Issue on Modelling and Simulation of Complex Systems. UKSim.Vol. 5, Nos 1-2*, pp. 47-57. 1-473-804X Online, ISSN 1-473-8031 Print

Tandayya P and Zobel R.N. 1998. "VISTA Real-Time Animation Software in a Distributed Spacecraft System". In *Proceedings of SESP'98, 5th Int. Workshop on Simulation for European Space Programs*, (ESTEC, Noordwijk, The Netherlands, Nov. 3-5).pp 183-190. ISSN 1022-6656.

AUTHOR BIOGRAPHY

RICHARD ZOBEL graduated in Electrical Engineering from London University in 1963. His first experience of simulation was obtained during 1962-66 at Sperry Gyroscope whilst working on naval surface to air missiles, using mainly valve analog computers. His Ph.D., obtained in 1970 at Manchester University, concerned hybrid analog-digital computing. As Lecturer and Senior Lecturer he became involved in digital signal processing, instrumentation and design environments with special emphasis on the simulation aspects of real-time embedded systems. He is a Committee Member and former Chairman of the United Kingdom Simulation Society (UKSim), Former Secretary of the European Federation of Simulation Societies (EUROSIM), and was a European Director of SCSI, the Society for Computer Simulation International. His current research interests concern distributed simulation for non-military applications, model re-use, distributed simulation model databases, issues of verification and validation of re-useable simulation models and security for distributed simulation under commercial network protocols. He is now an independent consultant, and still very active. He is currently teaching Computer Engineering during the winter months at the Prince of Songkla University, Phuket and Hat Yai Campuses in South Thailand.