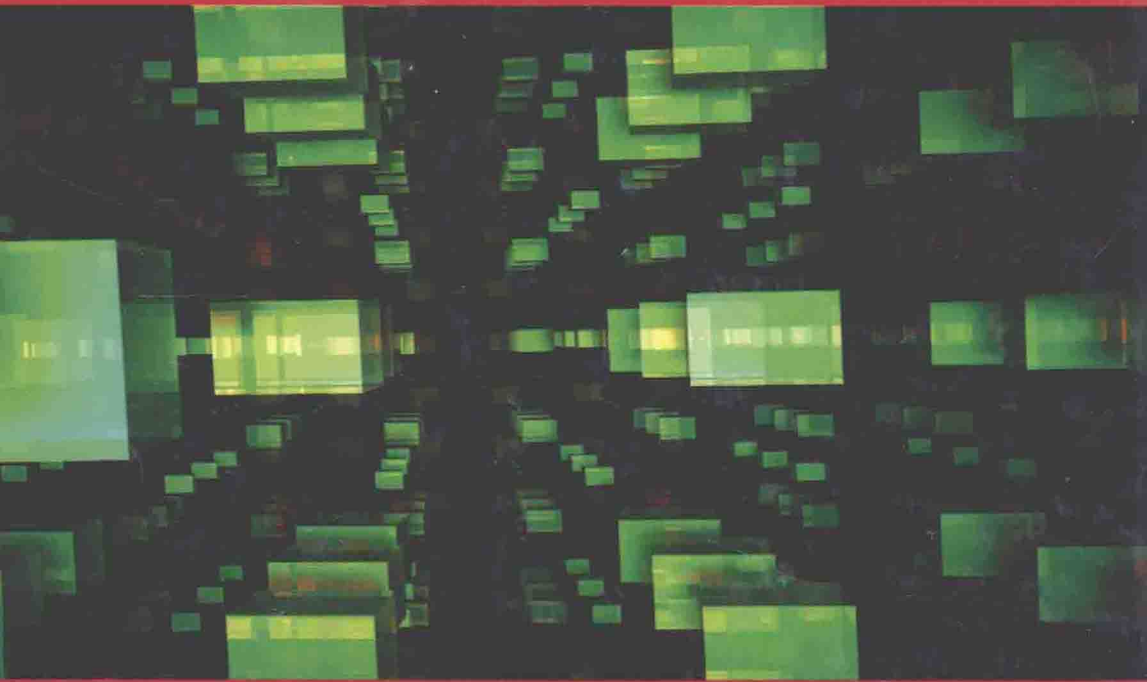
Simulation and Modeling of Systems of Systems

Edited by
Pascal Cantot
Dominique Luzeaux



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Introduction

In fields such as aeronautics, transport, telecommunications, banking, or defense, systems are becoming increasingly complex, containing more and more components, with significant heterogeneity and disparate lifecycles. The update process that follows the increasingly rapid obsolescence of sub-systems requires *a priori* mastery of architectures of systems of which we do not know the component configuration. Risk mitigation in the different phases of the project (from the expression of need to implementation, or even withdrawal, considering environmental protection constraints) thus becomes an essential consideration throughout the whole lifecycle of the system.

Needs have also evolved. Demands in terms of performance, interoperability, cost, security, and reliability have reached a level where each project becomes a technical and managerial challenge. It is, therefore, necessary to attain new levels of flexibility and reactivity in exploring system concepts. The changeable nature of the environment and the necessary capacity of the system to adapt to different evolutions contribute to its complexity. Moreover, the generalization of information and communication technologies pushes towards the interconnection of systems, leading to *systems of systems*, reinforced by the context of globalization of exchanges giving rise to shared developments between economic partners: this raises questions of integration, coherency, and interoperability of one system with a higher-level system. Finally, budget, time, profitability, and time to market constraints require mastery of acquisition costs: the utility of reuse becomes evident.

With such a wide variety of constraints, particular tools and processes are needed in the area of system engineering and system-of-systems engineering. Among these tools, modeling and simulation have already proven their utility and demonstrated possibilities of reducing cycle time, resource usage, and risks associated with system acquisition, while improving the quality of the systems in question and reducing global possession costs. However, the expected gains can only be achieved if modeling and simulation are used in the light of suitable processes, which typically take their inspiration from convergent engineering.

This work is neither an encyclopedia nor a simulation manual, although it does contain certain didactic aspects. It aims to allow the reader – be they an engineer, project manager, sponsor, or manager – to acquire a basic grounding in the field of simulation and to understand how simulation can help in mastering the challenges of complex systems and systems of systems. This work will also show situations in which simulation does not help; simulation not only has many qualities but also has specific limitations and constraints.

Each chapter may be read independently, but we would strongly recommend reading Chapter 1 first. Chapter 1 gives a first cultural overview of simulation. A brief historical summary shows the origins of the discipline, followed by an explanation of the broad basic principles of simulation. Examples taken from areas particularly concerned with complex system problems (e.g. aeronautics and defense) give an initial glimpse of the uses of simulation by large companies

Chapter 2 describes a typical model and simulation engineering process, followed by a detailed explanation of each step, illustrated by numerous examples to assist understanding.

Chapter 3 is dedicated to the reliability of data, models, and simulations. When decisions (e.g. design choices) are based on the results of a simulation, it is important to know how far the results of the simulation in question can be trusted. This consideration is of fundamental importance and demands particular attention, as much from the developer of the simulation as from the user or purchaser.

Chapter 4 deals with techniques used in modeling different aspects of a system. This section is slightly more technical, but it is important to understand what demands can reasonably be made of a simulation (and what we can reasonably expect to pay), and what this implies, for example, in terms of data collection, technology, development time, or processing power.

Chapter 5 tackles the specific case of complex systems. Without going into the mathematical detail often found in articles dealing with complexity, the principal characteristics are pointed out, information that we should keep in mind when concerned with the modeling and simulation of systems of this kind. In spite of being aware of precautions necessary when using complex systems, frequent users of models and simulations can easily revert to old habits, ignoring the traps and limitations found when using simulations.

Chapter 6 covers the software engineering aspect of simulations and describes how simulations are built, based on a foundation software infrastructure known as a host structure, which notably provides the core of the simulation, the simulation driver. This chapter provides an understanding of the development and operation of simulations from an IT viewpoint alongside strategies for use when developing and acquiring a simulation system.

Chapter 7 is based on Chapter 6 by dealing with a particular architecture, that of distributed simulations, which are particularly well suited to modeling complex systems and systems of systems, but which have their own specific set of problems. A good deal of work is currently being undertaken on these simulation construction techniques, which present numerous possibilities for development as long as they are used correctly.

Chapter 8 concerns a new concept in system capacity and system-of-system engineering: "battle labs", laboratories of engineering, system and system-of-system architecture. Battle labs use a variety of tools and techniques, including simulation, in addition to processes and an organization. Although the battle lab concept is relatively new, their great potential is already evident.

Finally, Chapter 9, which serves as a conclusion, goes back over certain cost aspects linked to simulation, used in an integrated manner in the engineering process for increasingly complex systems.

We, the editors, hope that this work will assist the reader in understanding simulation in the context of complex system and system-of-systems engineering, a area in which it constitutes a valuable tool, albeit one with its own specificities, pitfalls, and limits, the mastery of which is essential to use the tool to its full potential.

We would like to thank those individuals and businesses or organizations, other than the contributing authors, who have helped us in the creation of this work (with a very special mention for Jean-Louis Igarza for the dynamism and energy he communicated to several generations, including some of his managers!), especially Christian Sautereau, Stéphane Chaigneau, Eric Lestrade, Eric Pédo, Jérôme Martinet, the ONERA, THALES Training & Simulation, SOGITEC, EADS, MBDA, and, more generally, the members of the ADIS group (*Armées*, *DGA*, *Industriesur la Simulation*)[1].

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[1] Armed Forces, DGA (Defense Procurement Directorate) and Defense Industry on Modeling and Simulation.

Finally, we would like to dedicate this work to the memory of our colleagues and friends Guy Zanon and Pierre Bouc, early contributors on distributed simulation and the validation of simulation, who actively participated in the development of the concepts presented in Chapters 3 and 7.

We hope you enjoy reading this work and gain as much pleasure from reading it as we did in writing it.

Pascal CANTOT
and
Dominique LUZEAU
March 2011

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Chapter 1

Simulation: History, Concepts, and Examples

1.1. Issues: simulation, a tool for complexity

1.1.1. *What is a complex system?*

The world in which we live is rapidly advancing along a path toward complexity. Effectively, the time when component parts of a system could be dealt with individually has passed: we no longer consider the turret of a tank in isolation but consider the entire weapon system, with chassis, ammunition, fuel, communications, operating crew (who must be trained), maintenance crew, supply chain, and so on. It is also possible to consider the tank from a higher level, taking into account the interactions with other units in the course of a mission.

We thus pass from a system where a specific task is carried out to a system of systems accomplishing a wide range of functions. Our tank, for example, is now just one element in a vast mechanism (or "force system"), which aims to control the aeroterrestrial sphere of the battlefield.

Therefore we must no longer use purely technical system-oriented logic, but use system-of-systems-oriented capacity-driven logic[1] [LUZ 10, MAI 98].

Chapter written by Pascal CANTOT.

[1] [LUZ 10] defines a system of systems as follows: "a system of systems is an assembly of systems which could potentially be acquired and/or used independently, for which the developer, buyer and/or the user aim to maximize performance of the global value chain, at a given moment and for a conceivable group of assemblies". We shall consider another definition, supplied by Maier, later on, which approaches the concept by extension rather than intension.

This is also true for a simple personal car, a subtle mixture of mechanics, electronics, and information technology (IT), the conception of which considers manufacturing, marketing, and maintenance (including the development of an adequate logistics system) and even recycling at the end of the vehicle's useful life, a consideration which is becoming increasingly important with growing awareness of sustainable development and ecodesign. Thus, the Toyota Prius, a hybrid vehicle of which the component parts pollute more than average, has an end-of-life recycling potential, which is not only high, but also organized by the manufacturers who, for example, offer a bonus for retrieval of the NiMH traction battery, the most environmentally damaging of the car's components. In this way, the manufacturer ensures that the battery does not end up in a standard refuse dump, but instead it follows the recycling process developed at the same time as the vehicle. In spite of this, the manufacturer is able to remain competitive.

These constraints place the bar very high in engineering terms. Twenty years ago, systems were complicated, but could be simplified by successive decompositions which separated the system into components that were easy to deal with, for example, a gearbox, a steering, and an ignition. Once these components were developed and validated, they could simply be integrated following the classic V model. Nowadays, engineers are confronted more and more often with complex systems, rendering a large part of the development methods used in previous decades invalid and necessitating a new approach.

Thus, what is a complex system? Complex systems are nothing new, even if they have gained an importance in the 21st century. The *Semi-Automatic Ground Environment* (SAGE) aerial defense systems developed by the United States in the 1950s, or Concorde in the 1960s, are examples of complex systems even if they were not labeled as such. SAGE can even be considered a system of systems. However, the methods involved were barely formalized, leading to errors and omissions in the system development processes. In 1969, Simon [SIM 69] defined a complex system as being "a system made of a large number of elements which interact in a complex manner". Jean-Louis Le Moigne gave a clearer definition [LEM 90]: "The complexity of a system is characterized by two factors: on the one hand, the number of constituent parts, and on the other, the number of interrelations".

Globally, then, we shall judge the complexity of a system not only by the number of components but also by the relationships and dependencies between components. A product of which a large proportion is software thus becomes complex very rapidly. Other factors of complexity exist, for example, human involvement (i.e. multiple operators) in system components, the implication of random or chaotic phenomena (which make the behavior of the system non-deterministic), the use of very different time scales or trades in sub-systems, or the rapid evolution of specifications (changeable exploitation environment). An important property of complex systems is that when the sub-systems are integrated, we are often faced with unpredicted emergences, which can prove beneficial (acquisition of new capacities) or disastrous (a program may crash). A complex system is therefore much more than the sum of its parts and associated processes. Therefore, it can be characterized as non-Cartesian: it cannot be analyzed by a series of decompositions. This is the major (but not the only) challenge of complex system engineering: mastery of these emergent properties.

On top of the intrinsic complexity of systems, we find increasingly strong exterior constraints that make the situation even more difficult:

– increasing number of specifications to manage;

– increasingly short cycles of technological obsolescence; system design is increasingly driven by new technologies;

– pressure from costs and delays;

– increasing necessity for interoperability between systems;

– larger diversity in product ranges;

– more diverse human involvement in the engineering process, but with less individual independence, with wide (including international) geographic distribution;

– less acceptance of faults: strict reliability constraints, security of individuals and goods, environmental considerations, sustainable development, and so on.

To manage the growing issues attached to complexity, we must perfect and adopt new methods and tools: modern global land-air defense systems could not be developed in the same way as SAGE developed in the 1950s (not without problems and major cost and schedule overruns). Observant readers may point out that a complex system loses its complexity if we manage to model and master it. It is effectively possible to see things this way; for this reason, the notion of complexity evolves with time and technological advances. Certain systems considered complex today may not be complex in the future. This work aims to contribute to this process.

1.1.2. *Systems of systems*

In systems engineering, numerous documents, such as the ISO/IEC 15288 norm, define processes that aim to master system complexity. These processes often reach their limits once we reach a situation with systems of systems. If we can, as a first step, decompose a system of systems hierarchically into a group of systems which cooperate to achieve a common goal, the aforementioned processes may be applied individually. However, to stop at this approach is to run considerable risks; by its very nature, a system of systems is often more than the sum of its parts.

It would, of course, be naïve to restrict the characterization of systems of systems to this property, but it is the principal source of their appeal and of risks. A system of systems is a higher-level system which is not necessarily a simple "federation" of other systems.

Numerous definitions of systems of systems can be found in current literature on this subject: [JAM 05] gives no less than six, and Chapter 1 of [LUZ 10] gives more than 40. In this case, we shall use the most widespread definitions, based on the so-called Maier criteria [MAI 98]:

– operational independence of constituent systems (which cooperate to fulfill a common operational mission at a higher level, i.e. capacitive);

– functional autonomy of constituent systems (which operate autonomously to fulfill their own operational missions);

– managerial independence of constituent systems (acquired, integrated, and maintained independently);

– changeable design and configuration of the system (specifications and architectures are not fixed);

– emergence of new behaviors exploited to improve the capacities of each constituent system or provide new capacities (new capacities emerge via the cooperation of several systems not initially developed for this purpose);

– geographical distribution of the constituent systems (from whence the particular and systematic importance of information systems and communication infrastructures in systems of systems).

As a general rule, the main sources of difficulties in mastering a system of systems are as follows:

– intrinsic complexity (by definition);

– the multi-trade, multi-leader character of the system, which poses problems of communication and coordination between the various individuals involved, who often come from different cultural backgrounds;

– uncertainty concerning specifications or even the basic need, as mastery of a system of systems presents major challenges for even the most experienced professionals. This difficulty exists on all levels, for all involved in the acquisition process, including the final user and the overseer, who may have difficulties