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HISTORY OF COMPUTER SIMULATION SOFTWARE: AN INITIAL PERSPECTIVE

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ABSTRACT

The evolution of computer simulation software until the mid-1980's is subsumed by descriptions of the history of simulation programming languages. Since that time, the entire complexion of simulation model design, development, execution, and sustainment has undergone a radical transition. The transition to a large degree stems from technology advances in hardware and software coupled with the increasing expectations of simulation modelers and end users. This study, covering the evolution in its entirety, represents an initial perspective on the transition based on an examination and analysis of the Winter Simulation Conference Archive and a partial set of simulation software surveys published in *OR/MS Today*. The results characterize the modeling and simulation software evolution since the mid-1980's in terms of newcomers, endurers, fads, fades, trends, and trajectories. Prominent among the conclusions are that commercial firms are driving the major advances and the marketplace is quite volatile.

1 THE BEGINNING AND BEYOND (1958-1980)

1.1 Prior Treatments of Computer Simulation History

Historical descriptions of computer simulation (or, more specifically, discrete event, Monte Carlo, combined, and hybrid simulation) generally fall into one of three classes:

- an inclusive treatment of the technical field; e.g., Nance and Sargent (2002),
- a focus on a specific simulation programming language; e.g. Gordon (1981), or
- a focused treatment based on selected topics; e.g. Robinson and Taylor (2008), Hollocks (2008).

The example from the last class listed above recognizes the contributions of Keith Douglas Tocher, who created the first simulation package, the General Simulation Program (GSP), in 1958 (Tocher and Owen 1960).

An exception to this classification is the comprehensive history of discrete event simulation programming languages (Nance 1996). Coupling that work with the in-depth development histories of GPSS (Gordon 1981) and SIMULA (Nygaard and Dahl 1981) that are covered to a lesser extent because of their earlier treatment, an informative picture of Simulation Programming Language (SPL) technology, circa 1984, is achieved. More recent discoveries of contemporary works add details to that picture (Markowitz 1979), (Holmevik 1994), and (Krogdahl 2005). However, the advancement of computing technology since 1984, both hardware and software, expands the domain of simulation model development, execution, and use well beyond the SPL level.

1.2 Objectives of an Initial Perspective

The objective of this paper is to offer a view of the evolution from SPL to *simulation software*, or more accurately, *Modeling and Simulation (M&S)* software. The view proffered relies on an analytical component, coupled with a subjective approach. Two sources of data to characterize this evolution with quantitative and subjective examination are employed:

- The Winter Simulation Conference (WSC) Archive that includes proceedings, and in some years program and other material, from each annual conference (WSC Archive, http://informs-sim.org). The Archive is subject to Google search.
- Simulation software surveys conducted on roughly a two-year cycle by James J. Swain and published in *OR/MS* Today since 1991. Only a subset of the surveys, primarily the later issues, is accessible (https://www.informs.org/ORMS-Today/Past-Issues).

The population of contributors to these two sources is not independent sets. However, the contributors to each database, a broad cross-section of the computer simulation community in the first case and active M&S software vendors in the second, are likely to possess quite different views of their relation to the field.

The objectives of this work in no way include providing a comparative evaluation of M&S software products, and interpretations, observations, speculations, and conclusions offered herein should not be construed as doing so.

2 THE EXPANDED SCOPE OF M&S SOFTWARE

As early as the mid-1960s, prominent SPL designers, simulation educators, and application specialists recognize that the divergences among the elements of the community are drawn along language boundaries. Comparisons of languages are prominent in publications (Krasnow and Merikallio 1964, Teichrow and Lubin 1966, Kiviat 1966); and conferences and workshops focus on SPL characteristics and applications (Hollingdale 1967, Buxton 1968). A more detailed description of the early importance of conferences and workshops is provided in section 8.3.9 of Nance (1996).

The demise of comparative SPL publication and conference activities stems from two coincident factors: (1) the transition of extant languages to, and the rapid appearance of new languages as, commercial products vying in a competitive marketplace; and (2) the emergence of the WSC as a national and international forum for communications in all aspects of simulation. The strength of the latter (WSC) influence cannot be overstated.

Beginning in the late 1970's, a succession of major hardware advances creates an almost illogical situation wherein the:

- physical size of basic logic and storage units is decreased by orders of magnitude;
- cost of these elements is reduced in a similar fashion;
- central processing unit, memory access, and disk access speeds of these elements are increased accordingly;
- graphics device costs are likewise reduced; and
- computer networking costs and performance render less expensive distributed systems.

The manifestation of these advances in the 1980's results in microprocessors with storage and computational capabilities exceeding those of mainframe computers only a decade earlier. Multiprocessor architectures are implemented as software technology responds to enable communications realizing network computing, personal computer (PC) workstations, and new dimensions in computer graphics. The influence on computer simulation is affirmed by model development and simulation support environments supplanting a SPL; parallel and distributed simulation significantly extending the application boundaries; and graphics-based interfaces replacing the limited output animations of the past. The revival of gaming as vitally linked to simulation, through both training and entertainment applications, promotes an ironic recollection for those who once were members of The Institute of Management Sciences (TIMS) College on Simulation *and Gaming*. "Human-in-the-Loop" models also experience a revival. Virtual reality, "Big Data" analysis, and web-based simulation are fathered by the technology influences. The scope of M&S software evolution today dwarfs the SPL subject domain sketched in the preceding section.

3 CHARACTERIZING THE EVOLUTION OF M&S SOFTWARE

Any description of the evolution of a technical field, the influence of a movement, or even the biography of an individual, extending over 50 years, must include subjective judgments. Nevertheless, to the extent that arguments, conjectures, speculations, or claims can be grounded in quantitative analysis, the more likely the acceptance of the conclusions, especially in scientific fields. This rationale requires identification of a data source (or sources) that best reveals the features undergoing changes in M&S software over this extended period. Additionally, a procedure must be developed to identify the features and extract the nature of the changes. The basis for selecting the WSC Archive and the simulation software surveys from *OR/MS Today*, and the procedures applied to each, are described in the following sections.

4 THE WINTER SIMULATION CONFERENCE (WSC) ARCHIVE

The identification of a data source (or sources) that best reveals the M&S software evolution is not a simple matter. Beyond the obvious requirements that the source (or sources) be openly published and readily accessible, what other characteristics might emerge to determine "best reveal"? Several data source options deserve consideration, perhaps the most apparent among them being:

1. All M&S software papers from a selected number of peer-reviewed journals during the period 1967 to 2016.
2. All M&S software papers from the proceedings of a selected number of conferences, published during the period 1967 to 2016.
3. A combination of the above two options.
4. All M&S software articles from the WSC Proceedings for the period 1967 to 2016.

One argument against Option 1 is that no peer-reviewed journals dedicated to discrete event simulation, or the combined and hybrid modeling extensions, exist before 1990 when the *ACM Transactions on Modeling And Computer Simulation (TOMACS)* is launched. Simulation areas or departments with managing editors exist in a number of professional peer-reviewed journals; but the competition with other areas or departments is intense. Thus, a very small sample with only partial coverage of the target period is obtained. Additionally, this small sample is produced by the decisions of a few individuals from editorial boards (associate and area editors) that change very little from year to year. The effect of subject and treatment bias is likely. Option 2 would require the selected conferences to demonstrate a general approach to topics in M&S software rather than a specialized focus. Another problem is the longevity issue; i.e., the life of a conference is problematic, and a sample composed of different conferences from year to year would strain the desired homogeneity expectation. More troubling with regard to Option 2 is the quality of papers composing the sample; since the motivation to base acceptance decisions on the need for a sufficient number of conference registrations is widely recognized. Option 3 cannot be seriously considered given the shortcomings of both Options 1 and 2.

Option 4 appears to suffer less from the objections raised for the other three (or the first two). Although the acceptance criteria appear to have been tightened over the years, the changes have been gradual. While simulation software and "modelware" articles constitute but a subset of the M&S coverage within each conference, that focus persists for every instance. Furthermore, the submission population from which the papers are accepted consists of practitioners, researchers, students, teachers, and users in the field. As such, the articles (research papers, panel descriptions and position statements, and M&S software tutorials) are more likely to reflect trends and trajectories *in M&S software* than would be demonstrated by the papers from a peer-reviewed journal. Finally, the proceedings of the annual WSC are available online for the period 1968-2016 from the ACM Digital Library and from the INFORMS website. The INFORMS source appears to be more complete since the ACM Digital Library omits some presentations, particularly if only an abstract is available.

4.1 Examination of the WSC Proceedings

The procedure relies on the fact that M&S software, as a publication area, is divided into topical subsets, or categories, defined *a priori* to cover a large proportion of articles spanning the subject area. Modifications to the categories based on the examination to follow are permitted (a category may be added, deleted, merged with another, or retitled). For each year, a manual review of each available paper or abstract (article) is performed to identify those describing tools intended to support the creation of a model (conceptual to executable representation) or model element intended for use in a M&S study. A total of 1303 articles are identified. Each article considered to fall within the M&S software subject area is assigned to one or more of the topical categories. Note that "Other" is always a topical category, drawing 26 assignments, a relatively low number compared with other categories. In addition, several categories draw too few articles to make meaningful analysis possible and are discarded. The result is the number of articles (a frequency count) for each category for each year. The intent is to identify patterns and shifting interests, occurring over time, that reflect emerging, persistent, and receding interests in M&S support tool capabilities. Considering the high number of articles assigned and the restricted time allotted to each article, the examination cannot be considered in-depth; but the accuracy is believed to be sufficient for allowing a quantitative perspective on M&S software evolution.

4.1.1 Scope of the WSC Archive Data

The WSC Archive provides online access to 48 years of Proceedings of the Winter Simulation Conference, covering the period 1968 through 2016 that are amenable to Google search. The proceedings contents include the full text of research papers; initially, only title then abstracts in some cases, full papers in others, for panel discussions; papers and abstracts from software vendors; and abstracts of Ph.D. student posters. Figure 1 below illustrates both the growth in total proceedings contents (items) over time and in those items identified as describing M&S support software ("support sw ct"). Included in the item content count are research papers, keynote addresses, abstracts from software vendors, Ph.D. abstracts, and panel discussions. A total of 10,671 items are included in the Proceedings count, of which 1303 (12%) describe M&S support software. Somewhat surprising is that since 1996, while total items increase significantly, M&S support software items decrease slightly.

A plausible explanation for the relatively sharp increase in simulation support software items in the 1986-87 timeframe is the emergence of model development or simulation support environment tools in a design or prototype form. Two software tutorial tracks, one labeled, "General Purpose" with nine articles and the other, "Special Software" with 15, are shown in the 1986 program. The 1985 program has a single track with nine articles. Moreover, a session devoted to model development and simulation support environments appears for the first time in 1986, and the object-oriented paradigm is prominent in modeling methodology sessions. The relatively level or slightly increasing trend over the next decade might be attributed to the increasing appearance of environment-related articles and the relatively constant number of SPL tutorial articles; the total reaches a peak in 1997 and trends downward as the SPL

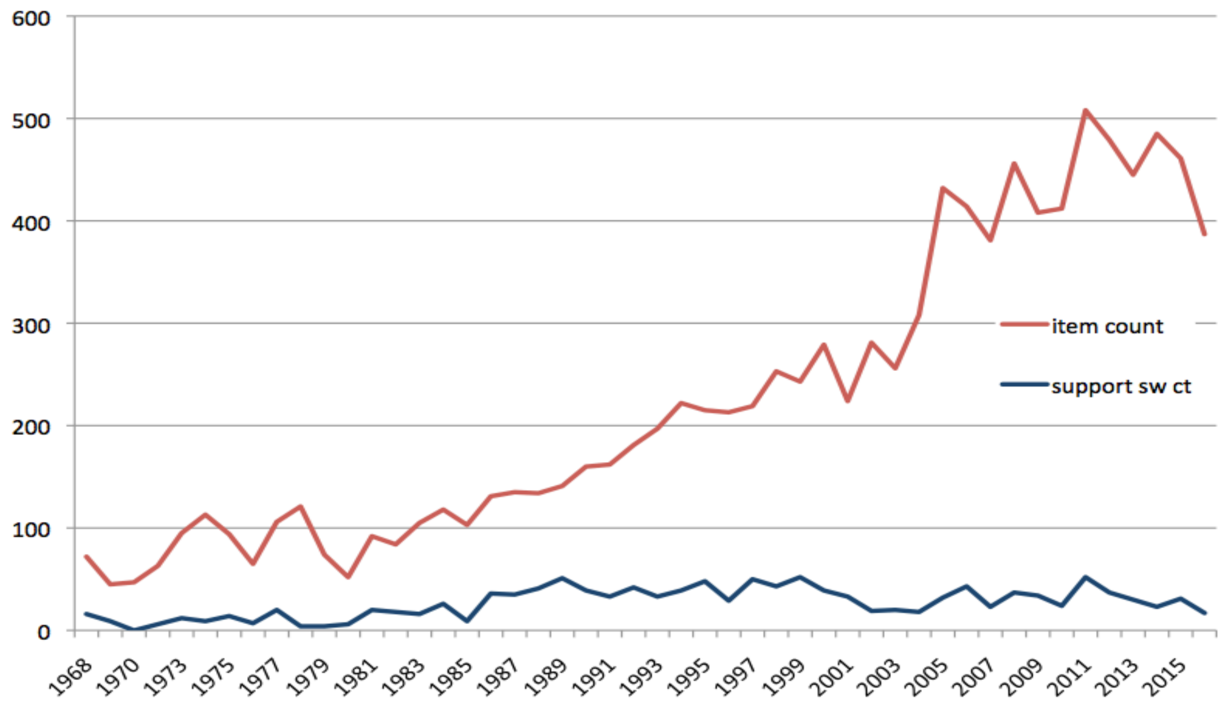

Figure 1: Content count in total and simulation support software items by year.

articles diminish. From 2003 to 2015, the relatively constant number of articles likely is reflective of commercial (vendor) dominance in this subject area. The identification of "Software/Modelware Track," introduced in 1990, gains the parenthetical "Vendor" designation in 2006. The next year and thereafter, "Vendor Track" is the designation. The slight blip in 2011 is explained in a subsequent section.

A repeated caution about the numbers. Given the large volume of data subject to examination, some counts presented here might not be exact but should be sufficiently accurate for the intended purposes: recognizing behavioral patterns, comparing count statistics, and identifying trends.

4.1.2 Frequency Count for Article Content

The examination identifies more than 1300 articles concerning tools to support the creation or sustainment of models used in M&S projects. Each article is assigned to a category; although a few are assigned to multiple categories when an article is judged to address each category. The assignment of an article to a particular category can involve varying levels of subjectivity; e.g., deciding whether an article describes a general-use SPL that can be employed to create models in many problem domains, a special-purpose SPL with application to a single problem domain, or an individual SPL model with parameters that allow some variation in the use of the model.

Some "hot" topical areas in recent conferences are yet to produce an influence on M&S software discernible in WSC articles. One such category is "agent-based modeling" that does appear, but not sufficiently frequent in its relation to M&S software. The increase in attention to the topical area of hybrid simulation is remarkable: six sessions in both WSC 2014 and 2015 and with a track consisting of nine sessions and an introductory tutorial in WSC 2016. Hybrid simulation at this point is decidedly application-domain driven. A notable influence on M&S software is yet to materialize.

Table 1 lists many of the frequently occurring topics. Recall that a single item may be counted in multiple categories. As noted above, infrequently occurring topical categories are omitted. Selected topical areas from Table 1 are also presented in graphs that follow to demonstrate how their frequency patterns vary with time.

Note that the highest category is "Language tutorials" (tutorials on SPLs). Most of these tutorials address languages that are commercial products. The tutorial frequency is influenced by the yearly repeats by the developers (vendors) to create product exposure and to promote marketing opportunities. Likewise, many special purpose SPLs, supporting model development in a particular application domain, such as design of network architectures or applications in a manufacturing domain, are also commercial products and are presented over successive years. Consequently, the higher frequency for these two areas is due both to the marketing efforts of the developers (vendors) and the continued interest of conference attendees in their products. In recent years, the larger vendors offer workshops featuring in-depth discussion of their products. User group meetings hosted by vendors is a tradition at WSC, and the combination of tutorials and the informal meetings enhance relationships with current clients and create discussions in a social atmosphere with potential users.

Table 1: Article counts by content area.

Topic	Count	Percent
Language tutorials	472	36
Simulation extensions to existing general-purpose languages	57	4
Special purpose SPL	233	18
Simulation implementation techniques	41	3
Simulation graphics	41	3
Statistical support of simulation	38	3
Writing simulations in non-SPLs	21	1
Virtual reality and simulation	26	2
Simulation development environments	68	5
Web-based simulation	24	2
Simulation support	20	1
Distributed and parallel simulation	115	9
High Level Architecture (HLA)	61	5

Observations emanating from the examination that are not revealed in Table 1:

- The technology transition, from research concept to commercial product, is exhibited in a few areas; e.g., the concept "model development environment" is projected as a research goal in two papers (Henriksen 1983, Nance 1983); then in 1990 with the evaluation of a prototype tool (Balci et. al. 1990); and subsequently in the realization of a commercial product, the Visual Simulation Environment (VSE) in 1995 (Balci et al. 1995).
- The encapsulating topical area, "simulation development environments" over time merges, at least in part, with evolving older SPLs and newly-designed languages. The early SPL products, providing only a compiler and language documentation, give way to a suite of complementary tools marketed in total by a single vendor or configured by the user from M&S software auxiliaries and utilities provided by multiple vendors.
- Graphics tools (to graph output data or to provide output animations), distribution-fitting software, and other utilities complement the SPL in an encompassing environment to expand and extend M&S capabilities.

- The high number of High Level Architecture (HLA) articles reflects both the interesting set of problems requisite in creating efficient large, reusable, and interoperable distributed simulations and the continued funding of the U.S. Department of Defense.

4.1.3 Time Traces for Selected Topical Areas

Figure 2 provides a set of graphs with data aggregated across multiyear intervals, typically ten years, to smooth year-to-year variations and to show long-term trends.

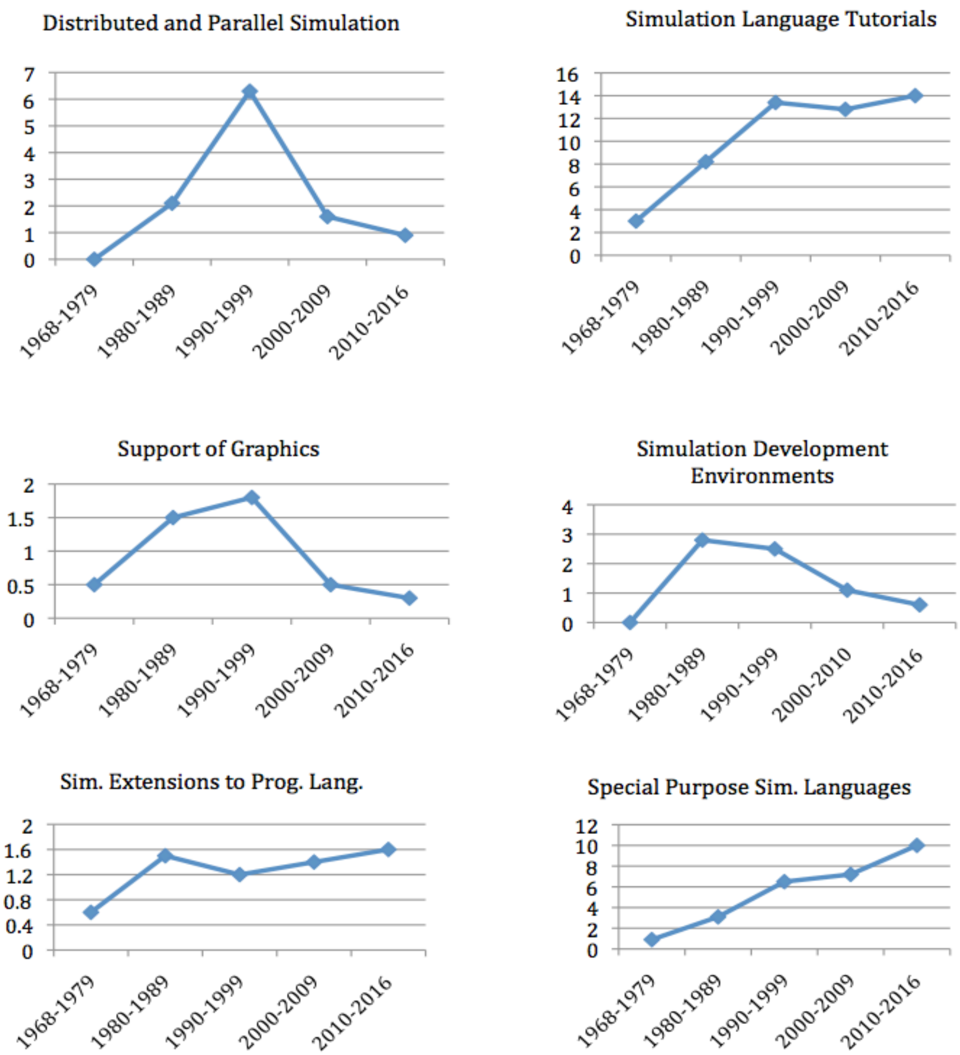

Figure 2: Topic frequency changes over time.

The plotted data are the average number of papers presented in each conference on the ordinate (y-axis) during the time interval identified on the abscissa (x-axis). An immediate observation is the clear differences among the graphs. Moreover, three identifiable subsets appear: (1) topical areas where the average number of articles demonstrates a steep rise followed by a significant decline (Distributed and Parallel Simulation, Support of Graphics, and Simulation Development Environments); (2) topical areas showing a steep rise followed by a leveling (Simulation Language Tutorials, Simulation Extensions to Programming Languages); and (3) a topical area (Special Purpose Simulation Languages) with a more gradual rise persisting throughout nearly 50 years. Admittedly, the scales on the ordinate axes differ, and the measures are relative to the total number of articles appearing in that topical area. Yet, the differences stimulate more specific explanation.

- The topic, “Distributed and Parallel Simulation” emerges in 1978-83; thus a count of zero articles in the first decade is self-explanatory. The steep climb during 1980-2000 shows the intense research activity in the techniques for efficient execution, initially creating two camps, nominally labeled “conservative” or “optimistic,” each advocating its position with religious fervor during 1984-1994. A conference, launched in 1985 to address distributed simulation adopts the name, “6th Workshop on Parallel and Distributed Simulation (PADS 1992)” in January 1992. Research activity in the topical area intensifies as the decades transition; and, in the opinion of many, a defining event is the publication of a challenging feature paper by Fujimoto (1993), accompanied by reactive commentaries from leading researchers in the area, and concluding with a rejoinder. The question of survivability of parallel simulation as a viable research area is viewed as a clarion call by the commenters, with possibly one exception.
- The plot for “Support of Graphics” shows zero papers in the first decade due to lack of affordable hardware to support these features. As the cost for graphics hardware decreases, a rapid rise is evident during the 1980-89 period followed by a lesser rate in 1990-99. The decrease after 2000 reflects the incorporation of graphic capabilities into simulation environments, largely eliminating a need for separate graphics support.
- Articles in the category “Simulation Development Environments” show similar behavior. The concept is introduced in 1982-83, materializes in research articles during the period 1980-89, followed by prototypes with gradual insertion into commercial products during 1990-99. By 2000 the SPL is supplanted by the suite of model development and simulation support tools.
- The rise and continuing level of articles in “Simulation Extensions to Programming Languages” stems from a recognized characteristic of human behavior: resistance to change or learning something new. While this interpretation might seem tinged with cynicism, the old claim that, “more simulation programs have been written in FORTRAN than any other language” still retains credibility. The rise from 0.6 during 1968-79 to 1.2-1.6 over the following 36 years can be attributed to the increase in programming languages introduced during that period; *e.g.*, Pascal, Ada, C++ and all the other extensions to C, Prolog, Modula-2, Java, Python, and the list goes on.
- The ascendant behavior from 1968 to 1999 in “Simulation Language Tutorials” in part reflects the effect of simulation extensions to general programming languages described above. Also a factor is the perception of unmet needs as software and hardware technology advances raise expectations that drive increasing modeling complexity. The transition from M&S software capability provided by a SPL to simulation development environments as vendor products during 1990-2000 accelerates the motivations for educational and marketing opportunities as WSC expands and consolidate its image as the premiere international conference in the field.
- The rather distinctive behavior displayed in “Special Purpose Simulation Languages” is more difficult to characterize. The meaning of the term “special-purpose” in the 1970’s is exemplified most notably by SIMSCRIPT II as a base for languages, such as ECSS II and CSP II, supporting computer systems performance modeling. In the 1980’s, application-domain-dependent user interfaces are created by the vendor (CACI) for performance modeling of general networks (NETWORK II.5) and communication networks (COMNET II.5). Adoption of terminology germane to the problem domain coupled with a menu-driven graphical user interface is touted as “modeling without programming.” A related software tool for local area networks, LANNET II.5

follows shortly (Garrison 1991). Additionally, languages simplified to support a single problem domain may be learned more readily.

4.1.4 M&S Language and Environment Analysis

The examination identifies 225 SPLs and environments as subjects of WSC articles, although this number should be treated with some caution since:

- distinguishing a new tool in a highly versatile SPL from the evolution to a new language can be difficult,
- some model implementations are intensely data-driven and might be regarded as a new language, and
- as languages evolve, sometimes names are changed; *e.g.* the transition from SLAM as a SPL to SLAMSYSTEM.

Table 2 lists the languages (or language-based environments) that have tutorials in at least three conferences. Interestingly, of the 225 languages, 159 (71%) appear in a single conference. The table is ordered by the year in which the first tutorial for the language appears, and a count of the number of tutorials for that language is given.

Clearly, GPSS exhibits the highest longevity. The top five SPLs or environments in frequency of tutorials are GPSS (35), AutoMod (26), Arena (22), SIMSCRIPT (18), and ProModel (17). Further observations are suggested by examining Table 2 or derived from the extensive review required for its production.

- General programming languages continue to play a significant role as a base; some are used to construct (library) packages (Pascal => PASSIM, C => CSIM, Java => JavaSim), others as language extensions (Pascal => SIMPAS), and yet others provide an implementation framework (Python => SimPy).
- Traditional SPLs are tailored to produce domain-specific dialects (SIMSCRIPT II.5 => NETWORK II.5 and COMNET II.5) or simulation support environments (SLAM => Visual SLAM => AweSim).
- Packages in newer programming languages are created from the early SPLs, in some cases from the underlying conceptual level. Of signal interest is javaSimulation where the basic constructs of SIMULA, including the co-routine structure employing the thread capabilities of modern operating systems, are implemented in simulation packages executable on PC, Mac, and Sun platforms (Helsgaun 2000). An interesting alternative approach is described in L'Ecuyer, Meliani, and Vaucher (2002), which cites several other Java implementations for simulation.
- With 157 of the 225 "languages" appearing in a single conference, a large number of "flashes" or "one-year wonders" is evident, indicating that simulation software could be perceived as a rich area for language designers while proving to be a "magnetic sinkhole" for prospective entrepreneurs.
- The rise and subsequent decrease of interest in areas of simulation software, such as graphics and parallel and distributed simulation, is confirmed by the figures reflecting the maturation (or "fades") in these areas.

Table 2: Tutorials for computer simulation programming languages or environments.

Software Item	First Year	Last Year	Number of Years
GPSS	1968	2016	35
SIMSCRIPT	1968	2005	18
SIMULA	1968	1986	4
GASP	1969	1977	6
SLAM	1978	1995	16
Ada	1982	1986	3
SIMAN	1982	1995	13
INSIGHT	1982	1990	8
TESS	1984	1988	5
NETWORK II.5	1984	1991	8
Excel	1984	2014	10
CINEMA	1985	1995	11
Smalltalk	1986	1991	3
SIMPLE_1	1986	1989	4
SEE WHY, WITNESS	1986	2012	11
SIMFACTORY	1986	1991	6
CSIM	1986	2001	10
SIMNET	1987	1991	4
FACTOR	1987	1999	8
RESQME	1987	1993	3
COMNET II.5	1988	1995	5
SIM++	1989	1991	3
MODSIM	1989	1999	7
AutoMod	1989	2015	26
SLAMSYSTEM	1990	1994	3
ProModel	1990	2013	17
SIGMA	1990	2015	4
MedModel	1992	2001	8
Arena	1993	2016	22
SIMOBJECT	1993	1995	3
Extend	1993	2003	8
AutoSched	1993	1997	3
SLX	1993	2007	8
QUEST	1993	1998	5
Taylor	1993	1999	5
ALPHA/Sim	1995	2000	5
PROSIM	1995	1998	3
Micro Saint	1995	2003	9
LayOPT	1995	1997	3
SIMPRESS III	1995	1997	3
AweSim	1996	2002	5
Flexsim	2002	2016	14
Anylogic	2005	2015	11
Simul8	2006	2013	4
ExtendSim 7	2006	2016	9
Emulate3D Framework	2007	2015	6
Simio	2008	2016	9
SAS Simulation Studio	2008	2016	7

4.2 Questions and Speculation

The persistent interest in using newer general programming languages and their extensions for simulation is intriguing. Is the explanation provided above for the "Sim. Extension to Prog. Lang." graph sufficient; i.e., reluctance of users facing the challenge of a M&S task to learn a new language? Historically, this explanation undoubtedly applies in the NGPSS case where the compiler is written in COBOL (Nance 1996), but does that alone explain why articles in this category continue to appear at about the same frequency? Does it apply to GASP_PL/I in which a statement-by-statement syntactic translation from FORTRAN into PL/I, utilizing none of the PL/I features, is apparent? Is the motivation driving the transitory interest in Ada for simulation in the mid-1980's the same as that for the more specialized language Prolog? From a wider historical perspective, alternative explanations might include: (1) broadening the potential user (client) community, or (2) utilizing features and capabilities in advancing software technology. Might another explanation be the desire by some to "show off the newest tool"?

5 *OR/MS TODAY*: SIMULATION SOFTWARE SURVEYS

The surveys of discrete-event and mixed (jointly with continuous) simulation software tools, occurring on an approximately biennial schedule, are published in *OR/MS Today*, the INFORMS membership magazine. The initial survey questionnaire, developed by James J. Swain, is described by him as questions that he would want to have answered if he were acquiring a simulation software tool. While the magazine staff handles the mailing of questionnaires to past respondents or to requesting firms, Swain assists in identifying new potential vendors, interpreting responses, and monitoring the questions used in the survey. According to Swain (2017), the current version of the questionnaire varies only slightly from the initial form.

An important distinction regarding the survey data is that the questionnaire is purposed to elicit data for making an informed decision; the motivation of the respondent to the questionnaire is to describe the product in the most favorable light. Using the survey results to uncover historical facts, detect trends, and recognize similarities and contrasts is, to a degree, inconsonant with the intent of either party (questioner or respondent). Caution is exercised in the interpretation of the data for describing the M&S software evolution.

5.1 Scope of the Simulation Software Survey Data

Results from the M&S software surveys are conducted biennially and published from 1991 to 2015 by Swain with a prefacing article and are informally referred to as "the Swain Surveys." Altogether, eleven (11) survey reports exist, access difficulties permit only six full surveys with prefacing articles and two (2) prefacing articles only to be included. A citation of the survey for 1999 indicates that one is published in the February issue. Data presented in Table 3 from these articles provide an overview (Swain 1997, 2001, 2003, 2005, 2007, 2009, 2011, 2013, 2015).

Table 3: Overview of Swain surveys data.

Attribute	1997	1999	2001	2003	2005	2009	2011	2013	2015
Extent of survey	Part	Part	Part	Full	Full	Full	Full	Full	Full
Month appearing	Oct	Feb	Feb	Aug	Dec	Oct	Oct	Oct	Oct
Survey series number	4	4*	5	6	7	8	9*	10*	11*
Number of vendors	--	--	--	38	37	26	29	23	31
Number of products	46	54	47	48	48	48	55	43	55

Note that the asterisk (*) for the survey series number in 1999 denotes a repetition of the number stated in the prefacing article for 1997. Similarly, an asterisk shown in the last three years is to indicate that the prefacing article refers to each with a value of one less than that shown; i.e., identification of the series number in 2011 as "8" repeats the value given in 2009, and the error is propagated in the following years.

The fall-off in vendor responses from 37 in 2005 to 26 in 2009 could be attributed to the effect of the recession in 2008-2009. The numbers for M&S software products in 2005 and 2009 do not parallel the nearly 30 percent decline in vendors. A stronger correlation between vendor and product numbers is shown in the 2011 to 2013 values, with both slightly above 20 percent.

5.2 Examining the Simulation Software Surveys Data

Even with a subset of one-half the total possible, the volume of data provided in the surveys is massive. A workable approach is employed to (1) reduce the data elements by eliminating any that do not contribute to characterization of the M&S software evolution, and (2) organize presentation of the remaining data elements to effect compression with minimal sacrifice of information. Elimination of data decisions forces a refinement of priorities in characterizing the evolution; technical information is considered foremost.

5.2.1 Software Surveys Data: Reduction and Organization

Responses to the 2003 questionnaire are represented in the source document by 23 descriptors (Swain 2003). Some entries are open-ended; e.g.., "Typical Applications of the Software"; four considered less relevant as historical information are eliminated. Two entries giving cost options are eliminated. Although technical, an entry describing storage requirement is eliminated since minimal storage disappears as a binding restriction by 2000. Three entries describing model packaging (for sharing or presentation) that appear under "Model Building" are eliminated. The retained descriptors are listed below.

1. M&S Software Product and Vendor.
2. Host Operating Systems.
3. Model Building.
    a. Graphical model construction (Icon or drag and drop).
    b. Programming access to programmed modules.
    c. Run-time debug capability.
    d. Input distribution-fitting.
    e. Output analysis support.
    f. Batch run or experimental design.
    g. Optimization (Specify).
    h. Code reuse.
4. Animation
    a. Animation.
    b. Real-time viewing.
    c. Export animation (*e.g.*, MPEG version that can run independent (sic) of simulation for presentation).
    d. Compatible animation software.

To this set are added "First Year Appearing", "Last Year Appearing", and "Modeling Paradigms" with the last specifying the M&S paradigms (e.g., discrete-event, continuous/mixed, system dynamics, agent-based, etc.) supported by the product. The model building and animation subsections constitute two vectors since the values for the elements of each are restricted: "yes", "no", or "-". After 2003, the explicit "no" fails to appear, giving way to "-". In 2005, two elements are added to both the "Model Building" and "Animation" vectors. For the former, "Cost Allocation/Costing" (attaching cost parameters to model components), and "Mixed Discrete/Continuous Modeling" are added; for the latter, "3D Animation" and

"Import CAD Drawings". The data structure employed for representing each vector utilizes the ordering shown in Figure 3. Data element names follow those used in the survey questionnaire.

	Element in Position Number (_)
Model Building Vector =	Graphical Model Construction (1)
	Model Building Using Programming / Access to Programmed Modules (2)
	Run Time Debug (3)
	Input Distribution-Fitting (4)
	Output Analysis Support (5)
	Batch Run or Experimental Design (6)
	Optimization (7)
	Code Reuse (e.g., Objects, Templates) (8)
	Cost Allocation / Costing (9)
	Mixed Discrete / Continuous Modeling (10)

Example: -,-,y,-,y,-,y,-,-,- indicates a M&S software tool that provides Run-Time Debug, Output Analysis and Optimization support.

	Element in Position Number (_)
Animation Vector =	Animation (1)
	Run-time Viewing (2)
	Export Animation (3)
	Compatible Animation Software (4)
	3D Animation (5)
	Import CAD Drawings (6)

Example: y,-,-,y-,- indicates a M&S software tool that provides Animation through Compatible Animation Software support.

Figure 3: Explanation of the model building and animation vectors.

A key for the interpretation of survey responses is provided in Figure 4. All responses are recorded as listed in the published survey except for "Modeling Paradigms" supported by the software product, which is not a survey question. The importance of this descriptor from a historical perspective seems self-evident, and the attempt is made to extract this information from other responses or, in a very few cases, resorting to an Internet search for the product. If the correct entry is uncertain, a "?" follows the designation provided. Not all answers are easily interpreted, e.g., does "message-based" mean "object-oriented" for a paradigm designation? Apparent inconsistencies are evident in a few cases; e.g., a tool described as strictly a Monte Carlo add-on for financial simulation also has the capability for mixed discrete/continuous modeling. A null answer or blank response is a rarity, suggesting that the cause might simply be an oversight.

5.2.2 Analysis of the M&S Software Surveys Data

Because of its extensive size (over 16 pages) Table 4 is stored as an Addendum that can be accessed at the North Carolina State University Libraries website. The organization and compression of the simulation software surveys data creates an analyzable database from the overwhelming mass faced in the

Symbol	**Represents**
DES	Discrete Event Simulation paradigm
MC	Monte Carlo Simulation
SD	System Dynamics
CS	Continuous Simulation paradigm
A-B	Agent-Based Modeling paradigm
EDUC	Educational use
Msg	Message-based Modeling paradigm
Auxiliary	Auxiliary M&S software tool; *e.g.*, distribution-fitting, animation
y	Yes, or capability/feature is provided
n	No, or capability/feature is not provided
-	Capability/feature is not provided or answer is undetermined
_	(Underscore) Blank or no answer is given
?	Uncertainty regarding answer or paradigm designation

Figure 4: The key for interpreting survey response presentation in Table 4.

published form. While only manual examination is employed in producing this initial perspective, an automated analysis might be a future objective. Explanation of the organization and compression applied to survey entries is the intent herein. Readers motivated to examine the complete results are encouraged to access the addendum, which is designed to assist in a full understanding of the results in Table 4 construction.

5.2.2.1 Analysis of Product/Vendor Data: Examples

Entries are organized by software product, with the vendor identified for each product. Each year a product appears is shown, with version changes if indicated. Changes in vendor associations with a single product are noted. Using the descriptors explained above, product entries are described for each year. An excerpt from Table 4 is shown in Figure 5 to illustrate the utility of the basic data structure.

Vendor Product Listed in Survey	**First Year**	**Last Year**	**Operating Systems**	**Modeling Paradigms**	**Model Building Vector**	**Animation Vector**
aGPSS	2011		Windows	DES	-,-,y,-,y,-,y,-,-,-	y,-,-,-,-,-
aGPSS Belber AB	2013		Windows	DES	y,y,y,-,y,-,y,-,-,-	y,-,-,y-,-
aGPSS aGPSS Simulation System Ed	2015		Windows, Mac	DES	y,y,y,-,y,-,y,-,-,-	y,-,-,-,-,-
atRISK	2005		Windows/Excel	MC	y,y,-,y,y,-,y,-,y,y	y,y,y,-,-,-
atRISK 5.5 Palisade Corporation	2009	2009	Windows/Excel	MC	y,y,-,y,y,-,y,y,y,y	y,y,-,-,-,-
AgenaRisk Agena	2005	2005	Windows, Unix, Linux	MC	y,y,-,y,y,y,-,y,y,y	_,_,_,_,_,_

Figure 5: An excerpt from Table 4.

The organization assists in an analysis of the evolution of an individual product, a vendor's slate of products, products offered in a given year, or the body of M&S software products over the period that survey data are available.

Three M&S software products are shown in Figure 5: aGPSS, atRISK, and AgenaRisk. Note that aGPSS shows a change in vendor from Belber AB to Simulation System Ed(ucation) in its listings for 2013 and 2015. The listing also indicates the product can now be hosted by a Mac operating system in addition to Windows. While aGPSS supports discrete-event systems (DES) modeling, atRISK and AgenaRisk support Monte Carlo (MC) modeling applications. AgenaRisk appears to exemplify the "one year wonders" or "flashes;" and atRisk, with a four-year separation between introduction and last appearance, might be described as a "fade."

Use of the two vectors can be employed on a macro or micro level. Observing the number of changes in the model building vector for aGPSS between 2011 and 2013, one can clearly conclude that additional capabilities are added. On a micro level, examining the individual elements added reveals that graphical model construction and access to programmed modules (library of components) are added to the 2011 capabilities of run-time debug support, output analysis, and optimization.

Improvements in the animation capabilities of aGPSS are indicated on the macro level by the addition of a single element. Dropping to the micro level reveals the addition of the capability for interfacing with compatible animation software in 2013. Is the apparent removal of that capability in 2015 a price paid for expanding the host OS capability to Mac? While intriguing, such a speculative question cannot be answered by the survey data.

5.2.2.2 Analysis at the Surveys Data Level

During the period 2003 to 2015, analysis of the six survey responses for which complete data are available identifies 135 M&S software products. Some 15 appear for the first time in 2015. Removing these from consideration, 43 products (36%) appear only once in the survey responses. Further, 22 products are listed in only two (18%). These figures reflect a volatile marketplace. Further analysis might cast light on these immediate impressions.

The (full) survey data begin midway in the series (six of eleven based on data from Table 3), and the existence of a commercial marketplace predates the initial survey (1991), according to the recognition of the 1997 survey as the fourth in the series (Swain 1997)). Thus, a "start-up effect" cannot be argued, either in terms of the surveys or the marketplace. The data structure organization in Table 4 facilitates further recognition of similarities and contrasts among vendors and within the slate of products for a single vendor.

Among the firms responding throughout 2003 to 2015, ProModel Corporation is the vendor for 13 products in one or more surveys. In 2015 products are identified for portfolio and process simulation, supported by an optimization suite. Prior products addressing specific application domain focus include health care, clinical trials, patient flow, capacity planning and project management. The strategy of "*tailoring*" is evident; i.e., narrowing modeling terminology; customizing a graphical interface; re-specifying the icon library; or re-defining the output to create a more comfortable and accommodating client experience. Such a strategy is extremely cost effective following the completion of a contract using the more general tool in the target application domain. Similar "*tailored products*" are shown in the responses for INCONTROL Simulation Solutions and Flexsim Software Products, Inc., The tailoring strategy contributes significantly to the appearance of volatility in the M&S software product offerings.

Returning to Figure 1 and the unexplainable slight blip in the software tools count in 2011, a possible explanation is furnished by the surveys data. Twenty (20) products are introduced (offered for the first time) in that year by all vendors; seven do not reappear in 2013. At the least, six of the 20 introduced in 2011 are tailored products.

From the displays in Table 4, the model building and animation vectors, more specifically, changes in either over the period, enable recognition of product improvement, adaptation, or stability. Examples of an improvement or adaptation strategy are the products BLUESSS simulation package, CSIM 20, GoldSim, and Micro Saint Sharp. More indicative of stable products are Analytica, Arena, ExtendSim AT, ExtendSim Suite, Simcad Pro, SIMUL8 Professional, and SIMUL8 Standard. The massive volume of data contributing to Table 4 warrants repetition of the caveat that errors are quite possible. Another caveat applicable to Table 4 is that minor variations in the vector values reported in survey responses for the same software product might be attributable to the varying interpretations between different individuals responding for the vendor.

A final comment, hinted by Table 4 data but more attributable to prior speculation concerning the strategies of simulation software vendors, relates to the unique approach of Wolverine Software that deserves notable mention. By developing SLX in 1997 to reinforce and *extend* the capabilities of its flagship product GPSS/H, introduced some 20 years earlier; Wolverine provides a layered architecture for creating a customized simulation language in response to future needs specified by a user (client). On a conceptual level SLX assumes the role of a compiler-compiler or meta compiler. This forward-looking view is impressive; how it fares in the commercial sector as a strategy is another matter.

6 CONCLUDING SUMMARY

Unsurprising is the magnitude of change in the nature of M&S software over the past sixty years (since K. D. Tocher's GSP). Also not a surprise is the acceleration of the change since the late 1970's. The expansion of the subject content from SPLs in 1993, when (Nance 1996) is written, to M&S software in 2017 is so vast as to make the task of capturing it to the same level of detail implausible. The treatment in the earlier work (Nance 1996) for the major SPLs is comparative: noting how each language fulfills the six mandatory requirements identified in the paper, examining the language syntax and semantics in doing so, and including application context and developer commentary and explanation. The description of *M&S software* in this paper is forced to adopt a view that examines the subject in terms of growth, trends, and trajectories. Recognizing the limitations, the characterization of *"initial perspective"* is appropriate.

The two data sources forming the basis for this study are believed to be quasi-independent; one (the WSC Archive) is a broad view produced by a wide swath of the simulation community (researchers, practitioners, educators, students, M&S product developers and vendors). The M&S software survey responses furnish a decidedly commercial perspective, formed from more narrowly focused views. Conclusions emanating from the examination and analysis of each source are provided in the individual sections. What follows is a synopsis based on a synthesis of conclusions from the two sections.

- Revolutionary advances in basic computing hardware in the 1960's and 1970's (vacuum tube to magnetic core to transistor to integrated circuit) render computational elements exhibiting radical decreases in cost, size, and requisite power accompanied by increases in switching speeds and packaging density. Concurrent order-of-magnitude reductions in access times and increases in sizes of principal and auxiliary storage (drum to magnetic tape to disk to hierarchical design) create a staggering succession of performance improvements and cost reductions.
- The responses in software technology, particularly in operating systems, are quick to follow (or on occasion to lead), and minicomputer, microcomputer, and workstation deliverers of computing services challenge the mainframe domination.
- The pervasive influence of hardware and software technology on the evolution of M&S software tools is difficult to convey; e.g., graphics and animation, parallel simulation, distributed simulation, interoperability of models, networking technology, virtual reality, and the re-emergence of "human-in-the-loop" modeling.

- Introduction of new M&S software capabilities and techniques becomes more apparent in the commercial domain; however, the linkage between academic and commercial interests remains quite visible.
- Although evident in individual papers since WSC 1981, the first Military Applications track appears in WSC 1988. Employment of simulation in training follows shortly thereafter, particularly in military and/or distributed simulation projects.
- Gaming reappears as sharing a close tie with simulation, stemming from both training and entertainment uses.

Additional information on software tools supporting Web-based simulation circa 2009 is available in a comprehensive and thorough review by Byrne, Heavey and Byrne (2010). Open-source M&S software tools are evaluated by Dagkakis and Heavey (2016) according to informative criteria defined by the authors. A list of simulation software tools, partitioned by "Free" or "Proprietary" is accessible on Wikipedia (https://en.wikipedia.org/wiki/List_of_computer_simulation_software).

The data compilation, organization, and compression in Table 4 represents an investment in future examination and analysis. Hopefully, further analysis is motivated by its existence. Is a more in-depth analysis useful? That question provokes a second: "How would such a study be conducted?" Answers to both questions, depending on the responder, are likely to be provocative.

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