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A Bibliography for the Development of An Intelligent Mathematical Programming System

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Abstract

The purpose of this paper is to provide references in the rapidly growing area of intelligent environments for modeling and analysis, particularly for the development and use of decision support systems couched in mathematical programming. This is the focus of the project to develop an *Intelligent Mathematical Programming System* (IMPS). One way to divide the project's scope is: formulation, analysis and discourse. There are, however, interdependent components that pertain to model management, software engineering, learning models, and other elements taken from a variety of disciplines.

Some History

The environment for modeling and analysis has become an active research and development activity due to need and to advancements in computer hardware and software. Although the primary purpose of this paper is to provide a comprehensive bibliography, at least for mathematical programming, some historical perspective is appropriate.

Special languages for modeling linear programs began in the late 1950's with special matrix generators. Report writing became integrated with the first full system, MAGEN, in 1963. Shortly thereafter, GAMMA (1966) and then DATAFORM (1970) entered the scene, so by the early 1970's there were three primary systems (plus some others that appeared and disappeared). Although these systems have undergone internal improvements (MAGEN evolved into OMNI and GAMMA into GAMMA/2000), the languages look about the same to the modeler.

Throughout most of the 1970's the environment was to write matrix generator and report writer programs, generally requiring the skill of a programmer, and batch process them. At best, patches were put on the old designs to take some advantage of interactive processing. Very few analysis aids were provided, but experts were able to make innovative use of what was available and develop their own, tailored aids. The first integrated analysis aid, designed for interactive query for any LP, was PERUSE in 1977 at the U.S. Federal Energy Administration. This evolved into ANALYZE (1978), which itself has evolved several levels, including a rule-based intelligent support component.

In the late 1970's Alex Meeraus, in collaborations with Jan Bisschop, Anthony Brooke, and David Kendrick, developed the first algebraic language, GAMS. Since the early 1980's, this has become a standard in academic communities and is widespread in companies due to its accessibility, power and ease of learning.

In 1983, Robert Fourer articulated a contrast between the *modeler's view* and the *algorithm's view*, and he built a case for new design considerations that would combine strengths of general, high-level languages (like FORTRAN, which was very popular at the time among mathematical programmers) with special-purpose languages. His own contribution to XML was an outgrowth of the deliberations he reported, and this inspired the developments of AMPL and MODLER.

As listed in [Greenberg and Murphy, 1992], the mid 1980's brought an upsurge of new modeling languages and systems for mathematical programming, and this stems from three basic reasons. First, early systems were written for specific computing environments and were not immediately adapted to modern programming environments that emerged in the 1980's. Second, a new generation of modelers and managers became dissatisfied with their perceived complexity of the early systems; in particular, these had (and still have) the requirement of a programmer's skill level, and most universities do not teach these languages, partly due to their computer dependence and partly due to their cost. Third, demands for computer-assisted modeling and analysis increased not only with need, but also with new technologies that render such demands achievable, notably database concepts, artificial intelligence and graphics.

One of the differences between the traditional and modern languages is that the latter are *algebraic*. What makes a language algebraic? One characteristic is the degree to which it is declarative, rather than imperative. The general idea is that a declarative language, which may be functional or logical, expresses what is being computed rather than how to compute it.

Another characteristic is the extensive use of domains over sets. Related to this is the perception that algebraic descriptions require the modeler to represent the model relations by its constraints, or rows.

Until recently, there had been an ongoing debate since the 1960's whether it is better to ask the modeler to write by rows, rather than by columns. Academics prefer the row form because it most closely resembles what is put on the blackboard during teaching. Many industrial users, particularly in process engineering, have traditionally preferred the column form because while the model is being formulated, it is more natural to think in terms of the transformations that comprise the activities. More generally, this is true for any network model because one thinks about arcs, which are the activities, rather than define the entire model node by node. While MAGEN forces a column-wise view in its design, other early languages, like DATAFORM and GAMMA, do not. Further, all three have the equivalent of a concept of sets and domains, so the distinction from an algebraic language is not crisp (Geoffrion [1992] makes this point very succinctly in the context of indexing).

Although an algebraic language need not force a row view of formulation, the algebra is more suited to this and makes it difficult to use a process formulation in the traditional sense. There are many examples in GAMS, however, to show that it is a matter only of style, not of feasibility, to write the code for processes, rather than what we tend to regard as purely algebraic. Moreover, AMPL has special specifications for networks that enable a formulation defined more naturally by the arcs, rather than the node-form, which is the purely algebraic representation. Thus, just as one could use a traditional language, generally regarded as non-algebraic, to write an algebraic form, one could use an algebraic language to write a process form. In both cases, however, these uses disturb the style of the language.

In fact, with modern environments, many more forms, or *views*, can be supported. Baker [1983] and Welch [1987] introduced the block schema view, which comprise interfaces for MIMI and MathPro, respectively. Although MODLER's input is algebraic, it supports the block schema and other views for query and reporting [Greenberg, 1992].

Another view, which has been around for decades, is that of a process network. Chinneck has recently developed this view for model analysis. The unpublished monograph by Fred Glover [1983], plus articles he wrote with Darwin Klingman and Nancy Phillips, extend this to *netforms*. Their recent monograph [1993] uses many applications to show the power of the netform view. Another formal basis for this view is that of *fundamental graphs*, introduced by Greenberg [1978], and subsequently analyzed in a series of papers by Greenberg, Lundgren and Maybee [1981-89]. Schrage's activity-constraint network, described in his LINDO book [1981], is the same view as the fundamental digraph, and Choobineh [1991] recently re-discovered this. Others present the fundamental digraph, with some name or another, to emphasize its power in diagramming. While these digraphs capture flow relations, the fundamental signed graphs (also part of the more general theory of fundamental graphs) capture *economic correlation*. It is also useful to consider the row and column graphs, which have been incorporated into the ANALYZE system [Greenberg, 1993].

One of the few formalisms for modeling is Geoffrion's *structured modeling*, developed in the mid 1970's and still progressing. His most recent annotated bibliography [1994] reflects the widespread vigor with which this has influenced new generations of modeling systems. Central to Geoffrion's structured modeling is its intrinsic ability to offer many different views to different constituents while representing one schema internally. This has been explored by many, notably by Krishnan's [1991] frame views, Kendrick's [1990] graphic views, and Baldwin's [1989] views in problem domains. Jones [1989] has related this to graph grammars; and, Ma, Murphy and Stohr [1989] have exploited model syntax for relating algebraic and graphic views.

In short, what is natural for one modeler may not be for another, so flexibility is the order of the day. We want to have a modeling environment that aids a person with the translation from a flexible, thought-capturing dialogue to appropriate forms of text, algebra and graphics during the modeling process, rather than place the full burden of translation on the modeler. This aspect is described more fully by Greenberg and Murphy [1991] on multi-view architectures and by Jones [1994] on visualization.

Besides modeling environments, we must consider why models are built: to support decision-making. This raises needs for supporting analysis and model management. As indicated by the category index following the bibliography, there have been fewer papers focused on environments for analysis than for modeling, although these are not entirely separable. The only system designed exclusively to support analysis of LP results is ANALYZE, and this includes a rule-based intelligence component that enables model managers to design rules to help those less expert in LP. (There are modeling languages with links into ANALYZE: GAMS, MODLER and OML. There is also a new link with OSL, and links with AMPL and LINDO are under construction.)

MIMI [Chesapeake Decision Sciences, 1988] is a state-of-the-art system that uses technologies of operations research, database, and artificial intelligence to provide many ways to view a linear program and analyze its solution. Its MIMI/E component is an expert system shell that interacts with the rest of MIMI to enable a model manager to design a rulebase to support analysis. The MIMI system continues to evolve, its latest development being a graphics component based on Chris Jones' work [Jones and Baker, 1994].

More generally, there has been increasing interest in reasoning about models, both in operations research and in artificial intelligence. Particularly interesting blends of linear programming and constraint logic programming are given by Van Hentenryck [1989] and by Lassez and McAloon [1992]. Issues of redundancy and consistency are among these interests, both theoretically and practically, which impinge upon the language design. Other integration for particular models are illustrated by the works of Glover [1989] and McBride et al [1989] (also see other papers in that volume of *Annals of Operations Research*).

As this bibliography reflects, there are many research activities about environments for modeling and analysis, with concomitant model management. The added dimension of intelligence is more recent, actively pursued by diverse professional communities. In part, intelligence has to do with discourse, such as natural language. Non-linguistic attributes of intelligence have been mostly aimed at assisting modelers, and this is still in its infancy. It appears that much less variety has been applied to intelligent analysis support until one ventures into other disciplines, outside operations research. Then, synthesis of methods and concepts from mathematics, physics, and elsewhere begin to reveal a common quest for structure (see [Forbus, 1985; Bradley and Stolle, 1995] for elaboration).

As large as this bibliography is, there are more results that are expected to bear fruit. These are discussed in some of the references and are not included here. What is intended with this bibliography is a starter collection for many avenues, and comprehensive references for those most directly connected to mathematical programming modeling and analysis. The IMPS project is chartered to investigate all of these and integrate the results into a system architecture that marks a new generation of mathematical programming systems.

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Some Statistics

Each paper that pertains directly to mathematical programming is counted in one category in the following table (unlike the Category Cross-Reference Index, where a paper can appear in more than one category), which gives the number of papers over the past decade. Specific modeling systems for mathematical programming (AMPL, DATAFORM, GAMS, GAMMA, LPL, MathPro, MIMI, MPL, OMNI) are counted under Formulation. Model management papers are restricted to those given in this bibliography, which is focused on mathematical programming models (there is a vast literature on general model management, especially in simulation). When a paper first enters this bibliography as a technical report, then gets published years later, not only is the reference revised, but so are the statistics.

	Analysis	Discourse	Formulation	Model Management
1983	8	1	7	1
1984	8	2	2	4
1985	11	2	7	1
1986	6	11	18	5
1987	7	7	15	2
1988	9	5	15	5
1989	10	4	20	0
1990	12	4	29	1
1991	8	2	17	2
1992	16	5	11	2
1993	26	3	14	4
1994	15	3	4	1
1995	9	1	2	0
	145	50	169	28

The total is less than the 502 citations because some are not counted, such as background books and all those before 1983.

The statistics indicate that most research and development activities have been spent on formulation support. This is especially true during 1986-91 when the number of new mathematical programming modeling systems surged. In total, analysis support is the second most active area. But, since 1983, new results for modeling and analysis have not generally been treated jointly. In particular, with few exceptions (notably, MIMI), modeling systems have not incorporated very many analysis aids. New results for discourse and model management have been relatively neglected in mathematical programming (with some exceptions), but there are recent activities for graphic discourse, which will begin to appear in the open literature during the next few years.

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43. J.S. Gu and X.C. Hu, "Trace Averaging Domain Decomposition Method with Nonconforming Finite Elements."
44. J.S. Gu and X.C. Hu, "Preconditioners for Nonconforming Element Discrete Problems. I"
45. J.S. Gu and X.C. Hu, "An Iterative Substructuring Method with Nonconforming Elements."
46. J.S. Gu and X.C. Hu, "Extension Theorems for Plate Elements with Applications."
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48. F.G.C. Valentin and L.P. Franca, "Combining Stabilized Finite Element Methods."
49. M. Lesoinne, C. Farhat and L.P. Franca, "Unusual Stabilized Finite Element Methods for Second Order Linear Differential Equations."
50. L. Langley, J.R. Lundgren and S.K. Merz, "The Competition Graphs of Interval Digraphs."
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52. J.R. Lundgren, P.A. McKenna, S.K. Merz and C.W. Rasmussen, "The p-Competition Graphs of Symmetric Digraphs and p-Neighborhood Graphs."
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