Visualization and Finite Capacity Planning in the Process Industries

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Practitioners often find it hard to grasp the mathematics of planning and scheduling models used in the process industries. Visualization is an emerging field of study that provides deeper understanding of finite capacity planning (FCP) models for both independent and dependent demand. Through this paper, we introduce the formal study of visualization to APICS and discuss its application to process-oriented FCP models. Our focus ranges from spreadsheet-based scheduling systems to traditional material requirements planning (MRP) applications run on minicomputers.

Visualization, as studied within operations research, seeks to improve understanding of mathematical models through various methods of representation, including visual interactive modeling, graphical user interfaces, animation and virtual reality. It provides a new way to comprehend mathematics and models from a visual perspective, rather than from the symbolic notation associated with methods such as linear programming and simulation. Woolsey [33] argues that useful modeling only takes place when the model builder makes results transparent to non-mathematicians. Often we see practitioners ignoring powerful methods of modeling because they can not visualize the algorithm, or the solution. As Harvey Greenberg, a professor at the University of Colorado once stated, "We can solve far larger problems than we can understand."

Capacity planning problems in the process industries involve huge numbers of variables and seldom have clear-cut solutions. Consequently, complex interactions take place between FCP models and users. The nature of this interaction determines the ability of planners using FCP models to find the best production plan. Visualization plays an important role in the understanding and implementation of FCP models. Hence, an awareness of the techniques of visualization will improve the productivity of FCP models in practice.

Our comments on visualization capture collective experience with FCP models in both industry and academia. We draw from independent research conducted at the Center for Process Manufacturing located at Penn State–Erie. The Center is a formal partnership between APICS, Penn State, and industry with the goal of transferring applied research from academia into practice. Each year since 1994, the Center holds the Process Industry Technical Conference to present applied research dealing with process-oriented firms. The conference provides a good source of information on the needs of the process industries. From presentations held at the conference, we formed opinions on the study of visualization and FCP models.

The body of this paper summarizes our research on visualization. As appropriate we add commentary on issues and applications we think interesting to members of APICS. Beginning with an analysis of the formal aspects of visualization, we follow with a discussion of the relationship between visualization and finite planning in the process industries. We then proceed with an exposition of visualization as part of model formulation and conclude the paper with some interesting developments in the representation of linear programming problems.

THE STUDY OF VISUALIZATION

The origin of visualization comes from the basic sciences, including biology, chemistry, geology, medicine and physics. Students involved in these disciplines learn about complex phenomena by drawing pictures or using scale models. At many universities, professors teach organic chemistry with computer animations that show molecules rotating through space as each step of a chemical reaction proceeds. This is an example of scientific visualization. With the advent of the microcomputer, and enhanced computer graphics, scientific visualization takes on an important role in the teaching and implementation of scientific principles. Larkin and Simon [16] state that many research mathematicians, physicists, and engineers use graphic and diagrammatic images as part of their everyday work lives.

In contrast, mathematical models of business problems deal with information rather than physical systems. In many situations, business information is not as easy to visualize as a physical system. When using models to find mathematical solutions for business problems, we employ techniques like optimization, simulation, or heuristics that are hard to understand because there is no concrete representation. Managers often struggle with conclusions drawn from abstract computations, and seldom recognize them as valid. It takes many years of training in mathematics and operations research to comprehend the notion of an abstract mathematical model for decision making in business. Visualization plays a vital role in creating awareness of models for those managers with little formal mathematical training. By using visualization, managers can analyze data and make decisions without detailed knowledge of the mathematics behind the models. Jones [14] notes that some are calling this emerging style of visualization *informational visualization* to distinguish it from scientific visualization.

In a classic article published by *Interfaces*, Vazsonyi [26] mentions that, until the 19th century, geometry dominated the thinking of natural scientists. It is only recently that algebraic thinking is more prevalent. He goes on to note that Isaac Newton proved every theorem in support of the basic laws of motion with geometric means. Because the current shift toward algebraic representation plays down the graphic way of thinking, modern managers not highly trained in mathematics are poorly prepared to visualize complex problems. We see an educational opportunity to resurrect the graphical way of thinking in management training. Though visualization is not a complete replacement for university education in model building, it does serve as a bridge for those managers not choosing operations research specialization as a career path.

The study of visualization also helps computer software companies solve practical business problems. Of the many mathematical models developed by industry and academia, only a small number make it to wide application. The low productivity of model implementation causes great concern. In every business firm, there are hundreds of applications for models, yet we seldom experience the full potential of applying models to improve decision-making. A very interesting article published in 1987 by Geoffrion [11] identified four causes for low productivity in model implementation:

1. In most situations, models require three representations: (a) a natural representation suitable for communication with managers without special training in mathematics, (b) a mathematical representation suitable for analytical use by model builders and (c) a computer-executable representation. Such multiple representations are inefficient by virtue of their redundancy and demand many different skills.
2. Upon formulation of a model, the analyst must choose a solver to run the model. This interfacing process takes a great deal of time and requires specialized skills.
3. Most modeling software addresses just one among the many kinds of models that arise. If several models need to work together, a common situation in practice, a great problem in integration results.

4. Modeling software typically caters to just one or two of the many phases of the total life cycle associated with model based solutions.

Process-oriented firms attempt to avoid low productivity in modeling by implementing software packages for finite planning, MRP, and other enterprise functions. When firms use packaged software for manufacturing planning and control, they may avoid the downfalls of (1), (2), and (4), but often packaged software is lacking in (3). We support the use of spreadsheets in conjunction with enterprise resource planning (ERP) software to develop flexible models and to offer more opportunities for visualization. Computer spreadsheets combine user-defined, visual representation with structured programming and database capabilities. In the hands of an experienced end-user, spreadsheets provide unlimited capabilities to model production and inventory management systems. Besides opportunities for visualization, spreadsheets also provide a strong interactive ability well-suited to the recursive problems encountered by material and logistics managers.

As we conclude our discussion of the study of visualization, we now turn our attention to the research available on visualization.

LITERATURE REVIEW

We found the published research on visualization and finite capacity planning in the process industries a bit thin. A book by Jones [14] proved a major resource and guided us to several interesting articles on the application of visualization to production scheduling. Walker and Woolven [28] provide a summary of a visual planning system implemented at Alcan Aluminum in Canada. Jones [13] details a three-dimensional gantt chart used for the m-machine, n-job shop scheduling problem. Both of these articles examine the role of interactivity in solving scheduling problems.

The application of visualization to logistics and network optimization yielded a greater number of sources. An article by Camm, et al. [7] tops the list as an excellent study of visualization in practice. The work deals with the process Proctor & Gamble (P&G) used to reconfigure its manufacturing network, resulting in savings of over $200 million per year. P&G merged integer programming, network optimization and geographical information systems to create maps visualizing plant location combined with the path of raw materials movement and shipments to customers. The article provides a prototype for anyone interested in the right way to do network optimization.

A well-quoted and very impressive article written by Lembersky and Chi [17] documents early work on decision simulators (DS) at Weyerhaeuser, Inc. They write about developing an interactive dynamic programming model for workers to test different crosscutting and log allocating decisions for economic value. The interesting aspect of their work flows from the following sentence: "With the flavor of video games and flight simulators, a DS provides an interactive visual (instead of numerical) simulation of the actual decision-making scenario, including the consequences of the decisions made."

At the end of the article, Lembersky and Chi list three points that provide a general characterization of successful DS systems:

1. A DS provides a believable representation of the actual decision-making environment
2. A DS is highly interactive and provides immediate feedback on the effect of decisions.
3. A DS is easy to use, without special training.

These observations are worthy of note in any attempts to build visual-based decision simulators for FCP models. However, we must mention this application of visualization deals with a physical system (cutting logs). Informational visualization still proves a much more difficult problem.

The final body of literature we reviewed deals with something called visual interactive modeling (VIM). Hurrion and Secker [12] published the first work on VIM in 1978. Bell [4], [5], and [6] provides a well-accepted overview of VIM spanning from 1985 to 1991. Early efforts in VIM involved simulation of manufacturing systems using interactive graphics. A common example involved the simulated flow of materials between work centers. As the simulation progressed, work in process queued up between work centers. The goal of the simulation involved the balancing of flow within the plant. Users observed the simulated material flow on the computer screen and had the ability to stop the simulation at any time to adjust throughput rates. This application of VIM received much criticism because the user could stop the simulation before statistically relevant results occurred. For this reason, VIM never caught on as an accepted part of mathematical simulation in the United States. In addition, many American researchers tend to focus on solution algorithms rather than the practice of implementation. Practitioners rank the level of interactivity, a strong point of VIM, as an important aspect of model implementation. Despite the lack of adoption in America, researchers in Britain and Canada continued to develop the concepts of VIM. O'Keefe [19] defines VIM as containing the following attributes:

- Visual output: portraying the dynamic behavior of the system model.
- User Interaction: allowing the user to interact with the running model. Interaction can be model-determined, where the simulation halts and requests input from the user, or user-determined, where the user halts the simulation at will.
- Visual Input: where a model can be created visually instead of being programmed or data driven.

With this approach to modeling, Kirkpatrick and Bell [15] found that 70 percent of modelers in a survey they conducted felt that their recommendations were implemented more often when a VIM model was used for the analysis. While little published, empirical evidence exists to support the value of VIM in solving problems more quickly, O'Keefe and Pitt [20] do report that users of VIM had more confidence in their solutions. In summary, VIM offers potential for communicating greater understanding of models. However, more research must take place before VIM gains widespread acceptance as a problem-solving technique rather than its status as an implementation method for models.

We acknowledge the technical aspect of visualization as an important part of the literature, but we also must cover the literature dealing with the softer aspects of modeling to provide a balanced view of visualization. Recently, the process of modeling received increased attention from model builders because algorithm development alone does not ensure successful model implementation. Although most members of APICS are model users, not model builders, we believe great value exists in learning how to build a model so that better understanding of full-scale, complex systems like FCP models occurs.

Every complex model was once a simple model. Practitioners can learn about simple models and extend that knowledge to visualize the workings of a full-scale model. This principle is so important in the implementation of FCP models that we believe APICS certification exams should include a section on building simple models to solve basic finite capacity problems. In addition, all practitioners should have a fundamental understanding of the process of modeling. One can learn models, yet not know modeling. Models deal with the mathematics of solutions, while modeling deals with the art and science of constructing an effective model to solve a problem successfully.

Willemain [30] and [31] does a detailed job of describing the process of model building based on his observation of a dozen expert modelers. He notes that modeling seldom follows a linear path, and that good model builders have the ability to verbalize and visualize the models they seek to construct. Willemain makes special note that expert modelers spend time drawing and doodling as they develop more than one alternative model to solve a problem. In each case they start small and add to the model in steps.

Powell [21] writes an outstanding article describing six key modeling heuristics for "quick and dirty" modeling. The article relates his experience in teaching a graduate level "studio" class on modeling for M.B.A. students. The class is quite popular, but Powell states that students find it very challenging because most of the modeling assignments are open-ended with no single correct answer. This type of class approximates real-world modeling very closely. Visualization is one of the six key heuristics he mentions. This article should be standard reading for APICS members involved with FCP models in the process industries.

THE CHANGING NATURE OF FINITE PLANNING

The first FCP models implemented in the late 1980s dealt with scheduling packaging lines in the consumer goods industry. These early commercial software scheduling systems usually consisted of a single model that provided the "best" answer. Since that time, FCP models developed into more sophisticated applications that deal with both independent and dependent demand. Based on our experience, we found it is seldom that a single, large model will provide useful solutions to finite capacity problems. Rather, multiple models must work in unison to obtain the best solution.

In 1994, we developed a table to visualize the functionality of the three main approaches for solving finite capacity problems: optimization, simulation and heuristics. **Table 1** shows that each modeling approach has strengths and weaknesses. By definition, a model is only a representation of some aspects of the total system. It is rare that a single model captures all aspects of a system.

TABLE 1.

COMPARISON OF DIFFERENT SCHEDULING APPROACHES

	OPTIMAL	SIMULATION	HEURISTIC	MIXED
HOLD TIME		X	X	X
QUEUE TIME		X	X	X
CUSTOMER SERVICE		X		X
FORCAST BIAS		X		X
SET-UP COST	X		X	X
HOLDING COST	X		X	X
OVERTIME COST	X		X	X
CAPACITY (LINE, PROCESS)	X		X	X
PRODUCTION LOT SIZING	X	L	X	X
PRODUCTION SEQUENCE	X	L	X	X
CUSTOMER DUE DATE	X	X	X	X
FAMILY STRUCTURE	X			X

X = Functional
L = Limited

Practitioners in the process industries would do themselves a great service by learning the characteristics of the different models used in finite capacity planning. By building prototype models, APICS members can better visualize how commercial software works in practice. In some cases, prototype models may prove useful enough for full-scale application. Computer spreadsheets provide an excellent platform for experimenting with prototype models. With object-oriented ERP systems, it is easy to download data into spreadsheets for developing new models. Every year, increasing numbers of business school graduates receive training in spreadsheet modeling as part of basic degree requirements. We predict that ever more versatile computer spreadsheets, combined with a generation of business students trained in spreadsheet modeling, will lead to an explosion of modeling applications developed by end users. The spreadsheet will become the basic building block of education and practice in production and inventory management.

Computer spreadsheets also allow end users some interesting opportunities for applications of visualization. With FCP software integrating master production planning and capacitated MRP, production planners now have many more variables to manage. They handle important trade-offs analytically, and they make fewer decisions based on intuition. At times, the amount of data becomes overwhelming, causing difficulty in building a mental picture of a particular FCP problem, or solution.

If an incorrect mental picture of the FCP problem exists in the mind of a production planner, poor decisions result. Vessy [27] makes mention of the "anchor and adjust" heuristic as part of the research into judgement under uncertainty. As production planners experience information overload from FCP systems, they tend to anchor with a past occurrence they take as true, or accurate, then make a mental adjustment based on an assessment of new conditions. From a practical view, this means production planners tend to look at past production plans that gave good customer service or optimal cost, and then compare to new production plans generated by FCP software. They make mental adjustments for changes in demand or inventory, and then gauge if the computer-generated production plan makes sense. Visualization plays an important role in this process by providing the proper tables and graphs to aid in understanding. Good FCP software has the ability to generate graphics and tables based on production plans, and to allow interactivity between the user and the software. Computer spreadsheets offer the ultimate in user-designed visualization tailored to the cognitive style of the user.

Beyond understanding the validity of solutions for FCP problems, many APICS members have difficulty visualizing which FCP models apply to specific situations. We adopt the view that various process industry FCP problems do not share a single, overarching solution. This philosophy breaks slightly from the traditional APICS assumption of a single body of knowledge. As an example, the APICS body of knowledge puts forth "MRP" as a general solution for all dependent demand planning problems. Though MRP has stood well the test of time in discrete manufacturing, it does not apply to all problems in the process industries.

Our approach to problem solving involves inductive thinking. By solving individual problems, we hope to develop a repertoire of models applicable to a wide range of specific situations. With this view, the task of practitioners becomes identifying the correct model application to a certain planning problem. In this sense, the identification process APICS members must accomplish parallels a case in pattern recognition. This may be the root of all modeling activity for builders and users of models.

Our library of models to solve basic problems in the process industries includes the following list:

Independent Demand Models
- Non Linear (chemical industry—take or pay [1])
- Deterministic Simulation (make to stock—lumpy demand [22])
- Mathematical Programming (family structure—near optimal solution [2])
- Heuristic (make to stock—sequence independent [3])
- Heuristic (make to stock—sequence dependent, [9])

Material Requirements Planning Models
- Capacitated MRP (finite planning for dependent demand [24] & [25])

Continuous Replenishment Planning Models
- Supply Chain Management (optimal truck loading [23])

Geoffrion [11] shows some interesting ways to group elements of models together into graphs. When we do some rough grouping of models, a form of visualization occurs, and we begin to see some potentially productive relationships between models. For example, [2] uses an integer programming formulation to determine the lot size of production based on product family grouping. With the integer programming formulation, large problems of over 100 binary variables sometimes take a long time to solve. Given some imagination, the heuristic model with sequence independence [3] accomplishes the same calculation in must less time, giving a near optimal solution. By combining [3] with some elements of [2], we produce a new set of models having greater computational speed. This example shows the importance of structuring our thinking concerning FCP models and visualizing new ways the models can work together to solve specific problems.

VISUALIZATION AND MODEL FORMULATION

Perhaps one of the most important applications of visualization in practice involves model formulation. Linear programming (LP) stands alone as arguably the most import model of operations research. Yet for all its importance, LP experiences barriers to implementation because practitioners find difficulty formulating, coding and debugging large-scale models.

Several authors made convincing efforts to change our thinking concerning the formulation of LP models. Welch [29] wrote an early article on the block wise formulation process taught at Ketron Management Science, Inc. He details a modeling language called PAM in which the practitioner describes an LP matrix with a set of two-dimensional tables: a table representing the block schematic of the matrix and supporting data tables. A computer program processes these tables to produce an LP matrix ready for optimization. Another group of authors, Murphy, Stohr and Asthana [18], give an overview of eight different methods for representing LP models during the formulation phase. Of the methods described, they include a simple overview of the work of Geoffrion [11], which received praise in Jones [14].

Despite the early work of these authors to make formulation of LP models a systematic affair using large-scale computing, spreadsheets now hold almost unlimited potential for practitioners to formulate their own optimization models. Spreadsheets offer a free form for building LP models and release users from the ridged convention of algebraic structures of formulation. The different feel of spreadsheet optimization came as quite a shock when we first used one of the popular add-in solvers called What's Best [32]. The spatial freedom of a spreadsheet allows for a great deal of creativity in model formulation.

As an example of the power of spreadsheets in making LP models, we recently reformulated the LP model documented in [25] to include a more complex network of transportation paths. The new model sized as 1,320 variables and 1,395 constraints. From a blank spreadsheet, we formulated a complete LP model in about six hours. By using the multidimensional indexing option of the spreadsheet and some creative data positioning, we rapidly replicated an initial LP formulation across several worksheets. The ease at producing relatively large spreadsheet LP models opens up new possibilities to build interactive models that simulate capacitated MRP. The "third model" approach we discussed in [25] allows limited capacity constraints to be impose on MRP and drastically improves visualization. In an early article, Geoffrion [10] offers a piercing insight to our later work on "third models." He writes: "Where will the desired insights come from to illuminate numerical mathematical programming models? The approach advocated here is that they should come from simplified auxiliary models that are both intuitively plausible and solvable in closed form or by simple arithmetic. The solution behavior of a well-chosen auxiliary model should be vastly more transparent than that of the full mathematical programming model, yet it should yield fairly good predictions of the general solution characteristics of the full model."

Geoffrion also gives an excellent general methodological approach about construction of auxiliary models:

- Reduce the level of detail and complexity of the full mathematical programming model until it can be solved in closed form or by simple arithmetic. Call this an auxiliary model.
- Derive from the auxiliary model a set of tentative hypotheses concerning the general behavior of the solution of the full model–the cost tradeoffs determining the optimal solution for a given set of data, the nature of the induced change in the optimal solution for a given set of data are changed parametrically, and so on.
- Generate specific predictions from the tentative hypotheses and test these numerically using the full model.
- To the extent that the numerical tests confirm (i.e., do not contradict) the tentative hypotheses, take these hypotheses as a conceptual framework for understanding and interpreting the numerical results provided by the full model.

Though Geoffrion's work occurred in 1976, we feel it has application in today's world of large-scale systems. We encourage APICS members to consider building a "third model" as a way of streamlining the decision making process in materials planning.

A final area of visualization and LP that appears quite interesting involves the work of Chatterjee, Das, and Bhattacharaya [8]. Many business problems involve data expressed in multiple dimensions. Adequate representations exist to visualize data in two and three dimensions, but the representations for n-dimensional data becomes esoteric. Even after long study of visualization, it remains hard to fully understand representations of data in n-dimensions.

In contrast to Cartesian coordinates, parallel coordinates offer the opportunity to visualize data in multiple dimensions. However, as imagined, a new system of coordinates proves a big challenge in thinking. One difference between the two systems of coordinates is that a point in Cartesian coordinates is represented by a line in parallel coordinates. Without great detail, let us assure that Chatterjee, et al. have found a way to visualize n-dimensional LP problems using parallel coordinates. This opens the possibility of graphical solutions to complex FCP problems in n-dimensions.

CONCLUSION

The study of visualization will have a great impact on the future application of FCP models in the process industries. Visualization proves a very interesting field of research and challenges members of APICS to improve their methods of using FCP models for analyzing complex, multivariable problems. The future direction of visualization involves increase use of animation to show practitioners how complex algorithms work. This area of applied research shows great potential to speed the rate learning about mathematics in practice.

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