Integrated Decision Support Models for Manufacturing:

An Example from the Electronics Industry Devanath Tirupati

In response to increased competition, shorter product life cycles, and more demanding customers, manufacturers in many industries have been forced to adopt a service orientation to be more responsive in meeting customer needs. These developments during the past decade have caused significant impact on the internal operations and emphasized the need for greater operational flexibility and improved coordination within the firm, in particular, between marketing and manufacturing. In this paper, Devanath Tirupati describes a decision support system that was developed in response to such needs faced by a printed circuit board manufacturer in the electronics industry. The core functionality of this order analysis and rescheduling system (OARS) was based on a hierarchical approach and comprised of a series of mathematical programming based optimization models, while data integrity was assured by an integrated set of data bases. Finally, successful development and implementation was, in no small measure, due to the use of an interdisciplinary approach with project team involving representatives from the user groups from the beginning.

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The past decade has witnessed significant and substantial changes in the competitive environment faced by manufacturers in a wide range of industries that include automobiles, electronics, semiconductors, consumer goods, etc. Short product life cycles, increased customization, quick turnaround are some of the key features of the new market conditions that require manufacturers to be more responsive and flexible in meeting customer requirements. Increasingly, manufacturers have relied on new developments in technology — both information and manufacturing, to respond to these challenges. For example, developments in computer and information technologies have permitted rapid data collection and dissemination and sophisticated data bases assure consistency and integrity of company wide data. Similarly, technologies such as computer integrated manufacturing (CIM), flexible manufacturing systems (FMS), etc. provide great deal of operational flexibility that enables production of a variety of products. Clearly, technological advances in these areas have contributed significantly to the enhanced productivities. However, the underlying decision models have been rather slow to change and this avenue provides further opportunities for significant performance improvements. The lag in model development is partly due to the fact that it is usually context specific and involves substantial effort both in time and cost for customizing to individual applications.

In this paper, we focus on the role of models in decision support systems and describe an approach for developing integrated decision models that consider the interests and needs of the diverse functional groups involved. We illustrate the scope of this approach with our experience in the development and implementation of an order analysis and rescheduling system (OARS) at one of IBM's Printed Wiring Board (PWB) plants. The motivation for this effort came from the changes in the business environment at IBM manufacturing. In the early 90s, as part of its corporation wide reorganization effort, manufacturing divisions in the company were no longer required to remain captive suppliers for other divisions. Instead, they were expected to become competitive in the wider global market and were free to serve markets outside IBM. However, satisfying the internal market was still a significant priority.

The change in the corporate strategy forced the PWB plant to look beyond the internal customers (other IBM divisions) and exploit the original equipment manufacturers (OEM) for productive use of its excess capacity. This excess capacity was the result of ongoing process improvements that led to higher wiring capability, more compact packaging, and greater degree of integration. The shift from captive market to a mix of internal customers and OEMs required a corresponding change in the manufacturing strategy and had serious implications for decision support and information requirements. Traditionally, the internal customer market was characterized by standard products, moderate volumes, and fairly predictable demand with mild seasonality and variability. The manufacturing facility was organized as a typical batch shop and the focus of planning and control was on determination of appropriate batch sizes to minimize production costs (setup and variable costs), inventory carrying costs, and shortage costs. While the initial design of the planning system was appropriate for the internal market, there was degradation in the system performance over time, primarily due to increased product proliferation resulting in a heterogeneous tool mix and corresponding increase in the complexity of the planning problem.

The OEM market introduced a new set of competitive requirements that made the original system obsolete. Fundamental to the OEM market is a very competitive market responsiveness. Typically, an OEM demand was initiated with a request for a price and delivery quote for an individual order. In this environment, a fast, competitive response was key to order capture. A delayed response provides the customer an opportunity for searching other avenues and thus could lead to loss of the order. Thus, the management at PWB felt that a response time of four hours was necessary to remain competitive in the OEM market. While securing the order was important, a second aspect for success is its timely execution in meeting the due date commitments. Thus, marketing decisions related to OEM orders had serious implications for production schedules and hence the need for an approach that integrated the needs of both manufacturing and marketing functions.

OARS was developed in response to the changes in the information and decision support needs described above. It is a multi-user, on-line system that could provide a rapid assessment of a customer inquiry and provide a price and delivery quote based on the manufacturing and process engineering needs specific to the order. We used a hierarchical approach in developing an optimization model as the engine for OARS. One of the key features was the recognition and provision for autonomy in decision-making among the various groups involved in the process. These include order acceptance/rejection, pricing, scheduling, etc. The system was developed as a team effort with full participation from members of the various groups involved and was implemented successfully with a graphical user interface running on AIX, IBM UNIX operating system.

Background The Manufacturing

Environment

PWB is one of the largest plants of its type in the US. Yet, its capacity was insufficient to meet the peak demand, which was highly variable and dynamic. As a result, the management of PWB developed and maintained cordial relations with several subcontractors and excess demand was off-loaded to them on a regular basis. External sourcing in this fashion imposed contractual limitations that affected production decisions. These included guaranteed minimum and maximum order quantities (in aggregate) for each of the contracted vendors in any given period and restrictions on changes in order quantities and delivery dates.

The product flow within the plant was straightforward and was typical of a batch shop — well-defined flows and routing for each product family, significant but predictable setup times and cost. The addition of the OEM market introduced several job shop features. These included the following:

- routing deviations within each product family as a result of increased customization in design,
- restrictions on batching within each product family, and
- shift in emphasis from cost based measures to due date related performance measures.

The Market

As mentioned in the introduction, the market served by the PWB became more diverse and demanding as a result of changes in the corporate strategy in the early 90s. The traditional market, represented mostly by internal customers, was dynamic and made-to-stock with standard products. This market was relatively well understood and production plans were based on fairly reliable forecasts. Historically, the plant lead times were reliable and acceptable. Exceptions were managed by well-established norms and protocols.

The OEM market, on the other hand, is make-to-order and imposes additional demands on manufacturing. These include the following:

- (a) Quick response to requests for quotes (RFQs) (target time: four hours). Typically, RFQs required price and delivery quotes on customer orders.
- (b) Order fulfilment and delivery reliability.
- (c) Short lead times.
- (d) Flexibility in product design, order quantity, and delivery dates.

In particular, item (d) above represented a culture change at PWB and shifted the emphasis to competition based on service, rather than cost. Thus, it was important that PWB be flexible in respect of order quantities, be willing to make design changes to suit customer needs, and have the ability to meet rush orders at short notice.

The changes in the market environment had additional implications for cost assessment and pricing strategies. While the service focus and diversity in product mix provided pricing flexibility, it required a good understanding of the costs involved and the ability to develop quick and fair estimates. The fact that opportunity costs were dynamic and a function of shop load and changing bottlenecks in the manufacturing facility further complicated the problem.

The Business Process

The basic order process for internal customers is fairly simple and consists of three stages. In the first stage, orders are received, evaluated for correctness, and assessed for effort required, cost and revenue potential, and ability to meet delivery requirements. Orders considered viable are then *slotted.* In the second stage, following discussions and negotiations with the customers, *slotted* orders are either *booked, held* or *rejected.* Booked orders denote accepted orders and are added to the order book for eventual execution and customer delivery which constitutes the third phase. Pending orders in the slotted stage are held till a final resolution on their acceptance/rejection. The order process for OEM customers is very similar, except that the first stage is more involved because of greater customization, resulting in more variability on almost all dimensions.

Agents in the marketing department are the contact points for customers and are responsible for orders release, tracking, and feedback to customers. The agents also deal with order changes. Because of large number of orders and customers base, agents were assigned to specific customer sets or order sets. As a result, over a period of time, the agents developed a rapport with the customers and had a good understanding of their needs.

The plant information support system had evolved through time and consisted of a number of subsystems not necessarily well integrated. Many assessment tools were personal applications on desk-top machines (for example, see Ahmadi *et al;* 1991). The plant had a work-in-process tracking system, but no formal scheduling or order release system. Orders were released based on Kanban notions. While this was appropriate for standard products serving the internal customers, the system performance degenerated significantly with the introduction of OEM customers. Most decisions were made with insufficient information, on the basis of meetings with fact sheets. Despite its shortcomings, the plant success was due to the diligence and familiarity of the agents with the plant and customer environment. Agents' knowledge and rapport with customers helped prioritize orders.

It became clear that the informal system described above did not have a plant wide perspective and was inappropriate for the new environment and this recognition formed the primary motivation for the development of OARS. OARS is a decision support system aimed at providing support for order assessment and rescheduling functions with users in both marketing and manufacturing departments. The primary goal of the system is to improve decision-making by integrating inter-operable data systems readily accessible by assessment and analysis subsystems, and provide the necessary information to the individual users. The system is built around two primary entities: (a) Resources (internal/external), each characterized by its capabilities and impact on costs, (b) Customers, each characterized by the product mix, demand features, contract terms and agreements.

Optimizing the system for maximizing profits was the primary goal of OARS; however, it was well recognized that the agents played a significant role and that it was important to preserve their autonomy in day-to-day operations. Accordingly, after discussions with the managers involved, OARS was designed with three types of autonomy. At PWB these were referred to as *wedges* and described briefly below.

Protected *Wedge:* This refers to the capacity allocated to each agent, based on the customer set characteristics. The allocation amount is based on the demand volume generated by this customer set and its variability. The agent has the flexibility to assign this pre-allocated capacity to incoming orders and may use a local optimizer for prioritizing the orders received. Any demand in excess of the allocation is transferred to the global optimizer for assessment and evaluation. Likewise, any unutilized capacity is also transferred to the global optimizer.

Dynamic Wedge: This is analogous to the protected wedge for order changes. There are no preset limits on capacity, but the agent has the autonomy to make changes within the capacity used up by current orders. Again, the idea is to permit the agent to make changes that do not affect other parties involved — other agents or manufacturing.

No *Wedge:* This represents the overflow from the agents. There are no preset limits and the global optimizer is used to determine priorities and recommend requests (both new orders and order changes) for either acceptance or rejection. Needless to say, the control of No Wedge is at a level higher than that of individual agents.

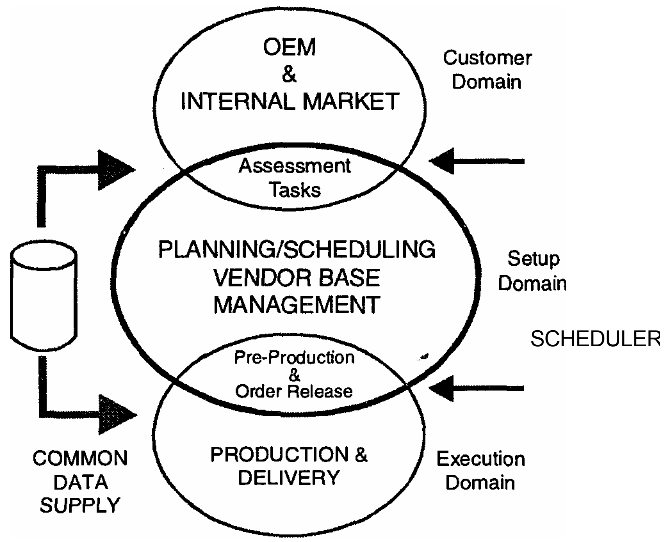
A detailed description of OARS, its functionality, design, and implementation are described in the reminder of the paper. We conclude this section by noting that additional details of OARS and the PWB environment can be found in Ahmadi and Tirupati (1994, 1996).

OARS System

As mentioned earlier, the objective of the OARS system was to provide an integrated environment between the major functions of marketing and manufacturing. Marketing is responsible for order setups, while manufacturing is responsible for execution of orders. Tasks in marketing include the following — respond to RFQs, subsequent negotiations with customers, ensure that accepted orders are viable and feasible based on manufacturing capacity and status, and follow-up on customer inquiries. Manufacturing would be responsible for timely delivery of products and supply of status information. An overview of this perspective of OARS is presented in Figure 1.

The functionality required is accomplished in OARS through a set of assessment and analysis tools which include a product assessor, a process planner, activity sizing, assessment of sourcing alternatives, costing system, and an optimizer (global and local). All communication between these subsystems and various users for information and decision support is through a multi-user interface and dialogue management subsystem. Figure 2 depicts this view of OARS and shows the interactions between the various

Figure 1 : Decision Support Domain of OARS



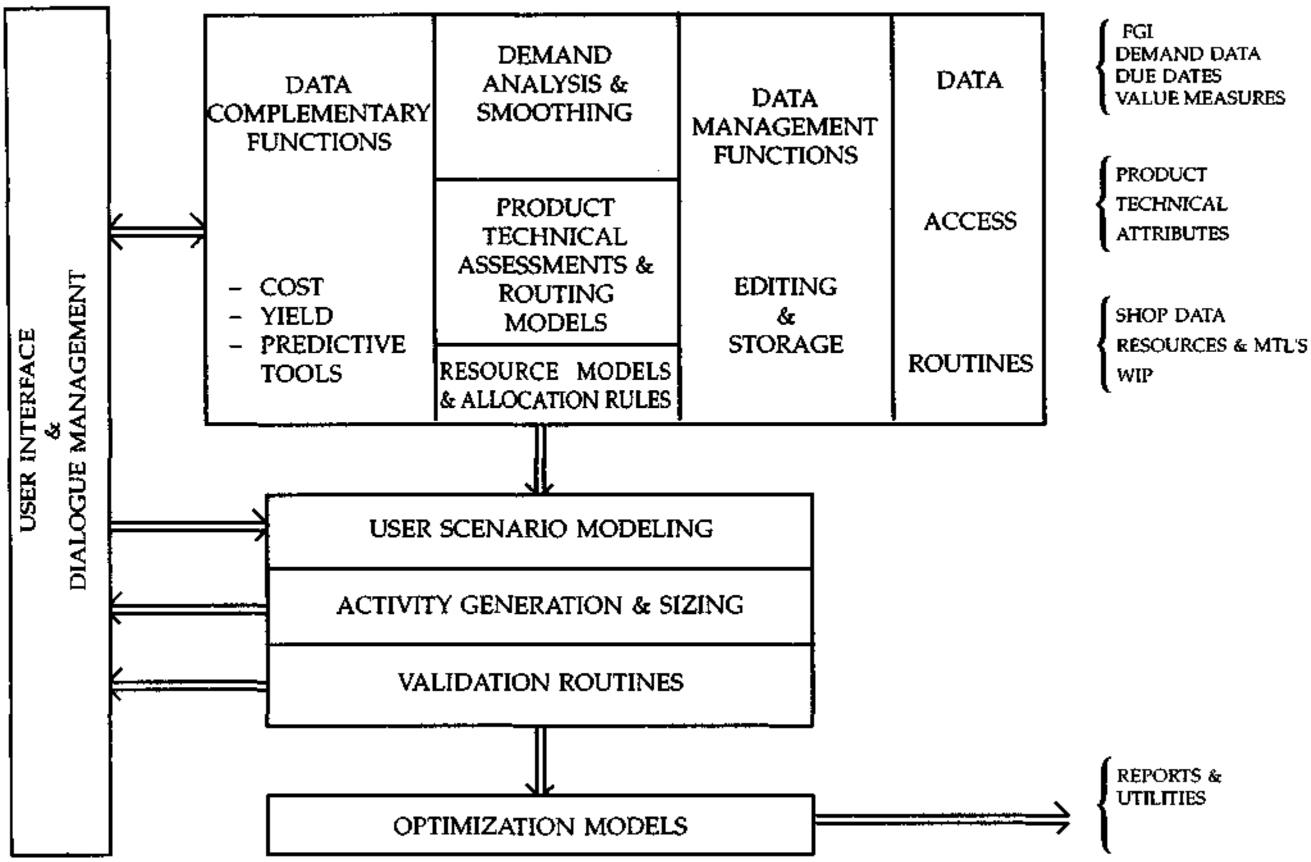
subsystems. In what follows, we provide a brief description of some of the key modules comprising the OARS system.

Order Capture: This module is responsible for receipt of orders from various input streams. It translates all orders into one format and will check order validity for dates, quantities, and their association with OARS products. It will also assign a status for each order, and if possible, a specific demand stream. The module supports both one-time orders and multiple orders arising from long-term contracts, as well as order changes. Standard information updates are generated automatically for all parties concerned.

Product Information: This module maintains the product technical data. The data are organized as two subsets — (a) product characteristics and vital product data, and (b) design and manufacturing data. The former include technical specifications and other information needed for product assessment. The detailed product information supports process planning tasks, yield, and cost analysis. The module has useful search functions that allow identification of similar products by matching key attributes and permits quick assessments of new products. Finally, order booking will be allowed only against pre-defined products in this data base.

Engineering: This module supports technical assessment of a product. The module includes functions for yield and cycle time computations and contains information on valid sources, manufacturing dependencies such as specific material requirements, and imaging masks development. A key component of this module is the process planner, described in some detail. The primary

Figure 2: OARS System



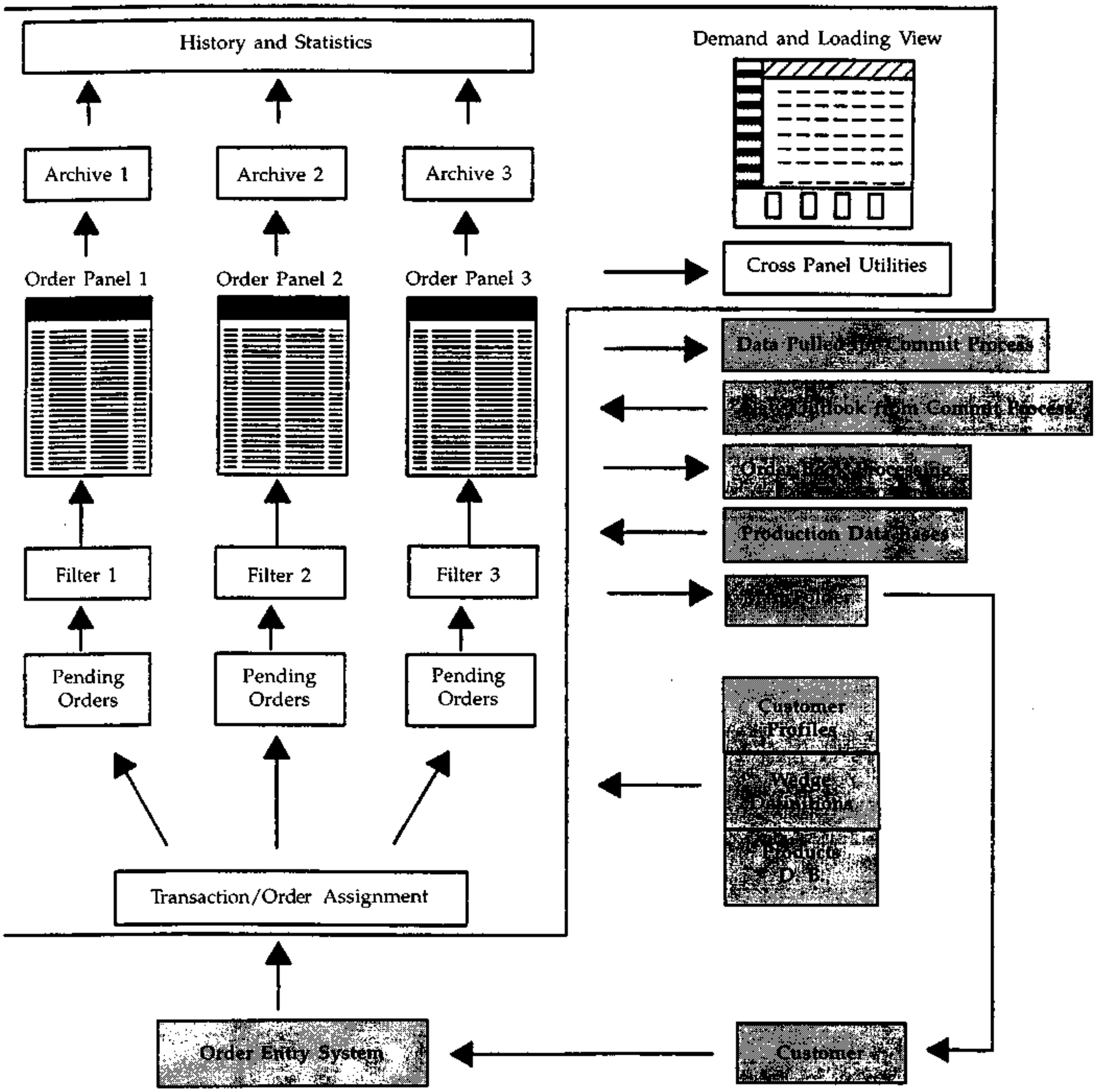
task of the planner is to generate product routing. The planner is completely graphical and the plan is described as network of nodes and arcs showing a top-down view of the process steps. Based on key product attributes, a default process plan is generated by following a pre-established logic. A process node contains default specifications that may be edited for content or modified by addition of special instructions. Once a plan is complete, it can be saved and key measures such as process yields and cycle time are recorded automatically in the product module. The process plan is completely editable. Nodes may be added or deleted by using drag and drop functions. Process nodes can be created using a customization function that permits definition of data needs and use of mathematical expressions for incorporating data elements. A validation function allows examination of the inputs before submission to the data base. Since graphs can become large and disorganized, the process plan is organized in a hierarchical fashion using a graph organizer with appropriate scaling functions.

Order Management: This module, shown in Figure 3, maintains status information on all orders. As shown in the figure, it supports a graphical view of order implications in plant loadings and other related metrics. The module is also responsible for maintaining customer profiles and mapping with demand streams that are organized by product. Demand management submodule represents the link between orders and their execution in manufacturing.

To ensure that orders are diligently processed, the module contains an archive utility that maintains order history and provides management with statistics on performance. The order history submodule, which has a very rich set of statistical data, has a controlled access.

Commit and Scheduling (Optimizer Modules): This module, shown in Figure 4, represents the main decision support module of OARS. We adopted a mixed integer programming model approach (described in detail in the next section) and used variants of the basic model for various tasks addressed in OARS. For example, it can be used in a global mode to develop a detailed schedule for manufacturing based on committed orders and resource status. Similarly, at the local level, simplified versions are used by agents to evaluate the implications of adding new orders.

Figure 3 : Order Management Module

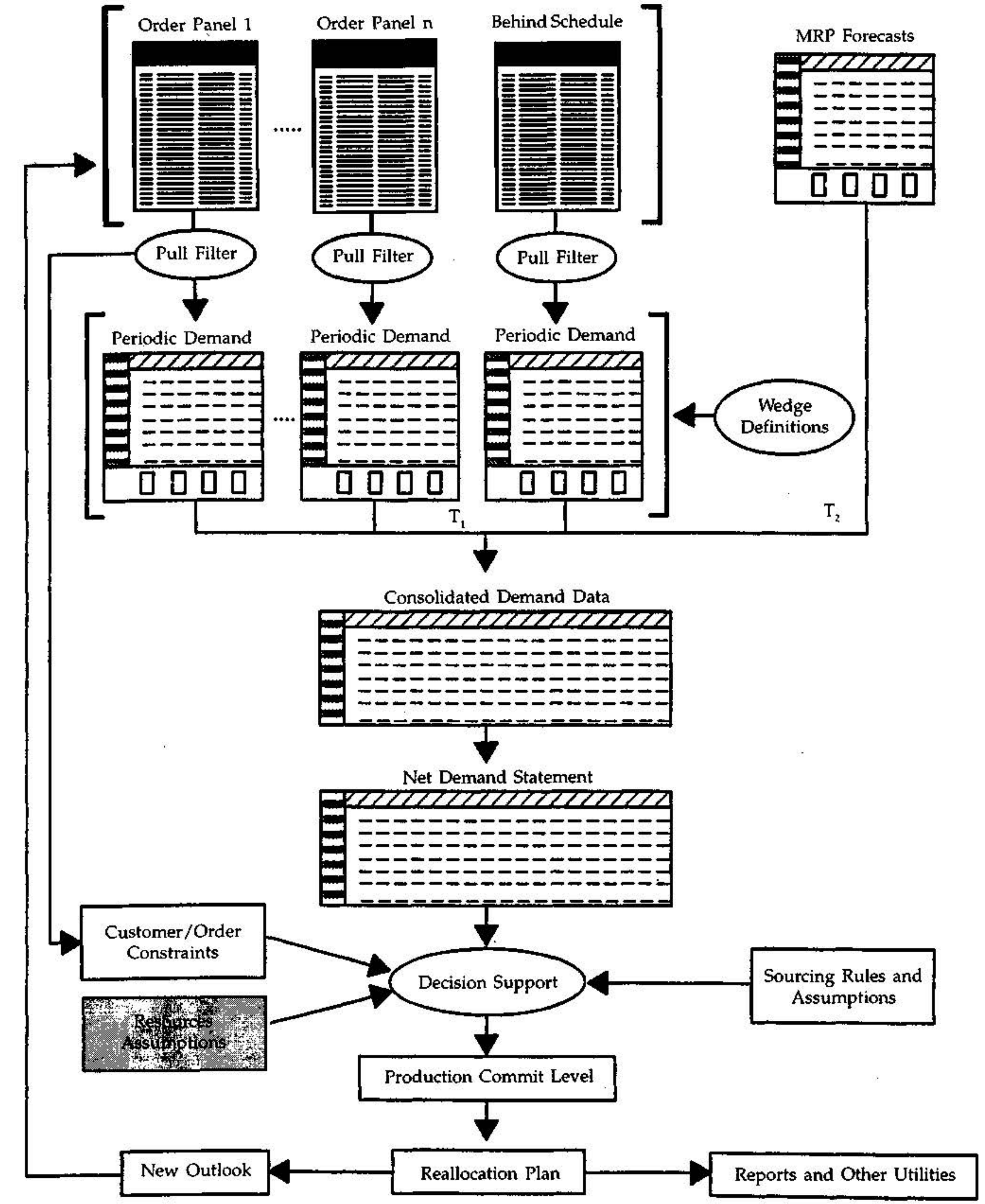


Execution of the module in a what-if mode permits evaluation of a set of assumptions on orders and resources. The objective of this module is to select and book those orders that are feasible and most profitable. The module includes sourcing decisions (selection from a valid set of sources) and the schedule is based on time buckets of varying length. The constraints include contractual limitations, capacity limits, production targets, inventory allocations, order conditions, etc. An algebraic formulation of the base model and our solution approach are the focus of the next section.

Optimization in OARS

As mentioned earlier, the objective of OARS is to use an integrated approach for decision support in a decentralized environment with substantial autonomy for individual agents and groups. Accordingly, we

Figure 4 : Commit Module



adopted a hierarchical approach (Bitran and Tirupati, 1993; Harhalakis *et al,* 1993) and developed a number of models to support the desired functionality. A complete description of the optimization module is beyond the scope of this paper. Instead, we provide a flavour of our approach by describing a global model and the corresponding solution approach used for scheduling at the plant level. (The interested reader can find the details of the optimization module in Ahmadi and Tirupati, 1994.) For ease of exposition, we make some simplifying assumptions and elaborate briefly on their implications. For example, the model is described at the order level and is based on the assumption that each order includes only one item. Orders with multiple items can be decomposed into several orders, one for each item. Without any loss of generality, such orders can include internal customers and made-to-stock items. The order quantities reflect any required stock adjustments. Similarly, we assume that decisions related to selection of subcontractors has already been made at a tactical level (perhaps using the tactical model of OARS). In the model described here, the impact of such decisions is captured in the form of capacity additions and other restrictions on minimum production quantities in each period. The scheduling model (SM) described here may be interpreted as a dynamic model run periodically to determine a rough schedule for committed orders. It is also used to make determination on pending (overflow) orders that could not be accommodated within the agents' capacity wedges. Since the model is run on a rolling horizon basis, each run inherits restrictions resulting from commitments already made and it is important to accommodate these constraints. Disaggregation of the schedules developed by SM to determine order assignments to different sources (internal, subcontractor, etc.) is considered by lower level detailed scheduling model based on a microview of the plant with details of various production stages and time delays.

The model SM captures some interesting order features that require some elaboration. First, the model includes provision for multiple, time-phased shipments with each order. Second, flexibility in order delivery is captured by specifying an acceptable time window for each order. Likewise, volume flexibility is permitted by suitably specifying a parameter (a) that allows partial shipment of orders. This feature is particularly useful for internal customers with made-to-stock products. Third, order and schedule decisions based on prior commitments are included as additional constraints. We now present an algebraic formulation of the model.

Notation

i : Index for orders

I : Set of orders, I_1 : Set of accepted orders

I_2 : Set of rejected orders, I_3 : Set of orders under consideration

R_{it} : Demand in period t for order i

R_i : Total demand for order i

W_i : Permissible time window for delivery of order i

α_i : Volume flexibility factor for order i

c_{it} : Unit profit contribution from order i

j : Index for resources, J : Set of resources

b_{jt} : Availability of resource j in period t

a_{ij} : Resource j required per unit for order i

x_{it} : Quantity produced in period t for order i

Y_i : Binary variable for order i

$= 1, i \in I_1$

$= 0, i \in I_2$

$\in \{0,1\}, i \in I_3$

[SM] Maximize $\sum_i \sum_t c_{it} x_{it}$ (1)

subject to $\sum_t x_{it} \leq R_i, i \in I_1$ (2)

$$\sum_t x_{it} \geq \alpha_i R_i, i \in I_1 \quad (3)$$

$$\sum_t x_{it} \leq R_i Y_i, i \in I_3 \quad (4)$$

$$\sum_t x_{it} \geq \alpha_i R_i Y_i, i \in I_3 \quad (5)$$

$$\sum_{\tau=1}^{t} x_{i\tau} \geq \sum_{\tau=1}^{t} R_{i\tau}, i \in I_1, t \in W_i \quad (6)$$

$$\sum_i a_{ij} x_{it} \leq b_{jt}, j \in J, \forall t \quad (7)$$

$$x_{it} \geq 0 \quad (8)$$

$$Y_i \in \{0,1\}, i \in I_3 \quad (9)$$

The model SM described above determines a schedule to maximize the profit contribution. The coefficients c_{it} are dynamic and can include any penalties associated with early or late deliveries. (2) and (3) specify the demand constraints for committed orders. Constraint (3) ensures that minimum requirements are guaranteed, while (2) limits the production to the order size. (4) and (5) represent the corresponding constraints for orders under consideration and are fot accepted orders only (Y. = 1). Constraints *m (6) impose the* time phased requirements and include any prior commitments. Finally, constraints in (7) denote manufacturing restrictions. These include capacity limits on various resources such as labour, equipment, tools, subcontractors, materials, etc.

We conclude this section by noting that a simplified version of SM is used as a local optimizer at the individual agent level to accept and schedule customer orders. Committed orders in this fashion impose constraints on the global model. Orders that cannot be accommodated with the agent's capacity wedge, but otherwise considered attractive are passed on to the global model as orders under consideration. The constraint set (7) is much simpler for the local optimizer and includes allocated capacity wedges.

The Solution Approach

The reader may recognize that SM is a large mixed integer programming model that belongs to a class of intractable NP-hard problems and hence not easy to solve optimally with standard software packages. Hence, we developed a heuristic approach based on Lagrangian relaxation of the capacity constraints (7). The procedure, which involves repeated solution of linear programs resulting from setting the integer values can be viewed as a greedy approach in which decisions are made for pending orders sequentially and the shadow prices for capacity constraints (7) are computed at each stage by solving the corresponding linear program. The sequence in which orders are selected is based on a priority index computed from the profit potential of the order and the shadow prices of the resources required to execute the order. An overview of the procedure is described in Figure 5. This procedure was tested with representative data and these results indicated significant improvements over the current practice based on standard costs.

System Design and Implementation Issues

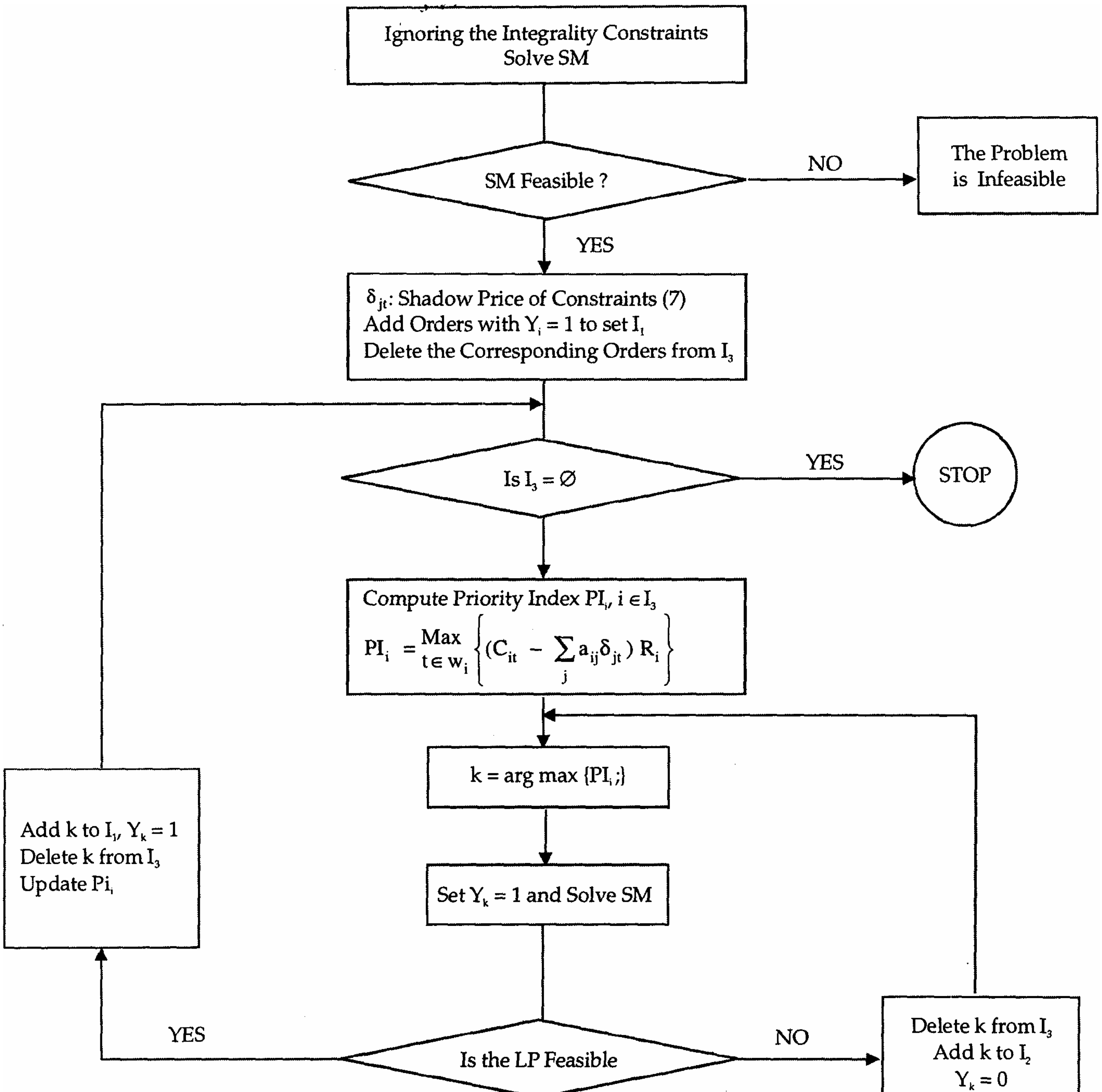
OARS was developed on a complete C platform using DB2/6000 data base system and implemented in a work station based environment comprising of IBM RS/6000 work stations running under theAlX operating system. This choice was dictated by the MIS strategy at the plant and the corporate level and was intended to be consistent with the other ongoing developments at PWB. For example, the work station environment and the operating system were defined by the plant MIS strategy. DB2/6000 offered facilities for migration of data from the existing host-based CMS and MVS IBM data bases and was free of charge, and hence the choice was simple. Our decision to use C platform was motivated by portability considerations and ease of code maintenance.

The development of OARS was an interdisciplinary effort and involved functional representatives from the various groups, programmers from internal support groups, and student interns from the University of Texas at Austin. The students were required to have proficiency in C, UNIX, X-windows, algorithms and data base systems, but lacked project management skill and had limited exposure to real world situations. The majority of the plant personnel were not trained in AIX and were in transition to the new environment. The group diversity provided a healthy learning environment for all, and thus turned out to be mutually beneficial, beyond the specific application development.

An important factor that contributed to the project success was the development of a user friendly interface. Since most users were familiar and comfortable with spread sheet tools and graphical and tabular displays, OARS user interface was designed with similar functions. Since AIX did not support such a tool, we undertook the development of the interface as an independent utility to facilitate the analysis and report generation functions. In the remainder of this section, we describe briefly some key considerations in the development and implementation of OARS.

- *System Configuration:* This provided several customization and administrative functions. These include security and access controls, format selections and multiple user contention controls.
- *Communication: A* complete messaging system that would allow communication between users and subsystems was developed as a part of OARS.
- *Data Base and Information:* All data are stored in the database system with critical fields identified for change control. Changes will cause messages to be broadcast to the users. For example, any capacity decrease may affect delivery schedules and require to be broadcast, while information on capacity increase is discretionary. The system includes data validation routines to ensure that all inputs are complete and consistent. As mentioned earlier, the system includes a host of utilities to support information and report generation.
- *Education and Training:* Involvement of the user groups in the development process proved invaluable. The majority of the help panels were developed and designed by the users, who also

Figure 5 : Heuristic Procedure for SM



participated in subsequent training tasks. User involvement had significant impact on the system design. The initial concepts were reviewed and modified based on inputs from the users. This was particularly important in the present applications since it represented significant departure from the systems already in place.

Summary and Conclusions

In this article, we have described the development and implementation of a decision support system to meet the challenges posed by a drastically altered environment faced by a printed circuit board manufacturer in the early 90s. The integrated approach

and optimization based decision models used in the design of the system are quite general and could be used profitably by other firms in similar situations. The role of optimization models in identifying good strategies and plans is clearly important and useful;
however, the success of our effort was predicated on a number of other factors. We conclude this paper with some comments on these aspects based on our experience in developing and implementing OARS.

Inclusion of potential user groups from the outset and obtaining their commitment at all stages of the process was perhaps the biggest factor that contributed to the success and assured continued application of the system. Their involvement was a definite factor in the acceptance of the new system. However, they also brought in new perspectives that enhanced the system design and significantly improved its scope. Second, the training and education needs are very important and cannot be overemphasized. We are aware of several applications that were not as successful simply because of insufficient attention to this aspect. Third, it is common to find Management Science/ Operations Research/Management Information Systems specialist to focus on the technology and get carried away into developing a very sophisticated system well beyond the users' needs. Our experience suggests that this may be counterproductive and it is more important, even at the cost of suboptimality, to ensure that speed and response time needs of the users are satisfied. Fourth, it is important to recognize that DSSs are only support systems intended to improve performance by providing information and flexibility in decision-making. Optimization models typically involve simplifying assumptions and the model solutions require some modification. Thus, the system design should facilitate user interaction and allow for user discretion to use the suggested solutions as good starting points. In the absence of such flexibility, it is unlikely that the system would be used for its intended purpose. We conclude by noting that a carefully considered and well designed system can provide valuable decision support and improve manufacturing competitiveness. However, it is important to recognize and avoid the many pitfalls during the design, development, and implementation of such systems.

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