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Mathematical Programming-Based Sales and Operations Planning at Vestel Electronics

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We investigate the sales and operations planning (S&OP) process at Vestel Electronics, a major television manufacturer located in Turkey. The company has a large product portfolio because its products have many configuration options, and its product portfolio changes rapidly as a result of technological advances. Demand volatility is high, and materials procurement requires long lead times. Hence, the S&OP process is critical for efficient management of company resources and its supply chain and to ensure customer satisfaction. We devise a mathematical programming formulation for Vestel's S&OP process and describe our experience in implementing a decision support system (DSS) based on our optimization model. We fully implemented and deployed our DSS at Vestel, which has used it every day since 2011.

Keywords: sales and operations planning; decision support system; television industry; mathematical programming
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Vestel Group comprises several companies operating in various areas such as manufacturing, household appliances, defense industries, and marketing, and has revenue of approximately $4.2 billion. Vestel Electronics, which operates in the consumer electronics industry, is the flagship company within the group because of its high revenue and market share within the industry. It produces LCD-LED televisions (TVs), which are its main product line, and digital set-top boxes. Vestel Electronics, which we will refer to as Vestel in the remainder of the paper, exports approximately 90 percent of its products to customers in 140 countries under its own brands and various leading Japanese and European brands. It operates from a single manufacturing location, Vestel City in Manisa, Turkey, which is one of the largest industrial complexes in the world; it comprises an area of 1.1 million square meters and has an annual production capacity of 15 million products (Vestel Electronics 2013).

Rapid technological evolution is a distinctive characteristic of the consumer electronics industry in general and the TV manufacturing industry in particular (Conlon 2012, Chang and Chung 2013). In the past few years, the mainstream TV industry has shifted from producing cathode ray tubes (CRTs) to plasma and liquid-crystal displays (LCDs), and then to light-emitting diode (LED) TVs. Recently, three-dimensional (3D) and smart TVs have become prevalent, and 4K ultra-high-definition (UHD) TVs, which provide four times as many pixels as high-definition (HD) TVs, have appeared in the market. Moreover, advances in broadcasting systems, including radical changes such as the transition from analog to digital broadcast and Internet protocol television (IPTV) broadcast, directly affect the products. In addition, minor technological improvements, cosmetic changes, and changes to reduce costs occur continuously. As a result, product life cycles are short, and Vestel spends a significant portion of its research and development (R&D) effort at the operational level.

The LCD-LED TV market is a buyer's market in which a product's marketability is sensitive to its price. Furthermore, customer loyalty is limited and demand volatility is high (Conlon 2012). TV demand fluctuates seasonally, and special events such as sports broadcasts heavily affect demand. TV prices tend to decrease over time, whereas prices of input materials fluctuate. This is especially true for the TV display (also called panel or screen), which accounts for a significant portion of a TV's total cost (Conlon 2012). Price-based competition in the market forces producers to work with low profit margins and employ opportunistic purchasing of input materials.

Vestel: Business Model

Vestel operates in a make-to-order environment and allows mass customization of its products. Mass customization is a paradigm in which products are customized in large quantities at low cost rather than standardized (Chen-Ritzo et al. 2010). Vestel produces approximately 10 percent of its products under its own brand names and manufactures the rest under original equipment manufacturer (OEM) and original design manufacturer (ODM) agreements with various customers, including well-known Japanese and European brands. For its OEM-ODM business model, Vestel follows customer demands and trends in the market, does R&D to design products, and produces them under its customers' brand names. This strategy—producing for a large number of customers under hundreds of different brands—requires Vestel's product portfolio to be very large and its products to be diverse in terms of both their electronics and cosmetic properties. A TV is a heavily customizable product that has various physical attributes (e.g., size, color), electronic options (e.g., display frequency, USB-HDMI support, 3D support, smart-TV capability), cosmetic properties (e.g., front and back cabin), electronic components (e.g., main card, power card, speaker type, remote control type), and various software options. When all combinations are considered, Vestel can produce at any given time tens of thousands of products, and this number increases as it adds new customization options. It adds approximately 5,000 new models to its product portfolio annually. Approximately 60 percent of the products it produces in a month are new products, and it refreshes its entire product portfolio approximately every six months.

Unlike several of its competitors that try to create stable operational environments by limiting product variety and limiting customer flexibility, Vestel's competitive strategy aims to maximize flexibility and responsiveness to customers. To this end, Vestel allows its customers to order any product that it can manufacture from a technical point of view. It also accepts orders of small batch sizes. In particular, 37 percent of its annual production of 9.5 million products is for orders of 200 or fewer units, and 66 percent is for orders of 500 or fewer units. Vestel accepts orders with short due dates. It employs no frozen zone (i.e., a period in which the existing plan cannot be modified) in its planning horizon, and it allows a customer to change order quantity, due date, or product specifications before it actually manufactures the product. Although providing such a level of flexibility to customers is a key component of Vestel's competitive strategy, it increases the difficulty of managing the supply chain.

Vestel works with over 500 suppliers to procure more than 20,000 stock-keeping units (SKUs). It procures a significant number of items from multiple suppliers for strategic reasons, to decrease costs, and resolve supply constraints. Using multiple suppliers is particularly important for the procurement of displays for which the global supply is limited, costs are significant, and prices fluctuate over time. Displays that share similar technical specifications are substitutable to a certain extent. That is, Vestel can produce a TV unit by using one of several equivalent displays produced by different suppliers; however, because of customer requirements, quality concerns, or technical reasons, some displays cannot be used in some products. Although exploiting the bill-of-material (BOM) flexibility is crucial for profitability, it also makes materials management more difficult because the requirements for several materials (e.g., power cards, optical materials) depend on the type of display used. Similarly, usage of a significant number of materials depends on the front and back cabin in a customer's order. Although cabin choice is mostly cosmetic and does not affect the electronic properties of the product, the requirements of many materials, such as plastic components, speakers, and paints, depend on the cabin type chosen. Customers tend to order different cabins in successive orders and also tend to delay ordering as late as possible; therefore, planning such materials is particularly difficult.

A unique characteristic of Vestel's supply chain results from Turkey's proximity to Europe, Vestel's primary market. Vestel sells almost 90 percent of its products to customers in Europe; however, less than one-third of its suppliers are located in Turkey, and it procures approximately 90 percent (in terms of monetary value) of its input materials from Far Eastern countries. Vestel's average order-satisfaction lead time is 30 days, and its average materials procurement lead time is 90 days. Efficient management of the timing difference between inbound and outbound materials flow is critical for balancing inventory holding costs and order-satisfaction performance.

Outputs of Vestel's S&OP process drive long-term material procurement plans. In this sense, S&OP is the most important process in determining inventory-optimization and demand-satisfaction performance. Because demand-satisfaction flexibility is Vestel's main competitive advantage, effective management of the S&OP process is vital to sustaining this advantage.

S&OP Process at Vestel

S&OP is a tactical-level integrated business process through which companies aim to keep demand and supply in balance and achieve synchronization among different functions in the organization (Wallace 2004, Sheldon 2006). S&OP has recently been the subject of significant research interest. In particular, Feng et al. (2008) propose several integer programming formulations that represent different levels of cross-functional integration. They compare these models using data obtained from a firm operating in the oriented strand board industry to estimate the potential financial impact of S&OP before actual implementation. Chen-Ritzo et al. (2010) investigate the S&OP problem in configure-to-order systems with configuration uncertainty. They propose a stochastic programming approach and test the efficacy of their approach on data obtained from IBM's Systems and Technology Group. Oliva and Watson (2011) report their experience on the organizational alignment and business processes perspectives of S&OP gained through a set of interviews at a consumer electronics firm. Affonso et al. (2008) propose a simulation model to investigate the effect on S&OP performance of lead times and level of collaboration between different entities. We refer the reader to Thome et al. (2012) for a review of S&OP literature. Although several authors have studied various aspects of S&OP, to the best of our knowledge no existing study addresses S&OP challenges, such as imbalance between inbound- and outbound-flow lead times, rapid technological evolution, BOM, and process flexibility, in a mass customization and make-to-order environment comparable to Vestel's.

Figure 1 shows an overview of Vestel's S&OP process. Because the lead time of some critical materials supplied from Far Eastern countries is up to 16 weeks, the length of the planning horizon is at least four months; however, customers tend to order late. As the example in Figure 2 shows, at the beginning of month t, fewer than 80 percent of forecasted sales for month t have become firm customer orders. Similarly, at the beginning of month t, fewer than 30 percent of forecasted sales for month $t+1$, fewer than 10 percent for month $t+2$, and fewer than 5 percent for month $t+3$ have been realized as customer orders. Customer orders, sales forecasts, market preferences, and trends are important inputs for the S&OP process.

Vestel Group has several subsidiary companies that handle its worldwide sales and marketing; these companies are responsible for generating sales forecasts. They consider and closely monitor various factors, including past sales, country-based pricing policies of competitors, screen size and technological preferences of customers, important sporting events throughout the world (e.g., the UEFA European Championship, FIFA World Cup, Olympics), and agreements with ODM-OEM customers. Sales companies make most forecasts at the screen-size and main-technology level (e.g., 32″ LCD TV, 40″ LED TV); however, they provide more specific forecasts for certain market segments and customers. This implies that Vestel needs to work with sales forecasts that have various levels of detail.

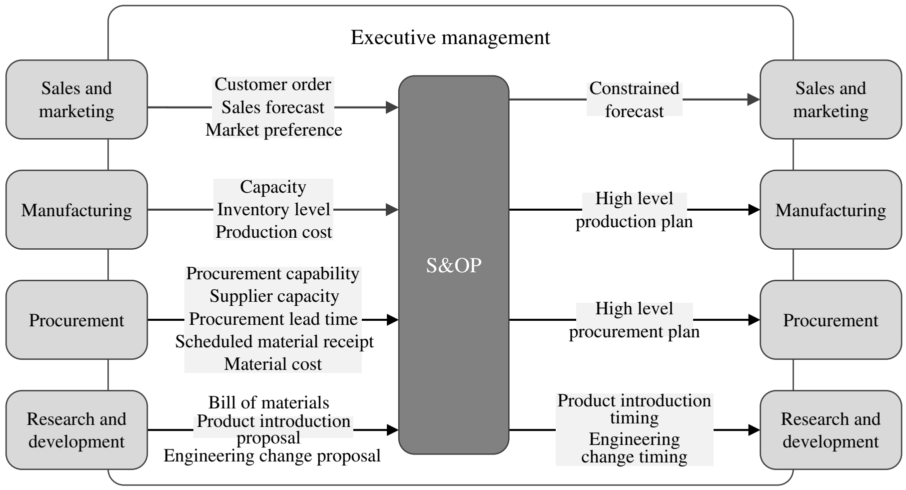

Figure 1: At Vestel, executive management leads the S&OP process to align the sales and marketing, manufacturing, procurement, and R&D functions.

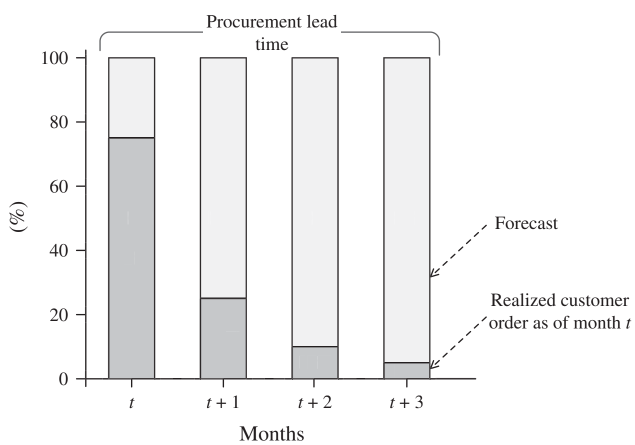

Figure 2: The ratio of firm customer orders (dark area) to total forecast (light area) as of the beginning of month *t* decreases rapidly for later periods within the procurement lead time. Forecasted sales drive long-term material procurement plans because customers tend to order late.

Vestel's manufacturing department provides information about production capacity, current inventory levels of materials, and manufacturing costs of semifinished components and end products. By analyzing the effect of capacity bottlenecks on sales targets and taking corrective actions, the S&OP process increases coordination between production and sales activities. Furthermore, the manufacturing department can use its knowledge of production costs and bottlenecks to guide sales activities toward a more profitable product mix.

Another important goal of the S&OP process is managing the demand and supply of displays and other critical materials with long lead times. As we discuss earlier, the global supply of displays is limited and display prices are subject to fluctuations. The procurement department provides information about display procurement capability, supplier capacity, procurement lead time, and the scheduled receipt quantity and timing of critical materials and material costs. The S&OP process facilitates the company's coordination between procurement and sales activities by allowing it to investigate the effect of procurement problems on sales targets. Furthermore, because many end products can be produced using other displays that have equivalent technical specifications, BOM flexibility can be used to improve profitability.

The R&D department is an important contributor to Vestel's S&OP process because product life cycles are short and new products continuously enter the market. R&D shares information about various projects in its pipeline to increase the BOM flexibility of existing products (e.g., add new display options), new-product introduction plans, engineering changes to existing products, or the replacement of components with new ones. R&D must align the timing of these projects with sales and marketing to improve customer satisfaction and with the manufacturing and procurement departments to decrease operational costs.

In S&OP meetings, executive management meets with representatives of the corresponding functions to formulate a consensus plan, given its financial and strategic goals and the input from various functions. The consensus plan represents the constrained forecast for sales and marketing, high-level production plan for manufacturing, and high-level procurement plan for procurement; it also provides target project timings for R&D. Executive management holds S&OP meetings on a scheduled basis and as needed (e.g., in case of major supply disruptions, manufacturing problems, or changes in market conditions).

Given the unique characteristics of TV manufacturing, Vestel's business model, and its organizational structure, Vestel's S&OP process presents some challenges, which we address in our study:

- How to plan for products that do not yet exist: Because product life cycles are short, new products often replace a significant portion of existing products by the end of a planning horizon. This implies that long-term production and material requirements plans must incorporate products that do not yet exist.
- How to identify and resolve inconsistencies between various targets and constraints: Because the separate functions involved in the S&OP process have their own goals and constraints, conflicts can exist between them. Furthermore, different sales companies make sales forecasts at varying levels of detail and at varying times; as a result, internal inconsistencies can exist among these forecasts.
- How to identify the least-costly, most-profitable operational plan: Although customer orders are associated with specific products, sales and marketing makes forecasts at a high level; thus, many products can be used to satisfy each forecast item. The manufacturing and material costs of these products typically differ; for example, these products might be compatible with multiple displays, use different types of electronic components, or have required components already in inventory or that must be ordered. This flexibility can be exploited to guide sales and marketing toward a more profitable sales plan.
- How to put the consensus plan into action: Vestel uses an enterprise resource planning (ERP) system for its operations. Once the functions reach an agreement, the consensus plan must be integrated into the ERP system so that it provides input for the material requirements planning (MRP) and long-term capacity planning processes. It must also be rapidly communicated to various employees within the organization so that the actions taken in other processes align with the decisions made as part of the S&OP process.

Planning Materials (PMs)

Figure 3 shows the main components of an LCD-LED TV, including mechanical and electronic components, a remote control, possibly an integrated DVD-DVR unit, printed documents, packaging materials, and software. As we discuss earlier, such a product has various customization options (e.g., size, color, display frequency, USB-HDMI inputs, integrated DVD-DVR unit, 3D and smart-TV capability, speaker, and remote control), and Vestel allows mass customization of its products. Because the number of products that customers can order approximates tens of thousands and the product portfolio changes so rapidly, creating a long-term operations plan based on existing products is impossible. Various components, however, are manufactured in-house (e.g., plastic materials such as front and back cabins), have relatively short procurement lead times (e.g., side cards, boxes, manuals), or are purchased in bulk quantities and used commonly in

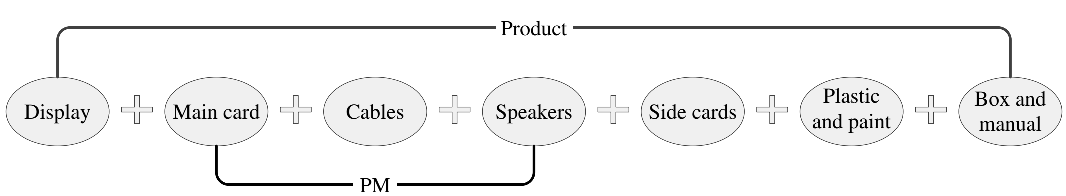

Figure 3: Although each product has several components, only components having a relatively long purchasing lead time are relevant for the S&OP process. PMs are representative virtual products that have simplified BOMs comprising such components.

a diverse range of products (e.g., paint). Such materials are beyond the scope of the S&OP process, and an operational-level MRP determines their requirements.

To provide a basis for the S&OP process, Vestel has defined high-level products called planning materials (PMs). PMs are representative virtual products that (1) capture basic product attributes (e.g., size, display type, power card type, customer group) and (2) have a simplified BOM that consists of components that have long procurement lead times (e.g., main card, cables, speakers) (Figure 3). PMs provide a grouping of products with common attributes and common components that are relevant for long-term procurement planning. Hence, each existing product corresponds to a single PM, but a PM can have several corresponding products. Furthermore, each PM has a corresponding set of displays that is compatible with it, considering technical specifications and customer preferences. Similarly, each display can be used by several PMs. PMs capture the information needed for long-term sales, manufacturing, and procurement planning, and are the main building blocks of Vestel's S&OP process.

In the simplified example in Table 1, we assume eight PMs (columns PM1, …, PM8). The second row of each column shows the attributes of the corresponding PM. Columns "Goal/Constraint," "Attribute," and "Quantity" represent various goals and constraints of stakeholders of the S&OP process. In particular, F1 corresponds to executive management's goal of manufacturing and selling 50,000 products (corresponding to all PMs). F2 represents the procurement capability of DVD units and indicates that the total quantity of products having integrated DVD units (i.e., PM3, PM4, and PM8, marked with 1 in the corresponding grid cells) cannot exceed 20,000. Similarly, F3 and F4 indicate manufacturing capacity restrictions on products supporting MPEG2 and MPEG4 (i.e., PM1, PM3, PM6, PM7 and PM2, PM4, PM5, PM8, respectively). F5 and F6 represent sales forecasts for products specialized for customer 1 and 2 (PM5 and PM6, respectively); finally, F7 indicates forecasted sales quantity on products having a smart-TV capability (PM7 and PM8). Note that this simplified version of the problem does not address (1) displays or compatibility of displays with PMs, (2) the multiperiod nature of the problem, (3) R&D inputs such as new-product introduction and engineering changes, or (4) BOM, current inventory levels, and scheduled receipts of upstream materials; however, it demonstrates that goals and constraints of the various stakeholders partially overlap with the others.

As we discuss previously, various people prepare inputs for the S&OP process and at varying levels of detail, possibly resulting in inconsistencies in the input data. For example, assume that the sales

			PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8
Goal/ Constraint	Attribute	Quantity	MPEG2	MPEG4	DVD, MPEG2	DVD, MPEG4	MPEG4 Customer 1	MPEG2 Customer 2	MPEG2 Smart TV	DVD MPEG4 Smart TV
F1	TOTAL	50,000	1	1	1	1	1	1	1	1
F2	DVD	20,000			1	1				1
F3	MPEG2	25,000	1		1			1	1	
F4	MPEG4	25,000		1		1	1			1
F5	Customer 1	10,000					1			
F6	Customer 2	10,000						1		
F7	Smart TV	25,000							1	1
Initial PM assignments			1,250	1,250	1,250	1,250	10,000	10,000	12,500	12,500
Realized customer orders			2,000	1,000	1,000	500	5,000	7,500	4,000	8,000
Revised PM assignments			2,000	1,500	1,000	500	10,000	10,000	12,000	13,000

Table 1: We illustrate the main dynamics of the problem using a simplified example. Columns PM1–PM8 represent a set of PMs and their attributes. Rows F1–F7 represent various goals and constraints of the stakeholders; we identify PMs contributing to each goal or constraint with a "1" in the corresponding column. The "Initial PM assignments" row shows a solution that satisfies all goals and constraints. The "Realized customer orders" row indicates realized orders, and the "Revised PM assignments" row shows an alternative solution satisfying all goals and constraints that are also consistent with realized orders. All quantities represent numbers for a particular month within the planning horizon.

forecast for smart TVs (F7) is 35,000. This would create an impossible situation because sales forecasts for customers 1 and 2 (F5 and F6, respectively) imply that the total sales of PM5 and PM6 are at least 20,000. Furthermore, because only PM7 and PM8 have a smart-TV capability, F5–F7 would imply that the total number of forecasted product sales of PM5–PM8 is at least 55,000. Because PM5 and PM8 support MPEG4, however, their total manufacturing quantity is bound by 25,000. Similarly, because PM6 and PM7 support MPEG2, their production quantity is limited to a maximum of 25,000. Hence, the total production quantity of PM5–PM8 is at most 50,000, and the forecasted sales are inconsistent with the manufacturing capacity. Although this example demonstrates an undercapacity problem, in practice, we have observed inconsistencies among sales forecasts and realized sales.

Assume that no realized customer orders are present during the execution of the S&OP process. The "Initial PM assignments" row in Table 1 represents a feasible assignment of PM quantities that meets all sales forecasts, satisfies capacity and procurement constraints, and ensures that total assigned quantity is in alignment with the goals set by executive management. Assigned PM quantities represent the consensus plan. The ERP system uses these quantities to calculate material requirements at lower levels via the MRP process. Note that because PM assignments are based on the information available at the time, they may need to be revised when market conditions change or supply disruptions occur. As new customer orders materialize during the month, no action is needed provided that all realized customer order quantities do not exceed assigned PM quantities. Assume that the "Realized customer orders" row represents actual customer orders received during the month. Because the realized customer-order quantity for PM1 (2,000) exceeds its initial assignment (1,250), the PM1 assignment must be increased to at least 2,000, and because this change affects goals and constraints in which PM1 participates (F1 and F3), other PM assignments must also be adjusted. The "Revised PM assignments" row shows a revised assignment of PMs that aligns with the original goals and constraints and realized customer orders. Note that without such an adjustment, the MRP would overestimate lower-level material requirements, resulting in an accumulation of unnecessary inventory. We discuss this issue in the *Benefits* section.

Implementation

Prior to our study, planning experts manually executed the S&OP process using spreadsheets. They used several interlinked spreadsheets to analyze the plan from various perspectives, including sales, manufacturing, procurement, and R&D. They manually downloaded the data used in these spreadsheets from several tables in the ERP and then manually made PM assignments on spreadsheets and uploaded the results back to the ERP. This process was time consuming and prone to errors at various levels. Furthermore, the large amount of data involved made it difficult for planners to investigate and analyze inconsistencies and identify the least-costly and most-profitable operations plan. To this end, Vestel made various attempts to automate the process by implementing spreadsheet macros and heuristic procedures within the ERP system. However, for a company that produces over 9.5 million TV units annually, has more than 5,000 different models, and procures approximately 20,000 different materials, such approaches did not provide the required flexibility, speed, and solution quality.

We began our study in December 2010 with the goal of developing a decision support system (DSS) to support Vestel's S&OP process. During the analysis and design meetings, in conjunction with all stakeholders of the S&OP process, we identified the following as the primary system requirements:

- Rapidly generate high-quality plans;
- Determine inconsistencies between sales forecasts, realized customer orders, supply constraints, R&D plans, and managerial goals;
- Choose among alternative plans that can satisfy the given goals and constraints to increase operational efficiency and reduce costs;
- Work with Vestel's ERP software bidirectionally and in an integrated manner;
- Perform scenario analyses on forecasts, procurement capability, and production capacity;
- Revise the plan to align automatically with realized customer orders;
- Store plans and compare previous plans among themselves and with realized orders, and facilitate the

analysis of differences between forecasts and realized customer orders;

• Eliminate the need for multiple spreadsheets; and

• Serve as the single source of truth regarding the S&OP process.

After an initial investigation of the problem and the required functionality, we chose to build a DSS based on mathematical programming. Our reasons for choosing an optimization-based approach rather than using heuristics or metaheuristics can be summarized as follows:

• Our investigation revealed that the problem structure is suitable for the development of a mixed-integer programming model based on linear programming formulations used in aggregate planning problems (Pochet and Wolsey 2006).

• If a linear or mixed-integer programming problem is infeasible, an irreducible infeasible subsystem (IIS) of constraints can be calculated (Gleeson and Ryan 1990, Guieu and Chinneck 1999). Such a subset is infeasible by itself; however, if any constraint is removed from the subset, the remaining set of constraints is feasible. Thus, an IIS provides a precise reason for the infeasibility of the formulation and can be used to identify conflicts between various data, goals, and constraints entered into the S&OP process.

• The planning horizon in the S&OP process is at least four months, during which Vestel produces and sells more than three million TV units and procures all related materials. Therefore, solution quality has a significant impact on operations costs, customer satisfaction, and profitability.

Given the requirements that became clear during the analysis and design meetings, we carried out our study in three phases:

• Phase I: Design the optimization model.

• Phase II: Develop a DSS based on the optimization model.

• Phase III: Expand the usage of the DSS within Vestel to enable stakeholders of the S&OP process to benefit directly from the system.

In Phase I, we formulated the planning problem in the S&OP process as an optimization model, which we describe in the appendix. Our model minimizes procurement and production costs while satisfying customer orders and sales forecasts, and meeting operational constraints. In Phase II, we developed a DSS based on the optimization model in Release 3 of ICRON advanced planning and scheduling system (http://www.icrontech.com). ICRON provides an object-oriented and visual algorithm modeling environment. It also has extensive support for database and ERP systems integration and interfaces to several mixed-integer programming solvers, including GLPK, Cbc, CPLEX, and Gurobi. The major functionalities and use cases of the DSS can be summarized as follows:

• The DSS downloads up-to-date data about realized customer orders, current inventory levels and scheduled receipts of critical materials, PM definitions, and BOM from the ERP software.

• It validates the input data and reports data problems via several validation reports. It also allows the user to evaluate input data and make changes before running the optimization.

• When the user initiates an optimization, the DSS constructs and solves the optimization model in memory.

• If the model is infeasible, the DSS performs an infeasibility analysis by computing an IIS. It then identifies the business objects (e.g., PMs, displays, sales forecasts) that are associated with the constraints and variables in the IIS. Thus, it automatically translates a mathematical description of infeasibilities to a business description of inconsistencies. It reports such inconsistencies in a graphical user interface (GUI) in a manner that allows the user to rapidly resolve the infeasibility by directly interacting with the objects causing the inconsistency. As an example, assume that the shortage of a display within its procurement lead time is causing an infeasibility. The DSS lists the display and all customer orders and sales forecasts that require the display in a window dedicated to infeasibility analysis. The user can then resolve the infeasibility by increasing the supply (after coordinating with procurement) or decreasing the demand (after coordinating with sales and marketing). The user can also manually enable or disable some constraints.

• The user can also instruct the DSS to automatically relax some constraints to resolve an infeasibility. When the user executes this functionality, the

DSS first converts demand constraints to soft constraints by adding an auxiliary variable to each customer order and sales forecast. These variables represent the quantity of the corresponding demand item that cannot be satisfied under the given constraints. It then solves an auxiliary optimization model whose objective function minimizes the sum of unsatisfied demand quantity variables subject to constraints in the original model. An optimal solution of this auxiliary model represents a minimum-unsatisfaction solution, and the demand items whose unsatisfaction variable takes nonzero values indicate the reason for the infeasibility. We then fix each demand item's unsatisfaction variable to its current level, switch back to the original objective function, and again solve the problem. The user can identify the demand items that are affected by the infeasibility in the original model and also can evaluate the plan that will be generated when the infeasibilities are resolved. Note that this functionality complements the IIS detection functionality. Users regularly use IIS detection to identify root causes of infeasibility. However, because the number of constraints within an IIS can be relatively large and multiple IIS sets can be associated with an infeasible model, the automated infeasibility resolution functionality is also necessary. We have observed that over time the users have become increasingly comfortable with interpreting IIS sets from a business point of view. They now often prefer to use the IIS detection functionality so that they can have an active role in the infeasibility resolution and have more control over the system.

• Once an optimal solution is found, the DSS presents the solution in various ways (e.g., reports, pivot tables) so that the user can easily understand and interpret the solution.

• The DSS also allows users to manually add, remove, or modify constraints. We have integrated these use cases into a pivot table to allow the users to dynamically filter and group PMs with respect to their product attributes. Each cell in the pivot table represents a subset of PMs that are to be produced in a particular month and that share similar attributes. The user can see the current result of the optimization model associated with that subset and month and can add a new constraint (Equation (6) in the appendix) to change it in the next optimization run.

• It also stores the results of the optimization in a database for future reference and updates the ERP system as needed.

The DSS keeps the optimization model and its solution active in computer memory. This capability allows it to immediately reflect to the optimization model any changes that the user has made to goals and constraints rather than building and solving the model from scratch each time the user triggers an optimization. Specifically, when the user executes an optimization for the first time, the DSS builds the mathematical model in memory. It communicates the resulting model to the solver component, which solves the optimization problem and returns an optimal solution and additional information (e.g., the optimal basis corresponding to the optimal solution that the solver has found). The DSS stores the mathematical model and its optimal basis in memory and reflects it in the GUI. If the user changes the model, the DSS incrementally changes the corresponding mathematical model objects. For example, if the user creates a new constraint, the DSS adds the new constraint to the mathematical model after calculating its variable coefficients and its right-side value. Note that this approach is significantly faster than rebuilding the model from scratch at each optimization request, because it saves model generation time and allows the solver to utilize its warm-start capabilities. As a result, this reoptimization capability enables the user to perform a scenario analysis within a few seconds and significantly enhances the system's usability.

We began user tests for the DSS in June 2011. In conjunction with users, we identified three test stages:

1. Data accuracy tests: Users compared data from ICRON with up-to-date data from the ERP software and made necessary corrections. At this stage, ERP data quality improved significantly, and we implemented various checks for data consistency. In particular, during this stage, we observed that purchase orders for various components in the ERP were not being updated promptly to reflect changes in inbound ship schedules. Vestel updated relevant business processes to resolve this issue. This stage lasted approximately six weeks, that is, until mid-July 2011.

2. Model accuracy tests: In conjunction with the users, we generated small data sets and executed the DSS using these data sets to check the results of the optimization model. We specifically analyzed extreme scenarios (e.g., no demand, very high demand, no materials-procurement capability) and made the necessary corrections until the system successfully produced correct and explicable results for these situations. We executed this stage in parallel with the first test stage, and it allowed us to identify and resolve various corner cases (i.e., problems that are unlikely to occur under normal operating conditions) before they appeared in real data.

3. Parallel usage tests: After we corrected the problems we encountered in the first two testing stages, S&OP planners thoroughly tested the DSS in parallel with their manual planning process, which uses spreadsheets. During these tests, planners checked the plan that the DSS generated using the same data as in the manually generated plan; they confirmed that the DSS produces high-quality plans and is able to consider some criteria that the manual planning process does not consider. This stage started at the beginning of July 2011 and lasted approximately six weeks. Our main challenge in this stage was managing the expectations of the planners. In particular, the planners initially expected the DSS to generate a plan similar to their manually generated plan. After several discussions, they started focusing on independently evaluating the DSS-generated plan and eventually observed that it consistently generated high-quality plans.

At the end of Phase II in August 2011, the DSS became operational for use by the S&OP planners. In Phase III of our study, we designed Web-based reports so that a large number of users in various departments could easily access the current plan. These reports take the plan directly from ICRON and allow users to compare the current plan with previously saved plans and realized customer orders. The system became operational in November 2011, and Vestel has been using it every day since then.

Figure 4 shows the architecture of our DSS in relation to Vestel's information technology landscape. The system consists of various components. Vestel uses SAP as its ERP software, which stores master data (e.g., product and PM definitions, BOM, cost information) and transactional data (e.g., customer orders, inventory levels, scheduled receipts). The planning database, a Microsoft SQL server database, stores required planning data that are not available in the ERP, in addition to scenarios and plans generated in planning sessions. We implemented the integration, planning, and execution modules in ICRON. The integration module transfers data between the ERP and planning database, and ensures data consistency via validation checks. The planning module is responsible for planning and scenario analysis. The execution module is responsible for tracking realization of customer orders, inventory levels, and scheduled material receipts, and adjusting PM assignments of the current plan as needed. We implemented these modules, which are primarily used by S&OP planners, during Phase II of our study. Finally, the Web module, which is an ASP.NET application, provides Web-based reporting functionality and is responsible for disseminating the current plan to other departments. We implemented this module during Phase III of our study.

Benefits

Since the DSS became operational in August 2011, it has provided Vestel with numerous benefits. Next, we discuss the tangible and intangible benefits we measured during 2012 and 2013.

Tangible Gains

Decrease in planning time: Although Vestel continuously introduces new PMs and some PMs become obsolete as a result of changes in the product portfolio, approximately 700 PMs are active (i.e., have corresponding customer orders and (or) forecasts within the planning horizon) in planning sessions. Approximately 5,000 processes are active because each PM has multiple alternative compatible displays. The time horizon of Vestel's S&OP process is at least four months. When the S&OP planners manually generated a plan prior to our study, they required at least two days to analyze inconsistencies and calculate PM assignments after they had obtained the necessary input data from all functions. After implementing our DSS, this time decreased to three hours. The DSS requires approximately 30 minutes of this time to read data from the ERP and three to four minutes to construct and solve the optimization model the first time.

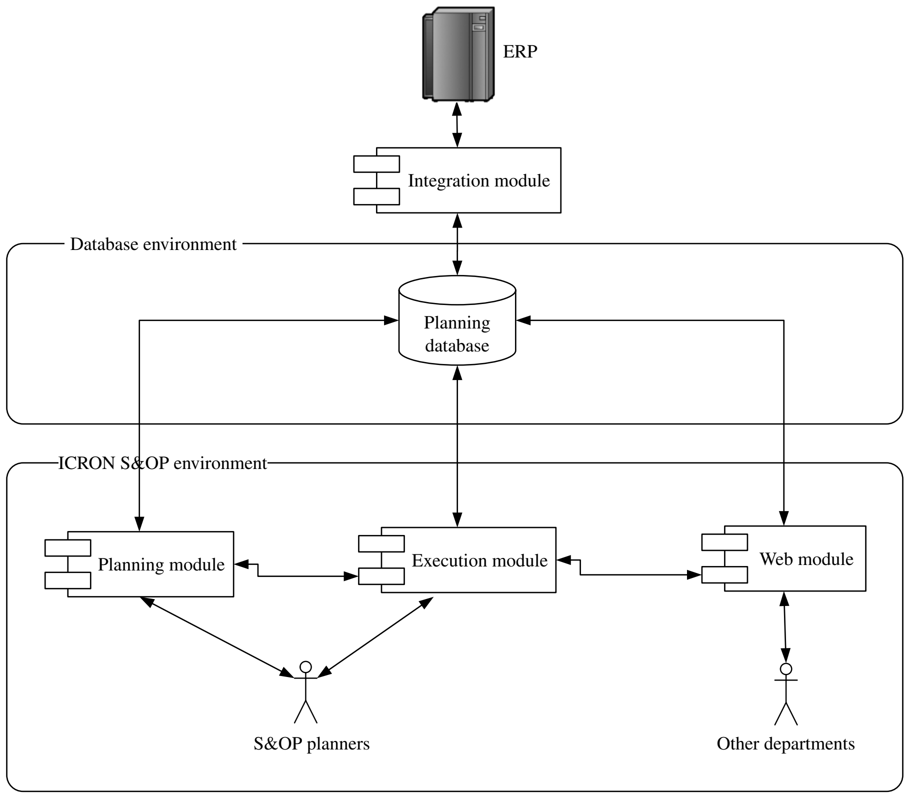

Figure 4: Our DSS comprises a planning and execution module that the S&OP planners use, and a Web module that users in other departments employ. The planning database stores inputs to and outputs from our DSS, and the integration module provides bidirectional communication with Vestel's ERP system.

Planners use the remaining time to define and analyze scenarios. The DSS stores the optimization model and its optimal solution in memory for efficient reoptimization; therefore, solving each scenario takes only a few seconds. When the DSS identifies an optimization model as infeasible, automatic infeasibility analysis and relaxation functions execute in less than one minute. Therefore, most of the time can be used to define and analyze alternative scenarios.

Increase in efficiency of the S&OP process: Prior to our study, S&OP meetings in which executive management and all functions participated were held only once per month because of the extensive effort required to manually gather input from all functions, identify and resolve inconsistencies, prepare scenarios, and generate alternative plans. After the DSS became operational, Vestel increased the frequency of S&OP meetings to weekly; however, it also holds meetings as necessary when a major change in supply or demand conditions occurs. Furthermore, because rapid scenario analysis and inconsistency detection are possible, participants can now execute the DSS during a meeting to investigate ad-hoc scenarios. Thus, the overall effectiveness of the S&OP process has improved significantly.

Improvement in planning accuracy: When the DSS became operational, discrepancies between the initial PM assignments made and the actual production decreased by 20 percent compared to manually made PM assignments, because the DSS (1) makes better use of available information on existing customer orders and supply state than manual planning process does because of its online integration with the ERP, and (2) generates an optimal solution that is communicated to sales and marketing to guide sales efforts. Recall that the DSS automatically revises PM assignments as needed. The discrepancy between planned and realized operations has decreased significantly as a result of these factors. Furthermore, the empirical rules that planners used have been replaced by an optimization model that provides consistent solution quality.

Decrease in inventory level: As we discuss in the *Planning Materials* section, the DSS transfers assigned PM quantities to the ERP system to derive the MRP and other relevant business processes. Prior to our study, planners manually adjusted PM assignments biweekly with respect to realized customer orders. Hence, the MRP ran with current data only once every two weeks; therefore, it produced correct results for long-term materials requirements biweekly only. This caused discrepancies in the MRP results; see the example in Table 1. Assume that the data in the "Initial PM assignments" row represent initial assignments with no customer orders yet realized. The MRP calculates the requirements of upstream materials by using only PM assignments, and the total requirement quantity that drives MRP calculations is 50,000 (i.e., the sum of all PM quantities). Assume that some customer orders have materialized during the month, as the "Realized customer orders" row shows, before PM assignments are revised in the ERP. Because PM1 has an assignment of 1,250 orders but has 2,000 realized customer orders, the MRP calculates requirements based on 2,000 orders. For other PMs, assigned quantity drives calculations because the realized order quantity is less than the assigned quantity (reflecting the anticipation of more customer orders in the future). Thus, the total requirements quantity that drives MRP calculations is 50,750 with no corresponding change in sales forecasts or management goals. The excess quantity disappears once PM assignments are updated to align with realized customer orders; see the "Revised PM assignments" row in Table 1.

Figure 5 graphically illustrates the situation. The x-axis represents time, and the y-axis shows total forecasted demand quantity for a particular month. The dark area (Forecast) represents the revision of the total demand forecast by sales and marketing over time. The light area (MRP) shows the total quantity that drove MRP calculations prior to our study; planners manually revised the plan based on up-to-date realized orders and sales forecasts once every two weeks. As we explain earlier, when realized customer orders correspond to PMs that differ from expectations, the

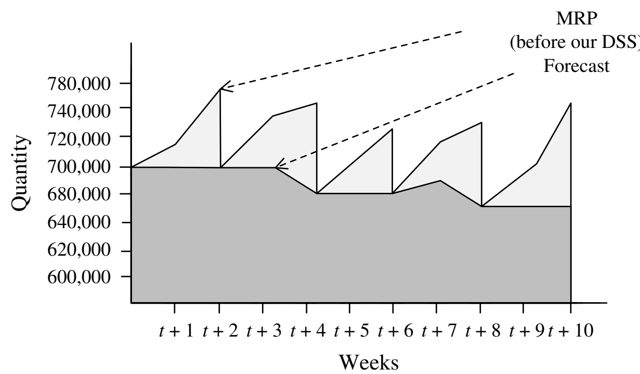

Figure 5: Sales and marketing revise sales forecasts over time as a result of changes in market conditions (dark area). Prior to the DSS implementation, planners manually revised PM assignments based on current realized orders and sales forecasts once every two weeks, causing the MRP to overestimate material requirements (light area). The execution module in the DSS automatically revises PM assignments to ensure that the two curves overlap each day; the result is a reduction in both inventory levels and MRP nervousness.

MRP calculations overestimate the actual requirement until the PM assignments are revised. Hence, the area between the two curves represents the overestimated requirement quantity and increases as the synchronization time increases. The execution module has reduced the synchronization time from two weeks to one day, because it adjusts PM assignments based on realized customer orders every day and ensures that the two curves overlap daily. Improving synchronization time has resulted in a decrease of approximately five percent in inventory levels of components with long lead times.

Intangible Gains

Reduction in MRP nervousness: As Figure 5 illustrates, the total quantity driving MRP calculations showed a sawtooth pattern prior to our study; total quantity ramped upward and then sharply dropped with a cycle length of two weeks. This pattern caused radical changes in calculated requirements and the timing of upstream materials. Thus, it created nervousness in the MRP results and required Vestel to keep high levels of safety stock. Nervousness in the materials requirement plan also affected the procurement plan; hence, it impacted Vestel's upstream supply chain. The execution module has eliminated the root cause of this nervousness.

Our model simultaneously considers Vestel's sales, procurement, and manufacturing operations; therefore, the effect of changes in one part of the system may propagate to other parts as a result of the holistic approach we take in the model. We note that increased frequency of planning may result in frequent changes to PM assignments, thus potentially contributing to planning nervousness. To mitigate this effect, we initially incorporated a term into our model's objective function to penalize changes from previously released PM assignments in the execution module within the DSS; however, planners challenged this approach during the testing stages for three reasons. The additional term (1) caused the model to deviate from cost-optimal solutions, (2) reduced the system's ability to react rapidly to changes in supply and demand conditions, and (3) created differences between PM assignments from the planning and execution modules; these discrepancies were difficult to interpret. Thus, we took a different approach. After several joint sessions with representatives of the sales and marketing, manufacturing, and procurement functions, the need to differentiate between PM assignments and firm order commitments became clear.

In these meetings, we identified firm commitments as customer orders (sales and marketing), production orders (manufacturing), and purchase orders (procurement). Furthermore, all functions agreed to interpret PM assignments as temporary calculated values that are necessary to ensure the consistency of the overall plan, rather than as committed decisions. This interpretation also conforms to Vestel's policy of not directly using absolute values of PM assignments in its operational decisions. We modified the DSS so that it downloads up-to-date information about firm commitments from the ERP, treats them as fixed, and optimizes PM assignments to align with firm commitments. In practice, this approach has provided a good balance between adaptability and the stability of the plan.

Increase in data visibility and correctness: Prior to our study, the S&OP process was based on data kept in multiple places, including ERP tables, spreadsheet files, and pivot reports. These data were updated manually and not integrated; as a result, ensuring that analyses were done on current data was impossible. The DSS has become the single source of valid information about the S&OP process, and presenting consolidated, current views of data to all stakeholders in a unified and consistent form is now possible. The increased data visibility, combined with improvements in data correctness obtained by automated validation algorithms, has enabled a structure that guides sales efforts, indicates procurement problems before they become evident, and facilitates analysis of deviations between sales forecasts and realized customer orders.

Providing a basis for further studies: Up-to-date information about long-term operational plans and sales forecasts has become available electronically. Availability of this information has enabled Vestel to automate other processes that require these data. In particular, Vestel management identified the capable-to-promise (CTP) process as its next-highest priority. This process is important in achieving customer satisfaction because it gives customers promised delivery dates before they finalize their orders. Existing customer orders and forecasted sales must be analyzed with respect to their capacity and material requirements to calculate a reliable delivery date. Following the DSS implementation, we developed a system for the CTP process that has also become operational. Thus, the DSS we describe in this paper has provided a solid basis for further studies to improve Vestel's operations and supply chain performance.

Conclusion

Operating in the highly competitive and rapidly changing TV manufacturing industry, Vestel is in a unique location. It is geographically close to Europe, where the majority of its customers are located; however, it is geographically distant from the Far East, where the majority of its suppliers are located. Although Vestel uses its proximity to Europe as a competitive advantage to satisfy customer demand on short notice, it must manage long lead times in material procurement and exploit its flexibility in manufacturing processes to decrease costs. The rate of technological advances in both end products and upstream components makes generating a realistic long-term plan difficult. As a result, Vestel's S&OP process is critical for its operational efficiency. In this study, we examined the S&OP process in detail and designed an optimization model that captures the dynamics of Vestel's S&OP process. The DSS we built based on this optimization model has replaced the manual planning process. Our system has become an integral part of Vestel's S&OP process. Vestel has used the DSS since 2011 and directly attributes both tangible and intangible benefits to its use. In addition, the DSS has enabled the development of systems for related processes to improve Vestel's competitiveness.

Acknowledgments

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Appendix

Mathematical Model and Its Business Implications

Table A.1 shows the symbols we used in our mathematical model and briefly describes each. We model each PM, display, and upstream material as a part (set I). Each part has an associated set of processes, and we model each production and procurement option of a part as a different process (sets J and J_i). In particular, because each product can be manufactured by using any of a number of displays, we model each alternative as a process of the corresponding PM. Our DSS automatically generates such processes by applying business rules regarding the compatibility of displays with PMs. In particular, it models business rules about (1) technical specifications (e.g., a display's dimensions must match the dimensions of its PM), (2) customer preferences (e.g., agreements with specific customers allow only the use of displays manufactured by specific suppliers), (3) international laws and legislations (e.g., displays manufactured in specific countries cannot be used in products that will be shipped to other specific countries), (4) managerial preferences (e.g., low-cost displays should be used in low-end products), and (5) R&D and quality concerns (e.g., specific displays do not perform well with products that use specific electronic components). Our DSS keeps these rules in a database and executes them to create PM processes. It also links PMs with sales forecasts (sets F_t and I_f) and calculates the total realized customer order quantity for each PM in each period (parameter o_{it}) by aggregating detailed customer order information downloaded from the ERP. We model the requirement that some upstream materials depend on the display used by defining a process-dependent BOM (parameter $b_{i'ji}$). We use upper bounds on process quantities (parameter $\bar{x}_{ijt}$) to model procurement capability and R&D issues such as new-product and process introductions. Finally, we use upper bounds on inventory levels ($\bar{y}_{it}$) to model end of life for obsolete components and to ensure that the production of PMs is planned only to satisfy customer orders and sales forecasts, but not inventory.

	Description
Set	
I	Set of parts
J	Set of processes
T	Set of planning periods
R	Set of resource groups that present a capacity restriction
J_i	Set of processes of part i
F_t	Set of sales forecasts for period t
I_f	Set of PMs that can be used to satisfy sales forecast f
C_t	Set of user-defined constraints for period t
U_{ct}	Set of PM-process pairs associated with user-defined constraint c in period t
Parameter	
q_{ft}	Quantity of sales forecast f at period t
o_{it}	Total realized customer order quantity of PM i in period t
y_{i0}	Initial inventory of part i
v_r	Available capacity of resource group r
u_{ijr}	Unit usage of process j of part i on resource group r
$b_{i'ji}$	Unit usage of process j of part i' on upstream part i
r_{it}	Scheduled receipt quantity (due to production/purchase orders) of part i in period t
c_{ijt}	Unit cost of process j of part i in period t
$\bar{x}_{ijt}$	Upper bound on process j of part i in period t
$\bar{y}_{it}$	Upper bound on inventory level of part i at the end of period t
d_{ct}	Right-hand-side value of user-defined constraint c in period t
Variable	
x_{ijt}	Production/procurement quantity of part i via process j in period t
y_{it}	Ending inventory of part i at the end of period t

Table A.1: We describe the sets, parameters, and decision variables we use in our mathematical model.

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J_i}\sum_{t\in T} c_{ijt}x_{ijt} \tag{1}$$

$$\text{subject to} \quad \sum_{i\in I_f}\sum_{j\in J_i} x_{ijt} = q_{ft} \quad \forall\, t\in T,\, f\in F_t, \tag{2}$$

$$\sum_{j\in J_i} x_{ijt} \ge o_{it} \quad \forall\, t\in T,\, i\in I, \tag{3}$$

$$\sum_{i\in I}\sum_{j\in J_i} u_{ijr}x_{ijt} \le v_r \quad \forall\, t\in T,\, r\in R, \tag{4}$$

$$y_{i(t-1)} + r_{it} + \sum_{j\in J_i} x_{ijt} - \sum_{i'\in I}\sum_{j\in J_{i'}} b_{i'ji}x_{i'jt} = y_{it} \quad \forall\, t\in T,\, i\in I, \tag{5}$$

$$\sum_{(i,\,j)\in U_{ct}} x_{ijt} \odot d_{ct} \quad \forall\, t\in T,\, c\in C_t, \tag{6}$$

$$0 \le x_{ijt} \le \bar{x}_{ijt} \quad \forall\, t\in T,\, i\in I,\, j\in J_i, \tag{7}$$

$$0 \le y_{it} \le \bar{y}_{it} \quad \forall\, t\in T,\, i\in I. \tag{8}$$

The objective function (1) minimizes the total production and procurement cost. Note that we do not allow backlogs, which aligns with Vestel's business policy. Constraints (2) ensure that sales targets are satisfied. Constraints (3) ensure that assignments for each PM are at least as much as its realized customer orders. Constraints (4) force capacity restrictions on resource groups. Constraints (5) are inventory-balance constraints. Constraints (6) are user-defined constraints. Users generate such constraints using the DSS's GUI for ad-hoc scenario analysis. The symbol $\odot$ represents the constraint's type, which is one of the following operators: $\{\leq, =, \geq\}$. Note that in our DSS, user-defined constraints are in the form of sum of process quantities in sets the user selects. We chose this specific form of user-defined constraints instead of more general ones such as weighted sums for the following reasons: (1) the corresponding sets can be selected by the user via the GUI by simple filtering and grouping on pivot tables; a more general constraint definition mechanism would require additional complexity at the GUI level, and (2) our observation that most constraints needed for ad-hoc scenario analysis at Vestel can be written as the sum of a set of process quantities. Finally, constraints (7)–(8) enforce nonnegativity and upper-bound restrictions on variables. Note that because Vestel's monthly production and procurement quantities are on the order of several hundred thousand, solving the problem as a linear programming problem and then rounding quantities to integral values does not introduce a significant error. Hence, we do not impose integrality restrictions in our DSS.

We note that the bucket-based modeling of time in our model and inventory-balance equations, Equation (5), is similar to the linear programming formulations used in aggregate production planning problems (e.g., Pochet and Wolsey 2006). Our approach extends basic models in two aspects: (1) modeling of alternative processes, possibly with different BOMs, and (2) Vestel-specific constraints—constraints (2)–(4) and (6)–(8).

We next discuss how our model handles some of Vestel's challenges described above. As we discuss at the beginning of this paper, in addition to long-term agreements with its suppliers, Vestel employs opportunistic purchasing of input materials, especially displays. We model input materials as parts that have their own buy processes (i.e., purchasing processes for materials that Vestel purchases from its suppliers). Hence, optimal values for x-variables corresponding to buy processes answer time-to-buy and quantity-to-buy questions. Furthermore, the r_{it} parameter corresponding to input materials represents the existing purchase order quantity, which our model treats as fixed. Planners can use our DSS to create dummy purchase orders to perform what-if analysis on the values of the r-parameters and investigate the impact of material-purchase opportunities. Note that some large suppliers in the high-technology sector sometimes offer complex procurement schemes to manufacturers. Such schemes could involve nonlinear discounts based on total volume or purchase quantity of a set of components aggregated across multiple periods. Although modeling such schemes is outside the scope of our study, we note that Vestel uses our DSS to analyze long-term procurement requirements by extending the planning horizon to at least 12 months while making annual contracts with its suppliers.

Our model contains $\bar{x}$-parameters that provide an upper bound on x-variables. The DSS reads as input R&D project timings about the introduction of new products and materials, and the phasing out of other products. It then uses the project timing information to calculate values of $\bar{x}$-parameters of parts and processes subject to engineering changes. In particular, if a new-product introduction is planned for time t, the DSS sets the $\bar{x}$-parameters of the corresponding part's processes prior to t to zero. We handle end-of-life planning of existing products and materials in a similar fashion.

Our DSS also allows planners to simulate what-if scenarios on R&D project timings. Thus, it allows planners to propose target timings for R&D projects. The $\bar{x}$-parameters can also be used to address material procurement capability and lead times. Because Vestel allows late changes to customer orders, these changes could affect material requirements within the procurement lead time. In such a case, the DSS calculates the additional procurement requirement because (1) our model treats realized customer-order quantities as fixed as a result of constraints (3), and (2) the x-variables represent the time and quantity-to-buy decisions. If an x-variable for a buy material takes a nonzero value within the corresponding material's lead time, expedited procurement is needed. If additional procurement is not possible within the material's lead time, then the planner can re-execute the model after setting the corresponding $\bar{x}$-parameter to zero, and create an alternative plan (if the model is feasible), or identify which particular demand items are affected by investigating the corresponding IIS (if the model is infeasible).

Note that our model does not contain any terms for minimizing the setup for the following reasons: (1) Vestel's manufacturing environment is highly optimized to minimize setup time to align with its business strategy of accepting orders of small batch sizes (recall that the batch size of 66 percent of its orders is for 500 or fewer units and annual production quantity exceeds 9.5 million TV units), and (2) setup times and costs are insignificant relative to the monthly time buckets used in planning. Finally, we note that our model's parameters are set so that (1) manufacturing costs decrease over time (because of continuous process improvements, this assumption is true), (2) although prices of input materials (e.g., displays) fluctuate in the short term, input-material costs decrease throughout the planning horizon, and (3) backlogs are not allowed; therefore, our model plans production and procurement as late as possible to satisfy demand and forecast on time. Therefore, we do not explicitly model inventory holding costs. To aid planners in planning inventory, the DSS generates reports that show material requirements, proposed purchasing timings and quantities, and projected inventory levels; planners view these reports via the GUI.

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Verification Letter

S. Engin Ergör, Material Management and Project Coordination Manager, Vestel Electronics, Organize Sanayi Bolgesi, 45030, Manisa, Turkey, writes:

"I am writing this letter in support of the paper entitled 'Mathematical programming-based sales and operations planning at Vestel Electronics.' The paper contains an accurate description of our S&OP process and the decision support system that has been developed to support it. We have been using the system on a daily basis since August 2011. In addition to the verifiable results listed in the paper, we have also observed that accuracy of procurement plans and our reaction capability to unexpected changes in supply and demand conditions have improved significantly. Furthermore, we have witnessed a substantial reduction in the need for 'firefighting' since the system became operational.

"The paper has been reviewed internally at Vestel Electronics, and has been cleared for publication. The project described in the paper received the Best IE/OR Application Award in 32nd National Congress on Operations Research and Industrial Engineering (YA/EM 2012) in Istanbul. Having recently been proudly featured in Mega Factories documentary series on National Geographic Channel, we hope that the publication of this paper will further increase visibility of Vestel Electronics within the OR/MS society and lead to further collaboration with academia."

Z. Caner Taşkın is an associate professor in the Department of Industrial Engineering at Boğaziçi University, İstanbul, Turkey. He received his BSc and MSc degrees in industrial engineering from Boğaziçi University in 2003 and 2005, respectively, and his PhD degree in industrial and systems engineering from the University of Florida, Gainesville, Florida, in 2009. His research is mainly focused on integer programming and hybrid decomposition algorithms with applications in medicine, telecommunications, and large-scale planning/scheduling. Dr. Taşkın is also involved in the design and development of ICRON advanced planning and scheduling system.

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