Title: A Linear Programming Model and Analysis of the Military Displays Business Manufacturing Operation at Tektronix, Inc.

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A LINEAR PROGRAMMING MODEL AND ANALYSIS OF THE MILITARY DISPLAYS BUSINESS MANUFACTURING OPERATION AT TEKTRONIX, INC.

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Abstract

The Military Displays Business at Tektronix consists of 29 separate operations used in the production of displays for fighter aircraft. The process is both slow and expensive. A project was conducted to evaluate the process and determine the bottlenecks in terms of increased output. The paper shows the results of a linear programming approach which was conducted using company data.

Executive Summary

Problem Definition

The Military Displays Business of Tektronix, Inc. reports into Tektronix Federal Systems Division. The business manufactures high quality cathode ray tubes (CRT) used for instrumentation displays in a variety of military aircraft. The products are manufactured in accordance with a monthly production plan which reflects contractual commitments and priority ratings (established by management) for orders competing for production. The products share manufacturing facilities, parts, production and test personnel. Availability of resources determines the maximum production levels. Production yields vary from month to month. Low yields resulting from a low level of investment have created a situation wherein the company is unable to meet its contractual obligations. Management is currently preparing to expand capacity by adding resources. In addition to finding the optimum production mix, management would like to determine which resources should be increased and the value of increasing those resources in terms of additional output of the system.

Model Purpose

The model's primary purpose is to provide Tektronix management with an understanding of the effect of possible management actions that could be taken to increase production of military displays (CRTs). The model is able to resolve the complex interactions of the many variables which effect the production process to produce a plan which maximizes output in accordance with the constraints imposed by management. Management can observe the effect of changes in the model, and therefore, predict the effect of similar changes in the business. Management can test the reasonability of their beliefs and assumptions about the business by incorporating them into the model and observing the outcome. Finally, Tektronix management can use the model within the company to demonstrate their understanding of the forces that are at work in the business thereby gaining credibility and support for their decisions.

Conclusions

A preliminary version of the model was developed for the purpose of fulfilling the requirements of Engineering Management 543. Working with a strict time constraint, we created a basic prototype which demonstrated that such a problem can be modeled as a linear program and that useful post-optimality analysis can be performed. We also identified certain shortcomings of employing a linear programming approach in this case. The creation of a more sophisticated model

Introduction

Linear programming (LP) can be applied to many fields. Using LP for purposes to enhance management's understanding of a problem or process flow within a company is both necessary and valuable. Management's insight of the process can be enhanced through LP. In this study, the manufacturing facilities of MDB (Tektronix) will be analysed. A model of its manufacturing process will be presented, the optimum production mix under the existing constraints will be shown and the areas where additional resources are necessary will be explored. This will help management make more informed decisions and allow them to test other assumptions which may not be apparent.

Background

The Military Displays Business of Tektronix, Inc. reports into Tektronix Federal Systems Division. The business manufactures high quality cathode ray tubes (CRT) for a variety of military aircraft. The products are manufactured in accordance with a monthly production plan which reflects contractual commitments and priority ratings (established by management) for orders competing for production. The products share manufacturing facilities, parts, production and test personnel. Availability of resources determines the maximum production levels. Production yields vary from month to month. Low yields resulting from a low level of investment have created a situation wherein the company is unable to meet its contractual obligations. Management is currently preparing to expand capacity by adding resources. In addition to finding the optimum production mix, management would like to determine which resources should be increased and the value of increasing those resources in terms of additional output of the system.

Data Collection

Collecting data for the model was readily accomplished since there currently exists an extensive historical database of production process documentation and results. Data collection was limited to information obtained for purposes of building the model. This information was in a form usable for Tektronix, but forced the modelers to make various assumptions concerning total available resources. However, the General Manager of Tektronix Federal Systems Division and the General Manager of the Military Displays Business were both cooperative and helpful in this effort.

The Military Displays Manufacturing Operation

The Military Displays Business (MDB) organization consists of some 50 people (exhibit 1). The product mix consists of four active products (exhibit 2). These products go into a variety of military platforms (exhibit 3). The manufacturing process is graphically depicted in exhibit 4. The shaded area of exhibit 4 highlights the testing area which demonstrated different characteristics from the preceding steps. Exhibit 5 shows the current and projected manufacturing levels. It is important to note that whereas a commercial CRT manufacturing process may produce 500,000 devices

MACHINE CONSTRAINT :

(M1*X1 + M2*X2 + M3*X3 + M4*X4)/(U/L) ≤ H/S *S/D *D/M

M1 = # OF MACHINE HOURS WORKSTATION1/UNIT X1
M2 = ...

<u>where:</u>
U/L = UNIT/LOT
H/S = HOURS/SHIFT
S/D = # OF SHIFTS/DAY
D/M = # OF DAYS/MONTH

<u>WORKSTATION 2:</u> Black Patinal

YIELD EQUATION:

YIELD(X1) WORKSTATION1 * X1 = X5
YIELD(X2) WORKSTATION1 * X2 = X6
YIELD(X3) WORKSTATION1 * X3 = X7
YIELD(X4) WORKSTATION1 * X4 = X8

X5 = INPUT WORKSTATION2 = OUTPUT WORKSTATION 1
X6 = INPUT WORKSTATION2 = OUTPUT WORKSTATION 1
X7 = INPUT WORKSTATION2 = OUTPUT WORKSTATION 1
X8 = INPUT WORKSTATION2 = OUTPUT WORKSTATION 1

(The input of workstation 1 times the yield is the input for workstation 2)

OPERATOR CONSTRAINT :

(O5*X5 + O6*X6 + O7*X7 + O8*X8)/(U/L) ≤ H/S * S/D *D/M

O5 = # OF OPERATOR HOURS WORKSTATION1/UNIT X1
O6 = ...

U/L = UNIT/LOT

H/S = HOURS/SHIFT
S/D = # OF SHIFTS/DAY
D/M = # OF DAYS/MONTH

MACHINE CONSTRAINT :

(M5*X5 + M6*X6 + M7*X7 + M8*X8)/(U/L) ≤ H/S *S/D *D/M

M5 = # OF MACHINE HOURS WORKSTATION1/UNIT X1

M6 = ...

U/L = UNIT/LOT

H/S = HOURS/SHIFT
S/D = # OF SHIFTS/DAY
D/M = # OF DAYS/MONTH (and so forth for all succeeding operations.)

The model was developed iteratively. Initial formulations produced results that were unrealistic and repeatedly forced us to re-examine the parameters and assumptions. This led to the introduction of additional constraints and information into the model. We have included results summaries from some of the final models to show the effects of adding upper and lower bounds to the production of the various products. These will be discussed in the section on sensitivity analysis.

One of the difficulties we encountered in formulating the model had to do with developing a method for representing the "rework loop" that existed in the manufacturing process. In the model formulation (exhibit 9), the model must quantify the amount of the output component (i.e. X13) which survives the phosphor deposition process and becomes input to the next process (i.e. X17). The yield of the process is represented by the variable "q" and is fixed at .65. (1-q) Components fail the first-pass yield test and are recycled one time through the process to see if they can be pass the test with an additional layer of phosphor. So the quantity of X13 that makes it through the process is (q + (q x (1-q))) or 2q - (q x q). This representation proved to work quite well.

A printout of the LINDO code for the model is provided in exhibit 10.

Key Assumptions

In modeling the operation of the production process without totally accurate information the following assumptions were made about labor time and other manufacturing specifics.

Machine Time

This is the total amount of available operating time for a particular machine. Machines can be run unattended and therefore have different capacity (hours) than their corresponding labor capacity.

The following can be said of the machine processes used by the Military Displays Business: (1) Machines which have cycle times longer than six hours can operate unattended and only need minimal setup and (2) since they run unattended there are more hours than exist for just the operators. This last point is born out in actual production where some processes are left to run, either overnight or between shifts, or both. All the operations with cycle times longer than six hours can run unattended with minimal operator supervision. One of the operators we saw was actually reading the newspaper during an operation.

Given the above description we have the following cycle times:

Cycle Time	Available Hours Per Day	Mach. Hrs/Yr
< 6 hours 7 hours	(9 hours per shift) x 2 = 18 hours per day	4,950
> 8 hours	If machine can run unattended then 24 hours per work day. If machine attended 18 hours per work day.	6,450

Assumptions for available labor time:

Labor time was calculated with an assumed 50 week year plus one shift working each Saturday. This results in a total of 4,400 worker hours per year for each station that has dedicated workers.

Additionally, the test area has further labor resources since the operations there run for three shifts per day during the week, thereby allowing the labor time available per year to increase to 6400. Machining time has also increased to 6450 hours per year.

Manufacturing Specifics

In order to fit the problem into a linear programming model instead of using monthly production goals the study group chose to use yearly goals. In monthly production planning there are constraints which force a certain ratio of semi-finished products through some workstations (e.g. "front end frit" workstation). This constraint has been relaxed in our model.

For some workstations (e.g. black patinal & black surround) only one worker is required. The workstation which is demanding lesser amount of resources has been excluded from the model.

There are no material constraints incorporated into the model. The management of MDB argued that use of Just-In-Time (JIT) manufacturing eliminated the material constraints. Although in real life there might be some material constraints in extreme ends because of unavailability of this data it has not been considered.

The demand for military displays of Tektronix has been steady. The management stated that it can practically sell all the products that are produced. However this assumption might not be correct in some of the low volume tubes.

Any future work on the model would have to include an analysis of these and other simplifying assumptions to determine which ones are acceptable and which ones should be modified. The sensitivity analysis capability inherent in linear programming would facilitate such analysis.

Model Verification and Validation

Model verification and validation was based primarily on testing, extreme value analysis, and sensitivity analysis. Reference mode behavior is feasible but not readily done on such a simple version of the model. The predictive power of the model can theoretically be tested by simulating history to see how closely we can parallel known data but again we are limited by the simplicity of the current implementation.

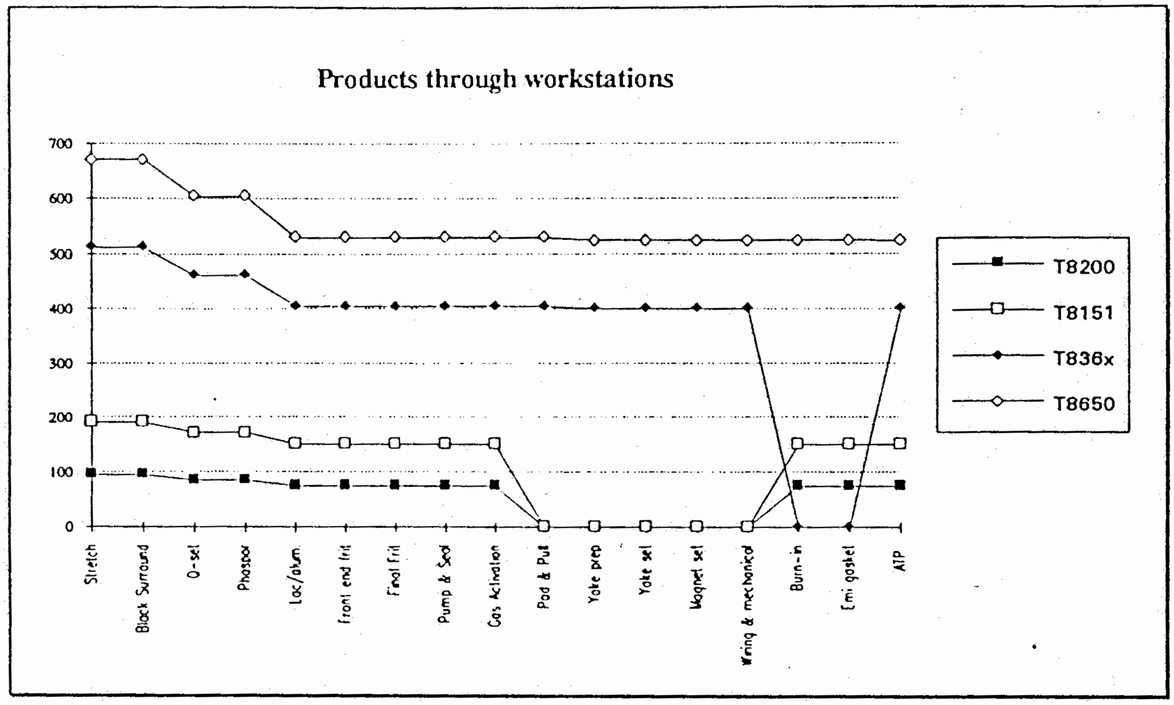
One of our objectives was to produce a model that would demonstrate the applicability of linear programming to this type of problem rather than accurately replicating the actual system behavior. We are satisfied that this objective was met.

Model Results and Interpretation

A printout of an optimal run from the model, incorporating upper and lower bound costraints, is provided in exhibit 11. In the optimum solution the quantity of the semi-finished products decreases through various workstations due to the yield factor. In reaching the optimal level of production, the amount of semi-finished products at the beginning will be higher than the ending amount. The proportion between the ending and starting amount of products is indicated as the product of all the yield factors.

The production graph (exhibit 12) enables the reader to visualize the following points easily.

Exhibit 12:



1. The relation between the starting and ending amounts of each product. For example without knowing the actual numbers, by looking at the graph it can be said that to produce 400 units of T8650, the production should start with approximately 520 units.

2. The relation between the input and output quantities of each product to specific workstations. Looking at specific processes makes commenting on the level of production and the magnitude of the yield on the specific workstation possible.

3. The workstations with the low yield factors. Black surround and Phosphor are the workstations where the major decreases in

the level of production occur for all products. Pad & Pull causes an identifiable decrease in the quantity of T8650 and T386X.

4. The processes that are not applicable to certain products. Pad & Pull, Yoke preparation, Yoke test, Magnet test and Wiring & mechanical are processes that are not applicable to both T8200 and T8151. Also the Burn-in and EMI gasket processes are not used for T8650.

Sensitivity Analysis

Scenarios are used to perform sensitivity analysis. The aim of the sensitivity analysis is to determine the effect of the upper and lower bound constraints on the production mix and level. The scenarios consist of cases without lower bounds, without upper bounds, without lower and upper bounds and without an upper bound for T836X. In each of these cases, after the first LINDO run the constraining workstsations are identified and the result of the changes which are higher than the allowable limits in these resources are determined by rerunning the model on LINDO. This process is performed two or more times for each scenario. Defining the constraining processes and possible increases in the resources enables the firm to decide on how to allocate the resources and to define the possible areas of investment. The shadow prices of the constraining workstations give the value of increasing those resources.

Sensitivity Results With Upper Bounds

When the model is run only with upper bounds (exhibit 13) it is observed that all the products except T8650 hit their upper bounds.

Exhibit 13:

Sensitivity Results only with upper bound

Scenario	TekUp	TekUp1
Objective function	1148	1217
x_{53} T8650	323	400 (u)
x_{54} T836X	600 (u)	592
x_{55} T8151	150 (u)	150 (u)
x_{56} T8200	75 (u)	75 (u)
Constraining Workstation	8	62
Shadow Price	0.260	0.123
Allow. Increase	230	50
Additional Resource	-	2000

where,

Workstation 8 = Black Surround

Workstation 62 = Yoke Set/Pot

The Black Surround is the constraining workstation for this case which limits the production of T8650 to 323 units. The allowable increase without changing the optimal solution in this process is 230 hours. To see the effect of an increase higher than the allowable limit the capacity of Black Surround is increased by 2000 hours. This time all the products except T836X hit their upper bounds and an increase in the level of production is observed. This implies that additional resources and some of the resources consumed by T836X, are used to produce more T8650 while causing a decrease in T836X. The increase in the capacity of the Black Surround forces the Yoke Set/Pot to become the constraining workstation. The shadow price of black surround is 0.26 which tells us that by adding one hour of more resource to black surround yields to an increase of 0.26 in objective function. Practically, by using 4 more hours it is possible to produce one more tube.

Sensitivity Results With Lower Bounds

Running the model with only lower bounds, results in production levels at their lower bounds for T8650, T836X and T8151 (exhibit 14).

Exhibit 14:

Sensitivity Results only with lower bound

Scenario	**TekLo**	**TekLo1**
Objective function	1149	1281
X_{53} [illegible]	360 (Lower bound)	360 (Lower bound)
X_{54} T836X	480 (Lower bound)	480 (Lower bound)
X_{55} T8151	120 (Lower bound)	120 (Lower bound)
X_{56} T8200	190	321
Constraining Workstation	8	45
Shadow Price	0.260	0.198
Allow. Increase	500	767
Additional Resource	-	2000

Workstation 45 = Pump and Seal

Only T8200 is produced above its lower bound. The Black Surround is again the constraining workstation. The allowable increase in capacity is 500 hours. Increasing the capacity of this process by 2000 hours results in an increase in the production level of T8200 while keeping the others at their lower bounds. This change makes Pump & Seal the constraining workstation. Additional Black Surround machine time is determined to increase the production of T8200 simultaneously with the aggregate production level. In this case the shadow prices of Black Surround and Pump & Seal are 0.26 and 0.198 respectively. Practically, by adding four more hours of labor to black surround or five more hours of pump & seal will allow production of one more unit.

Sensitivity Results Without Upper and Lower Bounds

Designing the model without bounds resulted in zero production of T836X and T8200 (exhibit 15).

Exhibit 15:

Sensitivity Results without upper & lower bound

Scenario	TekNo	TekNo1	TekNo2	TekNo3
Objective function	1157	1287	1612	1650
X_{53}	82	212	537	0
X_{55}	1075	1075	1075	1650
Constraining Workstation	8	45	81&87	51
Shadow Price	0.260	0.198	0 & 0.25	0.33
Allow. Increase	500	1639	3225 & 127	-
Additional Resource	-	2000	3000	81 by 4000 87 by 1000

Workstation 51 = Gas Activation

Workstation 81 = EMI Gasket

Workstation 87 = ATP

The production of T8650 is relatively low in comparison to the T8151. All resources are used to produce T8151 while those which are "excess" (or not consumed) are used to produce T8650. This implies that production of T8151 makes the best utilization of the available resources. Black Surround is the constraining workstation in this scenario. Increasing the capacity of Black Surround results in increased production of T8650 with no change in T8151. Adding capacity to Black Surround releases this constraint. The Pump and Seal Machine then becomes the constraining process. Increasing the capacity of this next workstation forces EMI Gasket and ATP to become the constraining processes and results in increased production of T8650 and no change in T8151. Increasing the capacities of EMI Gasket and ATP gives a different result. While the production of T8650 drops to zero, the production of T8151 jumps to 1650, thus increasing the total production level. It is possible to conclude that EMI Gasket and ATP are the constraining processes for T8151. Therefore increasing the capacity of these workstations only maximizes production of model T8151.

Sensitivity Results For T836X Without Upper Bound

The last scenario considered is the case where only T836X has no upper bound (exhibit 16).

Exhibit 16:

Sensitivity Results for x_{54} (T836X) without upper bound

Scenario	Tek400	Tek401	Tek402	Tek403	Tek404	Tek405	Tek406	Tek407	Tek408	Tek409	Tek410
Objective function	1148	1217	1217	1225	1227	1229	1231	1241	1279	1365	1375
X_{54}	523	592	592	600	602	604	606	616	694	740	750
Constraining Workstation	8	62	8	70	8	63	71	63	45	63	71
Shadow Price	0.260	0.260	0.260	0.125	0.260	0.1237	.125	0.1237	0.198	0.1237	0.125
Allow. Increase	261	2	8	0	8.5	0	0	0	334	0	0
Additional Resource	-	100	38	50	250	100	150	62 by 1000 70 by 1000 8 by 1000	1000	1000	-

In the solution to the original problem, all models except T836X are produced at their upper bounds. The constraining workstation remains Black Surround. To observe the effect of an increase in this process's capacity on T836X, the upper bound for this product is removed and the throughput of Black Surround is increased. This process is repeated several times. Increasing in the capacities of the constraining workstations results in expanding the production level of T836X. The Black Surround, Yoke Set/Pot, Wiring & Mechanical and Pump and Seal Machine become the constraining workstations interchangeably. As production of the other products can not be enhanced the additional resources are used to produce T836X. Using this model identifies the major constraining workstations on T836X.

General Comments on the Sensitivity Analysis

Without quantity requirements, T8151 is produced to the exclusion of T836X and T8200. T836X Is found to use high amounts of inputs which cause a low production level, and thus, poor utilization of the resources. The results demonstrate that T8151 utilizes resources in the most efficient way to augment production levels. Manufacturing T836X and T8650 consumes most of the resources, leaving lesser quantities for production of T8151 and T8200.

Black Surround is (still) the constraining workstation for production flow. It appears as the first constraining process in all the scenarios. This has several reasons. It is the second workstation and therefore due to the yield factor it stresses the number of quantities produced through the next workstations (Exhibit 12). It requires 6 hours of machine & labor time with a lot size of one which is very low compared to other ones and it constrains the process. The major constraining workstations that appear after an increase in the capacity of Black Surround can be identified as Yoke Set/Pot, Wiring & Mechanical and Pump and Seal Machine.

In actual manufacturing it is not possible to add a few units to the capacity of a machine or increase the labor hours continuously by small amounts. There can be overtime, but it would be difficult to sustain under MDBs current conditions. Further capacity increase can be obtained either by purchasing new machinery or by adding new workers or shifts. Due to these reasons, capacity increases in the sensitivity analysis are made higher than their allowable limits (range on b_j).

Conclusions

The model and results presented here can serve as the starting point and the guideline for management of MDB at Tektronix.

The Linear Programming model involves the flow of materials and work-in-process through the system. It uses existing data to calculate existing bottlenecks where possible investment would yield the greatest additional output. In this regard the model supports management as a valid tool.

The model provides management with an understanding of the effect of possible actions that could be taken to increase production of military displays. With our stated assumptions and the modification of the constraints, the model is able to resolve the complex interactions of many variables to help produce a production plan for output maximization. Management could also use the model to demonstrate their understanding of the forces that are at work in the business and thus gain credibility and support for their decisions.

The production process in the project is a continuous sequence with differing yields along that sequence. Rework is also required. In actuality rework and yields were difficult to model using linear programming due to the small quantities of output. These may have forced round off errors which would have possibly been mitigated through the use of integer programming. It was the modelers intention to eliminate the need for integer programming by using the time period of one year. However, this approach required assumptions which may not have been required in integer programming. Integer Programming may in the future be used for this same problem to obtain more accurate results.

Modeling the Military Display Business at Tektronix provided the team members with a clear understanding of some of the problems associated with the highly complex nature of high tech manufacturing. The process of model building required information gathering as well as the understanding of the manufacturing process. The team also gained insight into uses of LP within an organizational setting. These include optimal production, profit maximization and resource utilization. We chose output maximization since this is, in fact, the area which poses the greatest problem. Tektronix needs to output on a timely basis to avoid incurring possible penalties on their government contracts.

On top of all, the project serves a significant learning experience in Operation Research for the team members. From the visits to Tektronix, the formulation of the model, the sensitivity analysis to the completion of the project, it has been a valuable and enriching experience for all of us.