A RELATIONAL DATABASE MANAGEMENT

SYSTEMS APPROACH TO SYSTEM DESIGN

by

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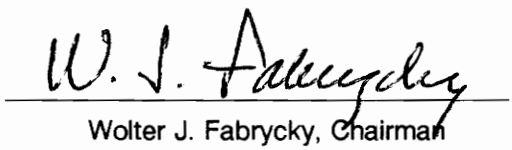

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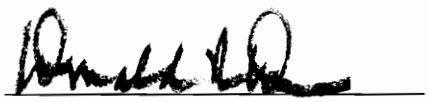

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Industrial and Systems Engineering

(ABSTRACT)

Systems are developed to fulfill certain requirements. Several system design configurations usually can fulfill the technical requirements, but at different equivalent life-cycle costs. The problem is how to manipulate and evaluate different system configurations so that the required system effectiveness can be achieved at a minimum equivalent cost. It is also important to have a good definition of all the major consequences of each design configuration. For each alternative configuration considered, it is useful to know the number of units to deploy, the inventory and other logistic requirements, as well as the sensitivity of the system to changes in input variable values.

An intelligent relational database management system is defined to solve the problem described. Table structures are defined to maintain the required data elements and algorithms are constructed to manipulate the data to provide the necessary information. The methodology is as follows: Customer requirements are analyzed in functional terms. Feasible design alternatives are considered and defined as system design configurations. The reliability characteristics of each system configuration are determined, initially from a system-level allocation, and later determined from test and evaluation data. A maintenance analysis is conducted to determine the inventory requirements (using reliability data) and the other logistic requirements for each design configuration. A vector of effectiveness measures can be developed for each customer, depending on objectives, constraints, and risks. These effectiveness measures, consisting of a combination

of performance and cost measures, are used to aid in objectively deciding which alternative is preferred.

Relationships are defined between the user requirements, the reliability and maintainability of the system, the number of units deployed, the inventory level, and other logistic characteristics of the system. A heuristic procedure is developed to interactively manipulate these parameters to obtain a good solution to the problem with technical performance and cost measures as criteria. Although it is not guaranteed that the optimal solution will be found, a feasible solution close to the optimal will be found. Eventually the user will have, at any time, the ability to change the value of any parameter modelled. The impact on the total system will subsequently be made visible.

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1.0 INTRODUCTION

In this chapter, the background of the problem under consideration is outlined and the output requirements are defined. The objective and the scope of this research are subsequently defined, and the approach that is followed, is outlined.

1.1 BACKGROUND

Complex systems are designed and deployed to accomplish one or more operational missions. A typical example of a complex system is a commercial airliner designed to transport people and cargo over a certain distance within a certain time limit. The total life cycle of the system is of concern. Not only the number of end items deployed, but the entire operating and support environment is of concern.

During the design and development of complex systems, many alternative concepts and alternative hardware and software items must be evaluated. Several different design configurations, each with its own logistic support requirements, may meet the required effectiveness, but at different life-cycle costs. An end item that requires too much maintenance may be less effective than an alternative item with a higher reliability. This will probably result from a higher demand on logistic resources and a resultant lower availability, despite a relatively low first cost. On the other hand, if the item is too reliable, its first cost may outweigh the savings on the logistic needs. What is the design configuration that will fulfill the user requirements at the lowest equivalent cost? What are the logistic needs for this configuration? How does the design team evaluate different design alternatives?

In order to develop a system that fulfills the requirements at the lowest annual equivalent life-cycle cost, the following decision variable values must be determined interactively for each possible design configuration:

1. The number end items to deploy at each location.
2. The inventory level for each item at each location.
3. The reorder point for each item in inventory at each location.
4. The throwaway age for each item.
5. The identification of all test and support equipment, facilities, personnel, documentation, training, and packaging requirements for each design configuration for each facility at each level of repair, including the different channels of repair.

It is also important to determine how sensitive the proposed system is (in terms of performance and cost) to changes in parameters. (The term "parameter" will be used for all variables and parameters that will be used in the analysis). This sensitivity is important not only in evaluating different existing alternatives, but also detecting trends that can serve as a target for the design team. In order to quantify the sensitivity of the system, a clear relationship must be defined between the number of end items deployed, the number of spare parts to be carried, and the reliability of the system. The spare parts that contribute most to the system effectiveness when added to the inventory must be determined for each deployment situation.

1.2 OBJECTIVE

The objective of this research is to define the structure of a relational database management system

that will enable the user of it to:

1. Evaluate different feasible design configurations of complex systems by manipulating parameters so that the required system effectiveness can be achieved at a minimum life-cycle cost.

2. Quantify the logistic support requirements and the total equivalent life-cycle cost for each possible design configuration, as well as the sensitivity of each configuration to changes in parameter values.

1.3 SCOPE

This research is undertaken to facilitate decision-making in the evaluation of alternative systems over the entire life cycle of a system. The proposed model (called the "System Design Evaluation Model") will be used primarily during the design and development phases, but will continuously be updated through the production and utilization phases. During the early phases of design, typically during the concept and preliminary design, different concepts and major components will be evaluated, using data at a relatively high level. During the detail design phase, the proposed model will use all the relevant data of all the items in the system that may influence the decision as to which item is preferable in the context of the system. Low level data are used. Also during the detail design phase, the number of end items to deploy at each deployment location will be determined, as well as the different levels of repair, and the facilities and test and support equipment required at each repair facility at each level of repair. The inventory level for each item in each repair facility will be determined, as well as when each item must be re-ordered, and in what

quantities.

Maintenance analysis of each design configuration is required to effectively evaluate different design configurations. During the early design phases, a relatively high level of maintenance analysis is required to evaluate alternative concepts. However, during the detail design phase, a detailed maintenance analysis is required. Although the proposed model uses the maintenance analysis data extensively in evaluating different systems and items, the model is not intended to be a maintenance analysis package; it merely prescribes what maintenance analysis data are required to effectively evaluate different systems and items over the intended life cycle of the project.

The proposed model will typically be used in evaluating different complex systems. A system is considered complex when it is comprised of a high number of component parts, has several different technology areas involved, and embodies several different performance features. The systems under consideration are mostly mechanical and/or electrical of nature. Typical examples include aircraft systems, ground moving equipment, radar systems, etc. Not only the system in its entirety will be evaluated; each significant item in the system will be evaluated to determine the most feasible system.

1.4 APPROACH

An intelligent relational database management systems approach is used to accomplish the objective of this research. The data required to perform the evaluation analysis are identified. The tables that are defined to maintain the data and the relationships between the different data elements are defined in Chapter 3. Algorithms are developed in Chapter 4 that will provide the user of the proposed model with a solution close to the optimal solution. The user is now provided with

the ability to change the value of any parameter or data element, as defined in the database structure, and the resultant effect on the entire system will be made visible. The proposed model will have the following characteristics:

1. Visibility: The user will have visibility of all the major consequences of each alternative solution, including the identification of all the logistic requirements. The level of visibility depends on the completeness of the maintenance analysis.

2. Consistency: Whenever the value of one parameter changes, the entire model will be updated (where applicable) and the results will be made visible in real time. For example, if new test data become available on an item and are entered into the system, the following will automatically occur without human interference (if the new data differ significantly from the existing data):

   2.1. Item reliability characteristics are updated.

   2.2. System availability is updated.

   2.3. New order quantities, reorder points, order intervals, and safety stocks are calculated for each repair facility at each level of repair where that item is kept in stock.

   2.4. Total available capacity of each location, and of the entire system, are recalculated and compared with the initial user requirements.

2.5. The new equivalent life-cycle cost is calculated and compared with the existing.

2.6. The net gain (or loss) in cost effectiveness is calculated according to the vector of effectiveness measures.

3. Ease of updating: Old data that need to be updated can easily be replaced by entering new data.

4. Information retrieval: Any relevant information in any format can be extracted from any concatenation of any number of relevant tables at any time. This is a tremendously powerful management tool.

5. Baseline comparison: Data can be kept for future projects that might have similarities with the existing project. Continuous improvement in the development of similar systems over time is likely. The result is a potentially ever-increasing learning curve.

6. Commonality of data: All users of the proposed model will share the same data. A change in data will immediately be visible to all users on the network.

7. Communication: The proposed model will serve as the basis of communication to the customer as far as the system is concerned.

8. Confidence building: The proposed model will increase the confidence with the customer since the user will have visibility of all major consequences of system related decisions.

9. Information source: The proposed model will serve as a basic source of information to develop logistics during the design and development phases.

10. Data source: The proposed model will serve as a major source of data for material requirements planning and manufacturing resource planning activities, especially aimed at the production phase (see Appendix B).

2.0 SYSTEM ANALYSIS

This chapter provides an overview of how the problem is approached. Figure 1 is an illustration of the proposed model structure and shows the different disciplines involved in analyzing the problem. Each of these disciplines is outlined in this chapter.

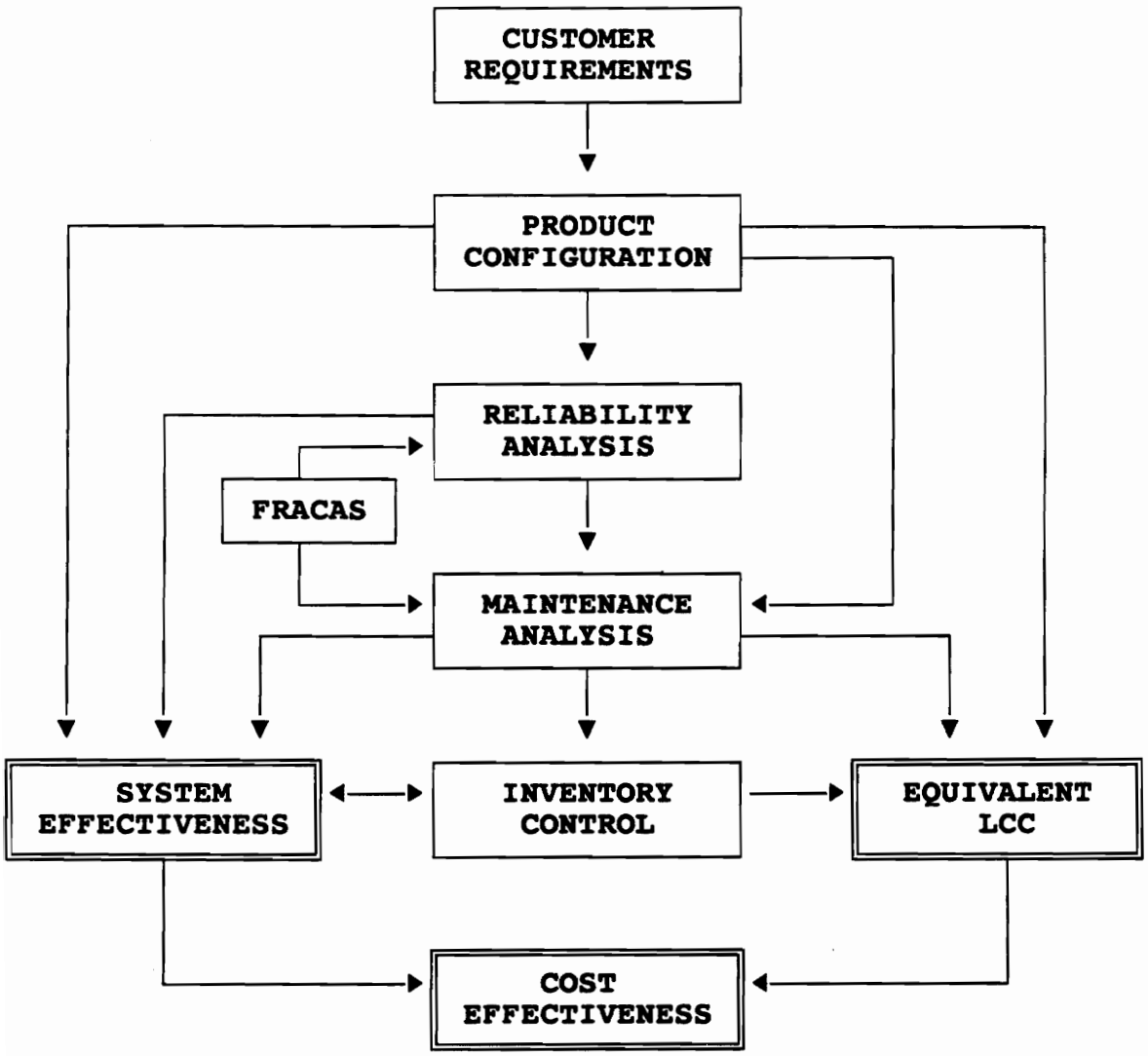

Figure 1 Overview how the proposed model is structured

2.1 CUSTOMER REQUIREMENTS

A functional approach is followed in analyzing the customer's requirements. These requirements are spelled out in terms of what the customer wishes to accomplish: the number of passengers to transport, the total amount of ore to mine, the total firepower required, etc.; all as a function of time. No solutions are offered at this point to fulfill the requirement.

2.2 PRODUCT CONFIGURATION

The product configuration is the most exact definition of each alternative. Although not necessarily initially defined, this will eventually be the exact definition of each alternative: item numbers, product structure, specifications, etc. All feasible alternatives are considered for evaluation. Unit capacities are considered to determine the minimum number of units to deploy.

2.3 RELIABILITY ASSESSMENT

The product configuration, the time period the customer anticipates the equipment to work, and the way the customer utilizes the system, determine the reliability. The reliability characteristics of each relevant item in the product structure are determined by test and evaluation. This information is typically fed to the maintenance analysis to determine the overall inventory requirements for spare and repair parts.

2.4 MAINTENANCE ANALYSIS

A maintenance analysis is accomplished to determine the logistic requirements of each alternative.

The proposed model utilizes maintenance analysis data to evaluate alternative solutions. The logistic requirements includes the identification of test and support equipment, facilities, manpower, training, consumables, transportation, and packaging requirements.

2.5 FRACAS

Maintenance analysis is not only accomplished during design and development; it extends over the entire life cycle of the project. The Failure Reporting And Corrective Action System (FRACAS) is a process that feeds back data to the developers during the utilization phase of the system. These data are analyzed to determine if the true reliability of the item deviates from the estimated value. All relevant logistic support elements are also evaluated.

2.6 INVENTORY ANALYSIS

The demand rate for spare and repair parts are calculated using reliability data, data from the maintenance analysis, and the system effectiveness requirements. The actual order sizes, reorder points, order intervals, and safety stocks are calculated for each item at each repair facility for all the levels of repair.

2.7 SYSTEM EFFECTIVENESS

System effectiveness is an indication of the system's technical capabilities. This includes the system performance, capacity of the system, reliability, availability, mean time to repair, etc. These requirements and capabilities are used in evaluating each alternative and the entire system. The system effectiveness is calculated from the product configuration, its associated reliability

characteristics, the maintenance requirements, and the actual inventory of spare and repair parts.

2.8 ANNUAL EQUIVALENT LIFE-CYCLE COST

The annual equivalent life-cycle cost (AELCC) is estimated for each alternative. This is done to aid in the process of evaluating different alternatives and in determining total costs. The AELCC is determined from the product configuration, the maintenance requirements, and the actual inventory.

2.9 COST EFFECTIVENESS

The final decision of which alternative to choose will depend on both the system effectiveness and the equivalent life-cycle cost. The cost effectiveness is the ratio of system effectiveness to the equivalent life cycle-cost.

2.10 LIST OF PARAMETERS

The following is a list of parameters that will be used in the proposed model. The user can change values for any of these parameters and the resultant effect on the whole system will be visible:

1. Capacity requirements and constraints.
2. Number of deployment locations.
3. Total amount of hours that the customer expects to work per year.
4. Number of identical items in a higher level item or system.
5. Exact system configuration.
6. The time that each unit is operational, given the total hours required.

7. Unit capacity.

8. Number or units deployed at each location.

9. Unit price.

10. Unit lead time.

11. Cost Escalating Factor, or inflation rate.

12. Allocated and actual item reliability values.

13. Item reliability distribution.

14. Failure data (test times, failure times, etc.).

15. Time constant used for reliability calculations.

16. Failure mode and failure rate.

17. Mean and standard deviation of failure times.

18. Service level.

19. Repair level of item.

20. Number and type of repair levels, and how they are structured.

21. Distance from repair channel to depot.

22. Different types of facility requirements and costs.

23. Different types of tool requirements and costs.

24. Different types of documentation requirements and costs.

23. Different types of overhead training requirements and costs.

24. Disposal requirements and costs.

25. Different operating personnel requirements and costs.

26. Different operating consumable requirements and costs.

27. Different corrective maintenance personnel requirements and costs.

28. Different preventative maintenance personnel requirements and costs.

29. Mean corrective maintenance time.

30. Preventative maintenance frequency.

31. Percentage of spare parts distributed amongst the different levels of repair.

32. Transportation cost.

33. Training cost as a variable cost.

34. Packaging requirements and costs.

35. Order quantity.

36. Order interval.

37. Reorder point.

38. Safety stock.

39. Order costs.

40. Holding costs.

41. Shortage costs.

42. Type of inventory model used.

43. Production rate and length of run for economic manufacturing quantity.

44. Economic Order Interval items that are acquired together.

45. Order cost per total order for economic order interval.

46. Variability of demand.

47. Variability of lead time.

48. Variability of lead time and demand.

49. Mean time between maintenance.

50. Mean active maintenance time.

51. Mean and total downtime of the system.

52. Availability of the system.

53. Availability of spare parts.

54. Number of spare parts deployed at each repair site.

Some of the parameters in the above list can be calculated from others. However, the user will be able to override each calculated value and all the relevant tables will be updated accordingly. Also, some of the parameters listed will have a unique value for each item, eg., reliability. Others may have a range of values, eg., the number of spare parts to be deployed per level and per customer for each year. For systems consisting of hundreds or thousands of parts it is therefore not uncommon to have thousands or even millions of parameter values for all the items. Many of these parameters have a changing nature: not only price increases and variations in interest rates are of concern, but numerous others. These include:

1. An alternative supplier has to be found for item X and his promised lead time can not be considered constant. Extra safety stock must now be carried.

2. New taxes on warehouse property increase the holding cost.

3. The customer wants to add a new intermediate repair facility for every six existing organizational facilities.

4. The customer wants to carry a greater percentage of parts at the intermediate level for parts that are repairable at the organizational level.

3.0 DEFINITION OF MODEL

The purpose of this chapter is to specify how the model is structured. Because the principles of relational database management systems are used to achieve the objectives, the different tables in the model are defined, as well as the relationships among them and the conditions for data existence and data extraction. Tables are defined as they would actually appear in the database with the name of the table in bold capital letters just above the table. Between the double lines at the top of each table are the column definitions. Examples are given to illustrate the types and format of data relevant for each field.

It is to be noted that all the tables specified in this chapter do not necessarily have to exist in the database. Tables that contain raw data (data that have not been defined in any other relevant format) must exist. However, tables that do not contain raw data do not have to exist, since the required information can be calculated as required from raw data. Whether tables containing non-raw data exist or not depends mainly on company-specific factors such as the complexity of the requirements, hardware and software capabilities, frequency of use, configuration management capabilities and policies, etc. However, for the purposes of illustration, the tables in this chapter are as extensive as possible without being unnecessarily redundant. (Although the terms "customer" and "end user" are used synonymously, the latter is preferred since each system will be developed for the user that will use it in its ultimate form.)

3.1 CUSTOMER REQUIREMENTS

As a result of the feasibility study in the conceptual design phase, it is anticipated that the

requirements of the end-user will be spelled out in functional terms. Examples include the amount of iron ore to be transported in a year, the number of passenger miles per year, or the volume of oil to be pumped per month. The functional objective of the model, as well as the global functional constraints that are imposed onto the system, are described in the CAPACITY_DESCRIPTION table and numerically constrained in the DETAIL_REQUIREMENTS table. These constraints define the feasible region in which the eventual system must fall. The objective determines the preferred solution within the set of feasible solutions.

CAPACITY_DESCRIPTION

CODE	DESCRIPTION
A	Tons of iron ore per year
B	Passenger miles per year
C	Barrels of oil per year

A separate table, the END_USER table, keeps track of end user data, such as customer definition (code, name, location, etc.); customer history (what and when did he buy); and financial status. The CUSTOMER_ORDERS table links customers and products via an order number. This detail of the end user is omitted for the purpose of this research.

What is of concern is the actual requirements in functional terms: how much iron ore does the end user want to mine (and at what locations) per year and for how many years? This type of data is acquired during the needs analysis phase before design and development actually commences. The DETAIL_REQUIREMENTS table gives the requirements of each end user per location. The number of end items is not of concern at this stage. The ITEM# is the end item that is be designed to fulfill the need. The CUST# is the end user who requires this capability. YR_0, YR_1, ... , YR_n

are the years he requires the functional capabilities as outlined. YR_0 is the first year that he requires the capability.

DETAIL_REQUIREMENTS

ITEM#	CUST#	CAP_COD	LOCATN	YR_0	YR_1	....	YR_n
CBA	C342	A	L31	7E3	9E3	....	21E3
CBA	C342	G	L31	21E6	23E6	....	49E6
CBA	C342	A	L19	11E3	12E3	....	31E3

The ITEM# used in the DETAIL_REQUIREMENTS table typically indicates the end item(s) required by the customer. Initially, this item does not have to exist; it is the final product to be delivered to the customer. The CUST# column refers to the customer, or end user, and the CAP_COD is the capacity code from the CAPACITY_DESCRIPTION table to determine the units involved. The LOCATN column indicates the location where the end user wants to deploy these units. A definition of these locations can be found in a LOCATION table with columns LOCATION# and LOCATION_DESCRIPTION (table not shown). The rest of the table represents the years ahead that contain the functional quantities that are required, corresponding to the type of capacity desired. As illustrated by the data in the DETAIL_REQUIREMENTS table, it is possible to have more than one objective, or constraint, for the same system at any location. (The reason why there is no distinction made between an objective and a constraint is that these constraints are the end user's constraints, and whatever is a constraint for the end user becomes an objective for the company developing the system.)

The TOTAL_REQUIREMENTS table indicates the total requirements for each end user, regardless of the location(s) where he anticipates using the system. The total requirements can be the

summation of the different detailed requirements, or it can be a constraint that is imposed on the system as a whole. If there are no constraints on the system other than what is imposed on the detail level, the TOTAL_REQUIREMENTS table will contain no raw data and can be considered redundant. Except for the omission of the LOCATN column, all the columns are the same as those in the DETAIL_REQUIREMENTS table.

TOTAL_REQUIREMENTS

ITEM#	CUST#	CAP_COD	YR_0	YR_1	...	YR_n
CBA	C342	A	20E3	28E3	...	65E3
GHI	C231	B	54E6	62E6	...	125E6

Also of concern in analyzing the end user's needs is the amount of hours the end user wants the equipment to work per week, as well as the number of weeks per year. This information is crucial in determining the number of units to deploy. The CUSTOMER_WORKING_HOURS and the CUSTOMER_WORKING_WEEKS tables indicate the number of hours the customer wants to work per week and the number of weeks he wants to work per year for the following n years. For the remainder of this chapter the columns YR_0 ... YR_n will indicate the relevant requirements for the following n years.

CUSTOMER_WORKING_HOURS

ITEM#	CUST#	YR_0	YR_1	...	YR_n
CBA	C342	60	60	...	40
GHI	C231	45	50	...	40

CUSTOMER_WORKING_WEEKS

ITEM#	CUST#	YR_0	YR_1	...	YR_n
CBA	C342	45	50	...	50
GHI	C231	48	48	...	48

The product of "hours per week" and "weeks per year" is considered the total time per year that the equipment will be operational. The system will be designed according to this time. The lower level components of each end item assume the same mission duration each year. This time duration is therefore passed down the product structure; each lower level component has the same mission duration as its parent component. If a particular item does not accept the same mission duration as that of its parent component, that item will be specified in the MISSION_FRACTION table as having a fraction of the time of the parent component. This fraction can be smaller or greater than one. The PARENT column shows the parent of the item and the FRACTION column shows the fraction of the parent's time that will be used as the mission time for that specific item. (The "parent" principle is discussed in the "Product Configuration" section.)

MISSION_FRACTION

ITEM#	PARENT	FRACTION
XDG	HJK	0.25
VBN	MKL	1.10

3.2 CAPACITY PLANNING

Each design configuration is designed to achieve and maintain a certain level of capacity to fulfill the customer's requirements, as spelled out in the CUSTOMER_REQUIREMENTS table. The

number of units to be deployed for the proposed configuration depends on, amongst other factors, the capacity requirements and the actual unit capacities, including logistics. The unit capacities, as "designed to" in the top down approach early in design, and the actual unit capacities (bottoms up) will be maintained in the ITEM_CAPACITY table in the DESIGN_TO and ACTUAL columns respectively. Both the "design to" and the actual capacities are the average operational capacity per hour when the item is in the "up state" (operational). All downtime activities are excluded in determining the capacity of each item.

ITEM_CAPACITY

ITEM#	CAP_CODE	DESIGN_TO	ACTUAL
CBA	A	0.145	0.140
CBA	G	13.750	12.210
...	...	....	....
LMN	A	0.125	0.124

When the system is analyzed in the early stages of design and development, the "DESIGN_TO" values are used to determine the number of units to deploy. However, as more reliable test data become available, these parameter values are being replaced with the ACTUAL unit capacity. The original values are kept to evaluate the design process later. The number of units to deploy depends primarily on the following:

1. Capacity required (defined in the two REQUIREMENTS tables).
2. Actual unit capacity per hour, if available, otherwise the target value (in the ITEM_CAPACITY table).
3. The time the end user wants to work (defined in the CUSTOMER_WORKING_HOURS and

in the CUSTOMER_WORKING_WEEKS tables).

Availability factors are considered at a later stage. The theoretical number of units to deploy, therefore, are the total capacity required, divided by the product of the unit capacity and the time that the end user wants to work. For each location, the number of units deployed are maintained in the UNITS_DEPLOYED. To obtain the total number of units deployed per location or per customer (the latter regardless of location), a report can be generated that will calculate the relevant values. A separate table for the total units deployed would be redundant since it would not contain any raw data.

UNITS_DEPLOYED

ITEM#	CUST#	LOCATN	TH_PRAC	YR_0	...	YR_n
CBA	C342	L31	T	18	...	72
CBA	C342	L31	P	21	...	85
CBA	C342	L19	T	28	...	107
CBA	C342	L19	P	33	...	126

The column TH_PRAC indicates a theoretical (T) or a practical (P) value. The theoretical values in the corresponding fields of YR_0 through YR_n indicate the number of units to be deployed in order to fulfill the capacity requirements at an availability of 100%. The reason for using the theoretical number of units to deploy is to obtain the total amount of effective hours of work needed fulfill the demand. The total effective hours of work is needed to determine the availability of the system and, therefore, the actual number of units deployed. The effective hours of work needed are used in the inventory section and in the heuristic model in Chapter 4.

The capacity that is planned to be deployed, as well as the capacity that is actually being deployed,

are maintained in the CAPACITY_DEPLOYED table. The TH_PRC column indicates whether the capacity is based on the theoretical number of units deployed (with availability of 1.0), indicated with a "T," or the actual number of units deployed with realistic availabilities, indicated with a "P." The actual number of units deployed are assigned during the detail design phase when the reliabilities and maintainabilities of the equipment become known with a reasonable amount of certainty and when a prediction of the relevant availabilities can be made.

CAPACITY_DEPLOYED

ITEM#	CUST#	LOCATN	CAP_COD	TH_PRC	YR_0	...	YR_n
CBA	C342	L31	A	T	7.05E3	...	20.88E3
CBA	C342	L31	A	P	6.85E3	...	19.62E3
CBA	C342	L19	A	T	10.96E3	...	31.03E3
CBA	C342	L19	A	P	10.26E3	...	30.56E3

As is the case with the UNITS_DEPLOYED table, the totals of the CAPACITY_DEPLOYED table can be obtained by a summation report. It is assumed that the summation of the capacities at the different locations is the total capacity required. The locations can be assigned such that this assumption always holds true. However, if this assumption is unacceptable, a separate table will have to be constructed for the totals: TOTAL_CAPACITY_DEPLOYED. It is strongly recommended that such a table does not exist and that the locations are selected such that the totals of the locations equals the total capacity deployed.

3.3 SYSTEM CONFIGURATION

The system configuration is the exact definition of the hardware. It is represented by an item

number and gives the lower level components in a product structure, or tree format. The product structure is a level by level breakdown of the system and of the products comprising the system. The product structure (sometimes also called the bill of material) is the backbone of the entire process. All relevant data is linked to the product structure by means of the item number. Different configurations can be evaluated simply by defining the required configurations either from an already existing database of items or by adding the required items to the database. The technical capabilities and the anticipated equivalent life cycle costs and logistic requirements are determined for each design configuration. A vector of cost effectiveness measures is developed for each customer against which each configuration will be evaluated. The effectiveness measures depend on each customer's objective, constraints and risks. The term "item number" is used for any component, combination of components, sub-assembly, assembly, or any group of assemblies. The following tree structure shows the product structure as revealed in the PRODUCT_STRUCTURE table:

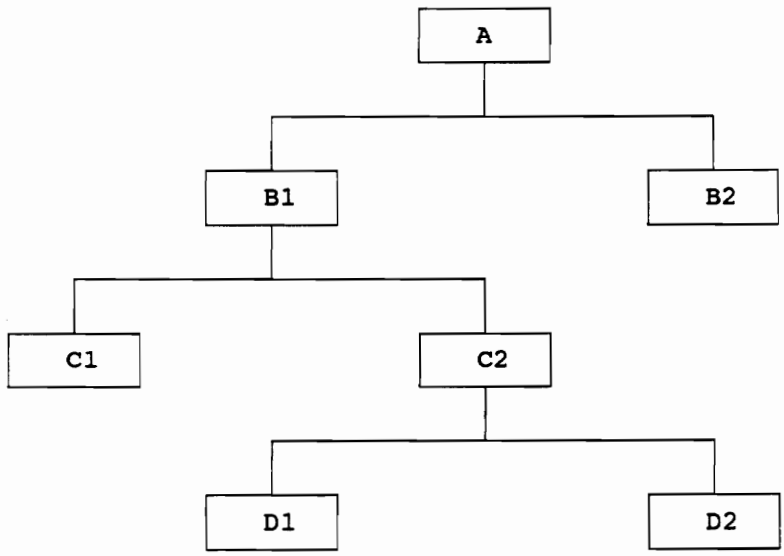

Figure 2 Typical product structure

PRODUCT_STRUCTURE

PARENT	CHILD	QTY_PER
A	B1	1
A	B2	1
B1	C1	1
B1	C2	1
C2	D1	1
C2	D2	1

The PARENT in the PRODUCT_STRUCTURE table is the item number for which the lower level item numbers are specified in the CHILD column. The entire product structure of any configuration, therefore, consists of a logical concatenation of single parent/child relationships. An item (such as item A above) is therefore not physically built. The advantage of this structure is that any item can be replaced by another item simply by deleting the original item from its parent and adding the new item as a lower level component of that parent. The entire system is then updated, provided the lower level items have been defined.

Another table, ITEM_IDENTIFICATION, is used to identify item numbers. Each item is referenced by only the item number. The item description is only for user interface. The table has the following structure:

ITEM_IDENTIFICATION

ITEM#	DESCRIPTION	COMMODITY
A	Model XYZ dump truck	236450
B1	Base structure	522200
B2	Container hull	533000
C1	Chassis	212016
...	.....	....
ABC	Powerpack	142162
...	.....	....
ZZ3	Hinge	800100
ZYX1	Fastener (2.5 x 1/2 inch)	303022

When the product structure is printed out, a level-by-level indentation distinguishes the different levels of components. In the printout the product configuration is taken from the PRODUCT_STRUCTURE table, while the description is from the ITEM_IDENTIFICATION table. Data which are item related can be grouped together or printed on the same line if space permits. Figure 2 shows a very simple example of a product structure printout:

LEVEL	ITEM #	DESCRIPTION
0	A	Model XYZ 18 wheeler dump truck
1	B1	Base Structure
2	C1	Chassis
2	C2	Suspension
3	D1	Blade springs
3	D2	McPhersons
1	B2	Cab

Figure 3 Example of product structure printout

The ITEM_PRICE table administers the price, lead time, and the cost escalating factor of each item. The assumption is made (in accordance with Just In Time philosophy) that any number of suppliers of any item can exist with different prices, but that each item is supplied by only one supplier at only one price at any one time.

ITEM_PRICE

ITEM#	SUPPLIER	PRICE	LEAD_TIME	ACTIVE	CEF
CBA	S432	78640.00	127	N	1.0550
CBA	S221	72986.50	142	Y	1.0650
CBA	S303	84080.00	113	N	1.0475
XYZ	S008	21.99	12	N	1.0450
XYZ	S105	19.79	10	Y	1.0525

The SUPPLIER column of the ITEM_PRICE table is the supplier of the item; PRICE is the current price of the item; LEAD_TIME is the lead time of the item; ACTIVE indicates which supplier is selected ("Y" is selected, "N" is not selected); and CEF is the cost escalating factor (the factor by which the price of the item is expected to increase per year). Each item must be selected once and once only. The lead time is in calendar days and is the amount of time needed to get the item to the end user, regardless of the path that it follows. An item may be received by the end user directly from a supplier.

The COMMODITY table defines classes of items, or categories, and is not item specific. Each item has a commodity code and is defined in the ITEM_IDENTIFICATION table. Several different items can belong to the same commodity code, but each item can only have one commodity code. The example in the table below is self-explanatory. The descriptions are only indented to illustrate how the commodity code is constructed.

COMMODITY

CODE	DESCRIPTION
140000	Powerpack
141000	Cast iron
142000	Aluminum
142100	Diesel
142160	V8, 32 Valves
142162	200 - 250 BHp

The power of the commodity code can be illustrated in the following example: Suppose there are 50 different engines in the database and the most suitable one is to be chosen. It is known from the needs analysis and the maintenance concept that the power range should be 200 - 250 horsepower and that aluminum engine blocks are not feasible. The query on the commodity code

can now be constructed to include only the feasible engines, and a simulation can be run to evaluate all these alternatives without human interference. For each alternative, the life-cycle costs and the logistic requirements are determined and the preferred alternative specified.

3.4 RELIABILITY ASSESSMENT

An initial system level reliability is assigned for the proposed system based upon knowledge of comparable systems (baseline comparison systems) and a thorough understanding of the customer need and of available technologies. This initial system level reliability is evaluated during subsequent stages of design in terms of technical and cost effectiveness measures. Depending on the specific situation, a whole range of system reliabilities are evaluated in order to determine the best alternative that will fulfill the need at minimum cost. This analysis process is described in the rest of this chapter.

System reliability must be broken down into component reliabilities. This is done by means of reliability allocation (as described by Blanchard and Fabrycky, 1990, chapter 13). The allocation process is a top down approach that occurs during the early design phases, typically during the preliminary design phase. The allocated values serve as a baseline against which the actual reliabilities can be compared.

SYSTEM_RELIABILITY

ITEM#	REL_ALLOCATE	REL_ACTUAL
A	0.960	0.9524
B1	0.989	0.9555
ABC	0.870	0.8450

Actual reliabilities become known with more certainty through subsequent phases by means of test and evaluation. The "actual" reliabilities are then calculated bottoms up to determine whether the system complies with user requirements or whether it should be (partially) redesigned. The allocated and measured reliabilities are captured in the SYSTEM_RELIABILITY table. To determine the reliability of a component, it is necessary to know what type of distribution represents the failure characteristics most accurately. The types are stipulated in the DISTRIBUTION_TYPE table.

DISTRIBUTION_TYPE

ITEM#	DESCRIPTION
ABC	EXPONENTIAL
DD1	LOGNORMAL
CDFB	WEIBULL
794D	CENSORED DATA

Items are subject to different types of failures. A separate table defines the different failure modes. The failure modes are constructed in the same way as the commodity codes in that the failure modes are generic and therefore not dependent on an item. Each item can have several failure modes. The FAILURE_MODES table maintains the different failure mode definitions.

FAILURE_MODES

MODE	DESCRIPTION
1015	SHEER
3550	OVERHEAT
4400	WEAR OUT
1650	LEAK
....	...
7777	[Bottoms-up summation]

Some failures can be grouped together, or all failures of an item can be treated alike, depending on what is required. However, the more elaborate the data requirements, the better the feedback to redesign. Also, the physical size of the failure mode identifier (MODE in the FAILURE_MODE table) does not have to be four characters; it can be any size.

The failure modes are constructed in such a way that each failure mode has a unique task type. A certain failure mode (or one or more characters within the failure mode) might indicate that the specific failure mode will be repaired by adjustment without replacement; again, regardless of the item number. The failure mode can therefore also be constructed such that a failure mode starting with any digit other than 9 necessarily implies repair by replacement. A 9... failure mode, therefore, does not demand a replacement. The failure modes are used extensively in the reliability model to determine the failure rate of an item.

A distinction is made between the total failure rate of an item and its inherent failure rate: An inherent failure rate is defined as a failure rate unique to an item where the item is treated as a complete entity in itself regarding that failure. For the purposes of this research, inherent failure rate does not necessarily mean "true" failure rate. If the failure demands a replacement, the entire item will be replaced, regardless of the level of complexity. For example, an engine might seize. The entire engine needs to be replaced instead of just the pistons, bearings, or the engine block. Therefore, inventory has to be carried for items other than just the lowest level components. An inherent failure rate is, therefore, a characteristic inherent to an item, while the total failure rate is the total failure rate of an item, calculated as the summation of the following:

1. The item's inherent failure rates.
2. The failure rates of the item's lower level components.

An item's total failure rate due to the summation of the failure rates of its lower level components is distinguished from its inherent failure rates by the way that the failure modes are structured. Failure mode 7777 typically denotes the summation of failure rates of lower level components, while the other failure modes can be failure specific.

Failure data become available during test and evaluation procedures. These data are then captured in the BASE_DATA table.

BASE_DATA

ITEM#	FAIL_MODE	FAIL_TIME	TST_TIME	DATE	ACTIVE
ABC	1015	1274	1274	2/04/91	Y
ABC	1015	1406	1406	2/04/91	Y
...	....	....	....	....	...
ABC	3550	1051	1051	6/07/90	N
ABC	4400	****	3207	7/08/89	Y

The column FAIL_TIME is the length of time that the item lasted before it failed. The TST_TIME column is the total time that the item was tested. If the item did not fail during the test (test aborted before failure), then the total time that the item was tested is noted in the TST_TIME column and the FAIL_TIME is cleared and flagged. Different conditions (other than normal working conditions) can be facilitated by means of the failure mode. The DATE column is the date when the tests were accomplished. The user can now choose the data that he prefers by specifying certain dates that will exclude undesired failure data. The dates also provide visibility in the reliability growth of the item over time. The ACTIVE column is a means to select data with or without specifying certain dates.

The data in the BASE_DATA table together with the type of distribution used from the DISTRIBUTION_TYPE table determine the reliability and failure rate characteristics. Each distribution type has a separate table to maintain the relevant parameter values as calculated from the data in the BASE_DATA table. The actual reliability values can be calculated directly from the BASE_ DATA table, but due to the frequent use of this type of information, separate tables are constructed for each of the distributions. This means that whenever the data in the BASE_DATA table change or when the selection criteria change, the relevant distribution tables must be updated.

Since the system is a repairable system, the reliability of the system degrades as the system is being used, but increases as the system is repaired. Because of this fluctuation in the reliability, a time period must be negotiated with the end user for whom the system is being designed to determine a desired reliability. This only holds if the system is employed "indefinitely" (i.e., used as long as it is economically feasible). Examples of such systems include ground excavation and transportation. If the system is used to fulfill multiple, discrete missions during which no repair is possible, the anticipated mission durations must be specified. The CUSTOMER_WORKING_WEEKS and the CUSTOMER_WORKING_HOURS tables will then be multiples of these durations. Examples of such systems include spacecraft and certain remote controlled equipment.

RELIABILITY_TIME

ITEM#	TIME
CBA	300

The RELIABILITY_TIME table specifies (in the TIME column) the time duration in hours for which the system is designed. All the lower level components are treated according to this time and the MISSION_FRACTION table.

The reliability of each item is calculated based on the time in the RELIABILITY_TIME table and on the parameters that define the specific distribution that represents the failure characteristics. The procedure to estimate these parameters is discussed in the rest of this section. The reliability values of each item and each relevant failure mode are defined in the ITEM_RELIABILITY table.

ITEM_RELIABILITY

ITEM#	FAIL_MODE	RELIABILITY
ABC	1015	0.9950
ABC	3550	0.9320
ABC	7777	0.9250
XYZ	1659	0.9650
XYZ	3550	0.9875

A distinction is made between failures that occur independent of the time that the item is utilized, and failures that are dependent on the time that they are utilized. Time-independent failure rates are maintained in the CONSTANT_FAILURES table. The column FAIL_RATE is the failure rate of the item for a specific failure mode. The units are failures per operating hour.

CONSTANT_FAILURES

ITEM#	FAIL_MODE	FAIL_RATE
ABC	1015	0.0050
ABC	3550	0.0704
ABC	7777	0.0780
XYZ	1659	0.0356

The total number of failures that are anticipated to occur during each year (as a function of the total theoretical number of units deployed per location) are maintained in the TOTAL_FAILURES table. Time-independent failures are calculated as the failure rate of the item in the CONSTANT_FAILURES table multiplied by the total time that the end-user expects to work. The latter is the product of the times for each year in the CUSTOMER_WORKING_HOURS and the CUSTOMER_WORKING_WEEKS tables. For time-dependent failures, the time that the system is operational per year is used as the time constant in calculating the failure rate. This is explained in subsequent sections. The columns YR_0, YR_1, ..., YR_n indicate the total failure rates in the first, second, and so on, until the n^{th} year.

TOTAL_FAILURES

ITEM#	FAIL_MODE	LOCATN	YR_0	YR_1	...	YR_n
ABC	1015	L03	12	15	...	31
CFG	3569	L21	45	57	...	76

These failures act as the primary demand for spare and repair parts. The TOTAL_FAILURES table is, therefore, a very important table as far as inventory control is concerned. The failure modes are all inherent failure modes that demand a replacement upon failure. The FAIL_MODE column should therefore include all failure modes except 7777 and those starting with a 9... . Inventory is, therefore, kept for all the items listed in the TOTAL_FAILURES table, although not in those quantities.

The primary sources of information for the remainder of Section 3.4 are the following: Dhillon (1983), Dhillon and Singh (1981), Lewis (1987), and O'Connor (1985).

3.4.1 Exponential Distribution

The reliability and the failure rates for items that are exponentially distributed are calculated and administered in the EXPONENTIAL table. The TOTAL_TIME column indicates the total time that the number of components under consideration were tested and is, therefore, a summation of the TST_TIME in the BASE_DATA table for the items selected by DATE and/or ACTIVE. The NO_OF_FAILS is the total number of times that the component under consideration failed during the total test period. The failure rate Φ is then calculated as follows:

$$\Phi = \frac{\text{number of failures}}{\text{total operating hours}}$$

EXPONENTIAL

ITEM#	FAIL_MODE	TOTAL_TIME	NO_OF_FAILS
ABC	1015	12351	17
ABC	3550	10867	4
...	....	...	...
765B	1960	973	3

The reliability is calculated from the relationship, and the CONSTANT_FAILURES, TOTAL_FAILURES, and ITEM_RELIABILITY tables are updated accordingly:

$$R(t) = e^{-\Phi t}$$

3.4.2 Normal Distribution

The lognormal and normal distributions are both maintained in the NORMAL table since they have the same parameters. The item, the failure mode, and the type of distribution (normal or lognormal) determine what the values of the mean and standard deviation are (columns MEAN and STD_DEV in the NORMAL table). This is done to allow for the probability that an item might be represented by different distributions under different failure modes. However, this is a rare case scenario. The SERV_LEVL column indicates the service level of an item. The service level is the probability that an item is available in stock upon request (do not run out of spares). The service level can either be assigned or it can be calculated, depending on whether the stockout costs are known. This issue is treated under the modeling of inventory in Section 3.6.

NORMAL

ITEM#	FAIL_MODE	DISTR	MEAN	STD_DEV	SERV_LEVL
ABC	1015	N	1200	200	0.95
ABC	3550	N	4800	400	0.95
ABC	4400	N	3600	1400	0.95
X8Z	2024	L	975	120	0.97

The mean and standard deviation for the normal distribution are calculated as follows:

$$P_r\left(X - t_{(n-1),1-\alpha/2} \cdot S/\sqrt{n} < \mu < X + t_{(n-1),1-\alpha/2} \cdot S/\sqrt{n}\right) = 1 - \alpha$$

$$P_r\left[\frac{(n-1).S^2}{(Chi^2)_{(n-1),1-\alpha/2}} < \sigma^2 < \frac{(n-1).S^2}{(Chi^2)_{(n-1),\alpha/2}}\right] = 1 - \alpha$$

$$S^2 = \frac{n.\Sigma(x^2) - (\Sigma x)^2}{n(n-1)}$$

and α is the fraction allowed outside the confidence interval. The upper limits on both the S and the t-distributions are used to determine the mean and the standard deviation. The reliability and failure rate from the normal distribution are calculated from the following relationships and are used to update the ITEM_RELIABILITY table:

$$R(t) = 1 - F(t)$$

$$= 1 - \phi\left[\frac{(t - \mu)}{\sigma}\right]$$

$$\Phi(t) = \frac{\frac{1}{[2\pi]^{\frac{1}{2}}.\sigma} . \exp\left[\frac{(t - \mu)^2}{\sigma^2}\right]}{1 - \phi\left[\frac{(t - \mu)}{\sigma}\right]}$$

3.4.3 Lognormal Distribution

For the lognormal distribution the reliability is calculated from:

$$R(t) = 1 - F(t)$$

$$F(t) = \phi\left[\frac{1}{s} \ln\left(\frac{t}{t_0}\right)\right]$$

and the MTBF, μ, and the variance, σ^2, are given by:

$$MTBF = \mu = t_0 \exp\left(\frac{s^2}{2}\right)$$

$$\sigma^2 = t_0^2 \exp(s^2) * [\exp(s^2) - 1]$$

t_o is calculated from the relationship (the geometric mean):

$$t_0 = (t^- * t^+)^{\frac{1}{2}}$$

where the values t^- and t^+ are chosen as the lower and upper limits of the data between which a large percentage of all data points fall. Since the user has the ability to select the values to be included from the BASE_DATA table by means of the DATE and ACTIVITY columns, the model assumes that t^- is the lowest value and t^+ is the highest value and that 95% of all data points are included in this range. However, the user is prompted to justify these assumptions or alternatively to adjust them. The value of n then satisfies the following relationships:

$$t^- = \frac{t_0}{n}$$

$$t^+ = n * t_0$$

From the probability anticipated that all the data points are included in the interval t^- and t^+ the value of Z can be obtained from normal distribution tables. The value of s is then obtained from:

$$s = \left(\frac{1}{Z}\right) * \ln(n)$$

3.4.4 Weibull Distribution

Only the two-parameter Weibull distribution is used since the assumption is made that there exists no threshold time within which no failures occur. The parameters of concern are Θ and m. The WEIBULL table maintains the values of these parameters.

WEIBULL

ITEM#	m	Θ
XDF	1.9	2.6

These parameters are calculated using a plotting approach. To update the ITEM_RELIABILITY table, the failure rate and the reliability of an item whose failures follow a Weibull distribution are calculated as follows:

$$\Phi(t) = \frac{m}{\Theta}\left[\frac{t}{\Theta}\right]^{(m-1)}$$

$$R(t) = \exp\left[-\left(\frac{t}{\Theta}\right)^{m}\right]$$

3.4.5 Censored Data

For reliability assessment on cencored data, the exponential distribution is used and the following relationship holds for the failure rate:

$$\Phi = \frac{T}{n}$$

where T = total operational time of all test units, and

n = total number of failures.

The CENSORED_DATA table is used in conjunction with the BASE_DATA table to determine the actual failure rates. The time to failure for each item is still maintained in the BASE_DATA table while the other information is stored in the CENSORED_DATA table.

CENSORED_DATA

ITEM#	TYPE	REPLACE	TERM_TIME	NO_FAILS
DEF	1	R	1500	***
HH1	2	R	****	35
234M	1	N	2250	***
C45P	2	N	****	17

The TYPE column is used to distinguish between the different types of testing: Type I censoring is when the tests are terminated after some time t^*, while Type II censoring is when the tests are terminated after a certain number of failures (n) have occurred. The column TERM_TIME is the time

(t^*) when the tests are terminated for Type I testing. Only Type I testing can have a termination time, whether the failed components are replaced or not. This column, therefore, is left blank in the case of Type II testing. The NO_FAILS column determines the number of failures after which the tests on a Type II testing should be terminated. Likewise, this field is left blank for Type I testing. Care should be taken in the selection of the correct data in the BASE_DATA table. Only the applicable test data should be selected by either the DATE or the ACTIVE column or by both. In the calculation of the failure rate, the value of T assumes the following values under the conditions stated:

Type I : Non-replacement

$$T = \sum_{i=1}^{n} t_i + (N-n)t^*$$

where t_i is the time at failure for component i. N units are tested and n failed. Therefore, N-n units operated the full time.

Type II : Non-replacement

$$T = \sum_{i=1}^{n} t_i + (N-n)t_n$$

The number of items that failed in areas other than those tested for (in the non-replacement case) are subtracted from the total number of failures.

Type I : Replacement gives

$$T = Nt^{*}$$

Type II : Replacement

$$T = Nt_{n}$$

3.5 MAINTENANCE ANALYSIS

The level at which an item with a specific failure rate can be repaired is indicated in the table REPAIR_LEVEL. Any number of levels can exist, as long as the level has been defined. No distinction is made as to which specific repair facilities are of concern; only the level is of concern.

REPAIR_LEVEL

ITEM#	FAIL_MODE	LEVEL
SDF	5604	O
KLM	1015	D
OPQ	2250	I

The different levels of repair and the actual repair facilities can now be constructed in similar fashion as the product structure, as is illustrated in Figure 4. The blocks L11 to L23 in Figure 4 indicate the different locations where the end items will be deployed. Each deployment location has its own organizational level of repair, denoted by O11 to O23. Intermediate levels of repair (I01 and I02) are provided for groups of organizational repair facilities. A depot repair facility (D01) is similarly

provided for intermediate repair facilities.

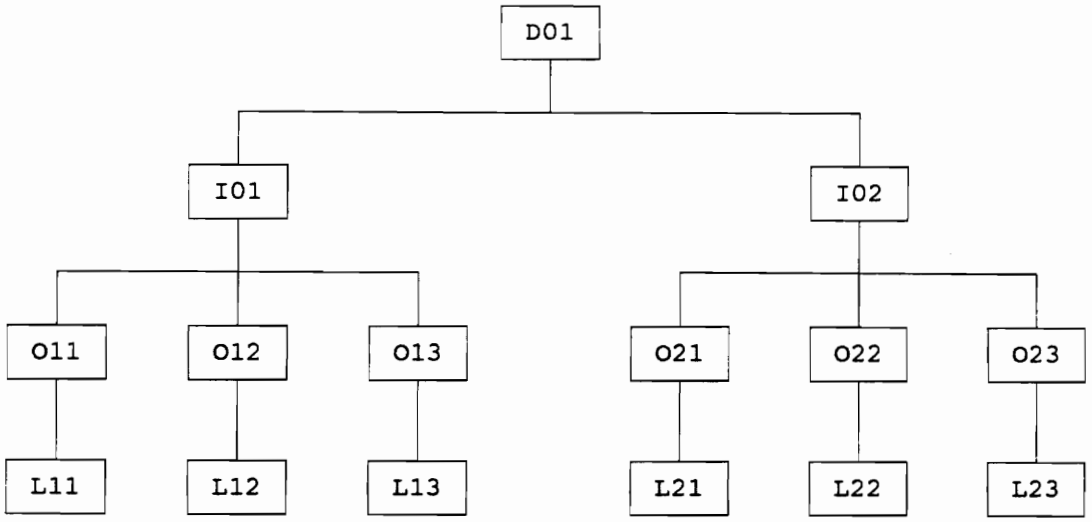

Figure 4 An example of different levels of repair

Figure 4 is only a schematic representation. The user can define a virtually unlimited number of levels (instead of the three given). In addition, any combination of any number of levels of the same type can have the same parent, as long as every component has only one parent item. A BILL_OF_LOCATIONS table defines the structure of the levels of repair. This table is similar to the PRODUCT_STRUCTURE table, except that the quantity of identical items per parent item is one in all cases. The DISTANCE column is the distance from the manufacturing facililty to the UNIT.

BILL_OF_LOCATIONS

UNIT	PARENT	DISTANCE
L11	O11	1528
L12	O12	1556
L13	O13	1123
O11	I01	1528
O13	I01	1123
...	...	....
I01	D01	658
I02	D01	849

For the remainder of Section 3.5, the primary sources of information are Blanchard (1991), Blanchard and Fabrycky (1990), and Fabrycky and Blanchard (1991).

The maintenance analysis results are expressed in terms of costs as the end user would experience it. These costs are divided into two categories, recurring and nonrecurring costs. Nonrecurring cost refers to "one-time" costs, while recurring cost is a function of time and the number of units utilized. The recurring cost is calculated every year.

3.5.1 Nonrecurring Cost

The nonrecurring cost is calculated from the following relationship:

$$COST_{NONRECUR} = C_{Facil} + C_{Tools} + C_{Doc} + C_{Train} + C_{Dispos}$$

where C_{Facil} = facility cost

C_{Tools} = test and support (tool) cost

C_{Doc} = documentation cost

C_{Train} = training equipment cost

C_{Dispos} = cost of disposal

The total nonrecurring cost is recorded in the NONRECUR_COST table. These costs are incurred to have the necessary repair capability at each level where each item is to be repaired. An additional column in the NONRECUR_COST table (not shown) can be used to indicate the time when the relevant costs are involved. It is therefore possible that these costs can be incurred more than once, e.g. a facility can be expanded several years after a system has been used the first time,

or new repair documentation may be required because of end items that were upgraded to a new configuration.

NONRECUR_COST

ITEM#	LEVEL	FACILT	TOOLS	DOCUMNT	TRAINNG	DISPOS
ABC	I03	120000	35000	16000	12000	25000
ABC	D	45000	35000	16000	8000	15000

The LEVEL column in the NONRECUR_COST table is the maintenance level of concern. The maintenance levels are operational (O), intermediate (I), and depot(D). These distinctions are made because the logistic requirements usually differ from level to level and even within levels. Therefore, the different levels can be further subdivided. Level O21 typically indicates a specific (probably geographically bound) organizational maintenance and repair facility. In such a way different levels can be evaluated, as well as different repair facilities within levels.

The type of maintenance level, and the items that will utilize these facilities (typically end items), are maintained in the MAINTENANCE_LEVELS table. The item numbers in this case typically are end items (i.e., the final product without support). The LEVEL column indicates the specific level where the maintenance is accomplished. The COST column indicates the cost associated with the specific level of maintenance for the item under consideration. The COST column shows the summation of all the nonrecurring costs for the item for that level of repair. In the ACTIVE column, each level of repair can be activated or deactivated for consideration.

MAINTENANCE_LEVELS

ITEM#	LEVEL	COST	ACTIVE
ABC	D	1265338	Y
ABC	I01	376751	Y
ABC	I03	567089	N
ABC	O21	236055	Y

The GENERAL_FACILITY table indicates the type of facilities that are available, or can be made available, with the associated costs. These facilities are not related to item numbers in this table This table houses a list of all relevant facilities. Alternative facilities can be selected in the FACILITIES table, which is item related. The FACIL# column in the GENERAL_FACILITY table is the unique identifier of each facility. The FACIL# is exactly the same as the ITEM# and, therefore, must also be identified in the ITEM_IDENTIFICATION table. The reason it is not called the ITEM# is that in the FACILITIES table the facilities are logically associated with items. The facilities that are needed to maintain and repair items are linked to those items. The reason the FACIL# and the ITEM# must be of the same type is that item descriptions are only maintained in the ITEM_IDENTIFICATION table; but more importantly, product structures must be constructed from the same source. Each facility is also associated with a commodity code, a requirement from the ITEM_IDENTIFICATION table. This association allows the user to make a printout of all the facilities under consideration, or to treat those as a separate group of facilities.

GENERAL_FACILITIES

FACIL#	LEVEL	** DESCRIPTION **	COST	COMMON
F541	O12	EMPTY WORKSHOP (SCRATCH)	75000	N
F446	I3	EXIST WORKSHOP (EXPAND)	52000	Y
F340	D	EXIST WORKSHOP (EXPAND)	15000	Y
D870	I4	UL.SON CRACK TESTING	23000	N
W368	D	DEGREASE WASH BATH	17000	N
G179	O7	CALIBRATION SHOP	85000	Y

The LEVEL column indicates the level at which the facilities are required. The DESCRIPTION column is not part of the GENERAL_FACILITIES table and is merely here for illustration. The item description is maintained in the ITEM_IDENTIFICATION table. The COST column is the cost associated with each particular facility. The COMMON column indicates if a facility is common to all the alternatives being evaluated. If it is, (i.e., COMMON = Y) the facility is considered available and the price is not of concern in the evaluation of alternatives since all common alternatives use that facility. The FACILITIES table links the hardware items with the facilities they need.

FACILITIES

ITEM#	FAIL_MODE	FACIL#	NO_REPAIRS	QUANTITY	ACTIVE
ABC	3065	F741	1	0.33	N
ABC	3065	F741	2	0.42	Y
...	....	....	....	....	...
ABC	3065	F741	25	3.65	N
ABC	4048	F741	1	0.15	N

The NO_REPAIRS and the QUANTITY columns in the FACILITIES table indicate the quantities of the specific repair facilities that are needed (as a function of the unit-values specified in the GENERAL_FACILITIES table) to repair the specific number of units due to the failure mode specified. The number of repair actions is expressed in weekly, or monthly, units. The number of failures that occur for a specific configuration due to a specific failure mode, as indicated in the TOTAL_FAILURES table, is converted to a weekly, or monthly, rate. All the facilities needed to repair the system are flagged in the ACTIVE column, depending on the weekly or monthly failure rate. The demand for each facility over all items with all failures is added together to determine the total requirements for facilities. This facility-allocation process is repeated for each deployment location and is calculated as a function of time (requirements for each year). The UNITS_DEPLOYED table,

the REPAIR_LEVEL table, the BILL_OF_LOCATIONS table, and the PERCENTAGE_DISTRIBUTION table (to be discussed later) are all used to allocate the facility requirements to each repair facility at each level of repair. This allocation process is discussed in chapter 4. The specific level of repair and the demand per year are not shown in the FACILITIES table.

The TOOLS, DOCUMNT, and TRAINNG columns in the FIXED_COST table have basically the same format as the FACILT column. The TOOLS column is the accumulation of costs of all test and support equipment. The GENERAL_TOOLS table is a listing of all tools that are available and is equivalent to the GENERAL_FACILITIES table. The same types of tables exist for the documentation and training as for tools and facilities. In all cases, the description is not part of the tables themselves. It is part of the ITEM_IDENTIFICATION table and is shown for clarity.

GENERAL_TOOLS

TOOL#	LEVEL	** DESCRIPTION **	COST	COMMON
T354	O12	HYDRAULIC TEST BENCH	128500	N
T337	I3	SPECIAL HOIST	52000	Y
G650	D	TRANSPORTATION TRUCK	87250	N

TOOLS

ITEM#	FAIL_MODE	TOOL#	NO_REPAIRS	QUANTITY	ACTIVE
ABC	3065	T337	1	1.25	N
ABC	3065	T337	2	2.50	Y
...	....	....	....	....	...
ABC	3065	T337	25	30.00	N
ABC	4048	T337	1	0.75	N

The TOOLS table (containing the requirements for test and support equipment) is constructed similar to the FACILITIES table. The test and support equipment is allocated to the different repair facilities in the same way as the facilities. As is the case with the FACILITIES, the test and support equipment requirements are given per year for each repair facility at each level of repair. This detail is not shown in the TOOLS table. The structure of the TOOLS table enables the user to determine the tool requirements for a specific failure mode at each repair facility, or for a given item and a failure mode, or for a failure mode (with or without the item specified) that involves some form of failure. For example, the user can now query the system for all the tools required to repair a cylinder head of an engine if the valves have burned.

The GENERAL_DOCUMENTATION and the DOCUMENTATION tables, as well as the GENERAL_TRAINING and TRAINING tables, are constructed in the same way as the tables for the test and support equipment and facility requirements.

GENERAL_DOCUMENTATION

DOC#	LEVEL	** DESCRIPTION **	COST	COMMON
D123	D	ILLUSTRATED PARTS CATALOG	357750	N
D668	I2	WORKSHOP REPAIR MANUAL	256800	N
D993	O23	PREVENT LUBR INSTRUCTIONS	65350	N

DOCUMENTATION

ITEM#	FAIL_MODE	DOC#	NO_REPAIRS	QUANTITY	ACTIVE
ABC	3065	D123	1	0.35	N
ABC	3065	D123	2	0.70	Y
...	....	....	....	....	...
ABC	3065	D123	25	15.50	N
ABC	3065	D987	1	0.75	N

GENERAL_TRAINING

TRAIN#	LEVEL	** DESCRIPTION **	COST	COMMON
TR03	D	FLIGHT SIMULATOR	2456750	N
TR68	I5	TEST BENCH (ELECTRIC)	45600	N
TRG3	O23	WIRING SIMULATION BENCH	35250	N

TRAINING

ITEM#	FAIL_MODE	TRAIN#	NO_REPAIRS	QUANTITY	ACTIVE
ABC	3065	TR68	1	0.15	N
ABC	3065	TR68	2	0.25	Y
...	....	....	....	....	...
ABC	3065	TR68	25	3.10	N
ABC	3065	TR03	1	0.75	N

3.5.2 Recurring Cost

The recurring cost (as a function of time and the number of units deployed per year) is determined from the following relationship:

$$COST_{RECUR} = C_{Unit} + C_{Oper} + C_{Inv} + C_{Labr} + C_{Trans} + C_{Train} + C_{Pack}$$

where C_{Unit} = Unit cost

C_{Oper} = Cost to operate the equipment

C_{Inv} = Inventory cost

C_{Labr} = Labor cost of corrective and preventive maintenance

C_{Trans} = Transportation cost

C_{Train} = Training cost

C_{Pack} = Packaging, preservation, and handling cost

Each of these costs has a table to maintain the different annual costs involved for the next n years: The unit cost is the cost of one unit of the end item. This includes development and production costs, but excludes support cost. For each year, this cost is the unit cost in the ITEM_PRICE table, multiplied by the product of the cost escalating factor (CEF) in the ITEM_PRICE table and the year that is of concern. These costs are maintained in the ACQUISITION table.

ACQUISITION

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	313757.00	...	7453698.00

The cost to operate the system is calculated as the sum of the personnel cost and the consumable cost, for example, gas. The OPERATE_PERSONNEL and OPERATE_CONSUMABLES tables indicate these respective costs. The total operations cost then is:

$$C_{Oper} = C_{Pers} + C_{Cons}$$

where C_{Pers} = personnel cost to operate one unit for the entire mission duration

C_{Cons} = cost of consumables (gas, etc) to operate one unit for the entire mission

OPERATE_PERSONNEL

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	1265045	...	7689345

OPERATE_CONSUMABLES

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	856500	...	2650000

The personnel cost is directly proportional to the mission duration of the system, i.e., the time that the system is operational in a year. The GENERAL_PERSONNEL table gives the personnel costs for the different types of skill levels. The hourly labor cost in the column HOUR_COST of the appropriate skill level is multiplied by the mission duration to give the total personnel cost to operate one unit of the system.

GENERAL_PERSONNEL

TYPE	SKILL	HOUR_COST
A	OPERATOR	13.50
B	ARTISAN (ELECTRIC)	17.75
C	HYDRAULIC TECHNICIAN	21.50
D	ARTISAN (MECHANICAL)	16.40

The ITEM_PERSONNEL table maintains the operating personnel requirements for each item. The PERS_TYPE column is the type (skill) of personnel required, as defined in the GENERAL_PERSONNEL table. The QUANTITY column shows the quantity of the specific type required to operate one unit of the end-item. This quantity is multiplied by the total theoretical number of units deployed each year to determine the total operating personnel requirements per year. The FRACTION column indicates the fraction of the total mission duration that the personnel are used.

ITEM_PERSONNEL

ITEM#	PERS_TYPE	QUANTITY	FRACTION
ABC	A	1	1
ABC	W	4	0.25

The CONSUMABLES table gives the consumable cost to operate the system for one hour. The total cost is the number of units employed, multiplied by the consumption per hour, multiplied by the hours given for the mission duration. The CONSUM# is the consumption item number and is identical to the item number in the ITEM_IDENTIFICATION table. (It is only named differently to avoid confusion.) The CONS_FACTOR column is the factor that the unit price in the ITEM_PRICE table is multiplied by to give the cost of an average hourly consumption. ACTIVE again determines which consumable is active for each item. Each item can have, at most, one consuming item, but is not required to have one.

CONSUMABLES

ITEM#	CONSUM#	CONS_FACTOR	ACTIVE
ABC	CC343	2.4	Y
DD1	CS081	0.25	Y

The corrective and preventive maintenance and labor cost for the next n years are maintained in the CORREC_MAINT_LABOR and PREVENT_MAINT_LABOR tables. The values in the CORREC_MAINT_LABOR table is calculated from the data in the CORRECT_PERSONNEL and GENERAL_PERSONNEL tables. For each failure mode the personnel requirements are determined from the hourly cost of the specific personnel type, or skill level, in the HOUR_COST column of the GENERAL_PERSONNEL table. This value is multiplied by the mean corrective maintenance time

for that failure (Mct in the CORRECT_PERSONNEL table) and by the frequency of occurence (i.e., the expected number of failures for the failure mode under consideration and in the relevant year in the TOTAL_FAILURES table). A summation is then made over all failure modes to determine the total corrective maintenance labor cost for each item in each year. These costs are not calculated bottoms up in the product structure since the time to repair a higher level item is independent of its lower level components, as is the failure rates for inherent failures. $Cost_{correct\ labor}$ is then:

$$Cost_{correct\ labor} = \Sigma \text{ (hourly cost) * (maintenance duration) * (maintenance frequency)}$$

The summation in the above equation is for all the failure rates and represents the cost of corrective maintenance per item per year. For each year, these costs can be added together to determine the total cost of corrective maintenance for that year.

CORREC_MAINT_LABOR

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	60650	...	86890

CORRECT_PERSONNEL

ITEM#	FAIL_MODE	PERS_TYPE	Mct	L&A_DELAY
ABC	1015	A	15	1.5

The preventive maintenance labor cost is calculated as follows: the personnel type in the PREVENT_PERSONNEL table determines the hourly cost for the specific skill level from the

GENERAL_PERSONNEL table. This amount is then multiplied by the frequency for preventive maintenance in the PMAINT_FREQ column in the PREVENT_PERSONNEL table and also by the total time that the system is working per year, as in the CUSTOMER_WORKING_WEEKS and CUSTOMER_WORKING_HOURS tables. $Cost_{prevent\ labor}$ is then:

$$Cost_{prevent\ labor} = \Sigma \text{ (hourly cost) * (maintenance duration) * (maintenance frequency)}$$

The summation in the above equation is for all the failure rates and represents the cost of preventive maintenance per item per year. For each year these costs can be added together to determine the total cost of preventive maintenance for that year.

PREVENT_MAINT_LABOR

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	15450	...	45750

PREVENT_PERSONNEL

ITEM#	TYPE	Mpt	PMAINT_FREQ	L&A_DELAY
ABC	G	3	0.000250	3

The transportation cost of an item is given as a function of the distance that the item is expected to travel (as indicated in the BILL_OF_LOCATIONS table), the total number of units to be replaced (from the TOTAL_FAILURES table), and the percentage distribution of items to the different levels (in the PERCENT_DISTRIBUTION table), as a result of the maintenance analysis.

PERCENT_DISTRIBUTION

ITEM#	LEVEL	ORGAN	INTERM	DEPOT
BNM	O	60	25	15
SD4	I	0	60	40
T8U	D	0	0	100

The columns ORGAN, INTERM, and DEPOT indicate the percentages of spares of an item that should be kept at the organizational, intermediate, and depot levels. If an item can only be replaced at the intermediate and depot levels, obviously the organizational level should carry no stock. The same holds for depot repair. The LEVEL column indicates the level at which the item is designated for repair. The data in this table will be assigned and not calculated.

COST_PER_MILE

ITEM#	COST
XDF	1.85

The COST_PER_MILE table indicates the typical cost per mile to transport the item. The COST column indicates the cost per mile. The transportation cost per item is calculated as:

$$Cost_{transport} = \Sigma \text{ (\# of units) * (distance) * (cost per mile) * (fract. spares)}$$

where

\# of units = number of units to be transported (TOTAL_FAILURES)

distance = the distance to be traveled (BILL_OF_LOCATIONS)

cost per mile = cost of transportation per mile (COST_PER_MILE)

fract. spares = the fraction of all the units that go to the specific level under consideration (PERCENT_DISTRIBUTION)

The summation in the cost calculation is over all the different levels of repair, with the accompanying fractions of inventory at each level of repair.

The training cost is given as a total cost per item per year. This value is assigned and maintained in the TRAINING_COST table. The item number is typically the end item. However, any item that requires specific training can be specified. A summation gives the total cost of training for each end item.

TRAINING_COST

ITEM#	CUST#	YR_0	...	YR_n
CBA	C342	75750	...	185000

The packaging cost is calculated as a function of the number of units that are held in inventory. The unit packaging cost and the type of packaging required are given in the UNIT_PACKAGE table. The total package cost per item per year is given in the PACKAGING table.

UNIT_PACKAGE

ITEM#	PACK_TYPE	COST
TRG	P34Z	64.80

PACKAGING

ITEM#	CUST#	YR_0	...	YR_n
TRG	C342	4536	...	11458

The shortage cost is not considered since a functional approach is followed. The total cost is calculated to perform an activity with a certain capacity. The end user, therefore, buys this capacity. If the system is an item short, the total cost is that of not performing the task with the relevant capacity. The number of spare parts to deploy already considers the shortage cost of an item. The inventory costs are dealt with in the next section.

3.6 INVENTORY ANALYSIS

The primary sources of information in Section 3.6 are: Fogarty and Hoffmann (1983), Naddor (1982), Reinfield (1987), Tersine (1988), and Thomas (1980).

Regarding the management of spare and repair part inventory at the end user, the following are the four most important parameters and must be determined for each item: 1) Order quantity (Q); 2) Order interval (T); 3) Reorder point (B); and 4) Safety Stock (S).

The order interval and the reorder point are not always both required. For example, in the fixed order interval the orders are launched regardless of the size of the current inventory, given that the need exists. Separate tables exist for these three parameters for each item for the following n years. In all cases, the column LEVEL indicates the level at which repair takes place. The order quantity is the number of items that are ordered at the same time and it is maintained in the

ORDER_QUANTITY table. The order interval for each item is maintained in the ORDER_INTERVAL table, and the reorder point in the REORDER_POINT table.

ORDER_QUANTITY

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	236	...	173

The order interval is the interval at which orders are placed. It can be presented to the user in terms of an annual, a monthly, weekly, or daily interval. The original form is in working days but can be converted into other time periods by the appropriate factors.

ORDER_INTERVAL

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	5.9	...	4.3

The reorder point is the number of items in inventory that triggers an order for new stock and is given in units. Whenever the units provide any problem (some material is acquired by length, others by units, some by volume, etc.), a new field, typically a UNIT_OF_MEASURE column, can be added to indicate the unit measure under consideration.

REORDER_POINT

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	200	...	200

Also of concern is the safety stock that should be carried at each location for each item in each year. This data is maintained in the SAFETY_STOCK table.

SAFETY_STOCK

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	0	...	0

Once these four parameters are known for each situation, the total inventory costs for each item at each location can be calculated. This is maintained in the TOTAL_INVENTORY_COST table.

TOTAL_INVENTORY_COST

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	1002121	...	1002078

The order quantity, order interval, reorder point, and safety stock calculations are all dependent on the type of inventory model used and the different costs and demand rates that are involved. The unit price of an item is maintained in the ITEM_PRICE table. The exact price in the year of concern may vary, as may the cost escalating factor, also in the ITEM_PRICE table. The other costs involved are the order cost (in the ORDER_COST table), the holding cost (the fraction of the item

price devoted to holding is maintained in the HOLD_FRACTION table), and the shortage cost (in the SHORTAGE_COST table). These costs and factors are base data and are also dependent on the location of concern.

ORDER_COST

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	25.00	...	18.00

HOLD_FRACTION

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	0.15	...	0.20

SHORTAGE_COST

ITEM#	CUST#	LEVEL	YR_0	...	YR_n
GTX	C342	I21	2450.00	...	2860.00

The shortage cost of an item is the cost of being short an item. The shortage cost is given per unit per year. The shortage cost is usually difficult to determine, especially if the system can still operate without the item. If the shortage of the item causes an end unit to be down, the loss of potential income must be determined in cooperation with the end user. If the system is partially down, the lost cost must be calculated accordingly.

The annual demand rate (R) is a very important parameter in determining inventory levels and costs. The total number of failures that are expected to occur during each year is the demand rate. These values are kept in the TOTAL_FAILURES table. The theoretical number of units deployed (in the UNITS_DEPLOYED table) is used since the availability of the system is not known yet. Further, repair actions are considered to happen instantaneously for the purposes of calculating the demand rate. The fact that an item can have different reliability characteristics (and, therefore, different annual demand rates) for different locations, different applications, or different end users can be overcome by structuring the failure modes intelligently in the FAILURE_MODES table and having a good configuration management plan.

In order to determine the number of spares that should be carried at each level of repair, the following procedure is used: From the BILL_OF_LOCATIONS table and the TOTAL_FAILURES table all the inherent failures per item that result in replacements are added for all the organizational levels that belong to each intermediate level. The percentage of the inventory of that item that is kept at each level of repair can be obtained from the PERCENT_DISTRIBUTION table. The total failures are then divided accordingly. If the item with a certain failure mode is replaceble at the organizational level, then the number of spares to be deployed at each organizational site will be divided in the same proportion to the number of failures at each location. The PERCENT_DISTRIBUTION table determines the percentage of the total number of spares (as a result of the demand at each deployment location) that will be carried at the different levels of repair. The costs involved (order, shortage and holding costs) are initially weighted in the same fashion to establish the global requirements. After the number of spares at each location is calculated, the exact costs will be calculated accordingly. If the difference in cost is significant, the system must be modelled again with the actual costs (explained in chapter 4).

The inventory model used for each item is depicted in the INV_ITEM_MODEL table. An exhaustive list of models used is given in the INV_MODEL_LIST table. The TYPE column in the INV_ITEM_MODEL table refers to the TYPE column in the INV_MODEL_LIST table. Again, the LEVEL column in the INV_ITEM_MODEL table refers to the specific level or channel of maintenance.

INV_ITEM_MODEL

ITEM#	LEVEL	TYPE
GTX	I21	C

INV_MODEL_LIST

TYPE	DESCRIPTION
A	ECONOMIC ORDER QUANTITY : NO STOCKOUTS
B	ECONOMIC ORDER QUANTITY : STOCKOUTS ALLOWED
C	ECONOMIC MANUFACTURING QUANTITY
D	ECONOMIC ORDER INTERVAL
E	LOT-FOR-LOT
F	PERIODIC ORDER QUANTITY
G	PART-PERIOD ALGORITHM
H	PROB.: VARIABLE DEMAND & CONSTANT LT (K KNOWN)
I	PROB.: VARIABLE LT & CONSTANT DEMAND (K KNOWN)
J	PROB.: VARIABLE DEMAND & VARIABLE LT (K KNOWN)
K	PROB.: STOCKOUT COSTS UNKNOWN

The Economic Manufacturing Quantity (EMQ) is used as an example of how the inventory is analyzed. The EMQ is only of concern if the end user produces some of the items himself. The order quantity, order interval, reorder point, and total annual cost (TC) are calculated for the EMQ model as follows:

$$Q^* = \left[\frac{2CRp}{H(p - r)}\right]^{\frac{1}{2}}$$

$$T = \left[\left\{\frac{2C}{HR}\right\} \left\{\frac{p}{p - r}\right\} \right]^{\frac{1}{2}}$$

$$B = \left[\frac{RL}{N}\right]$$

$$TC = RP + \frac{RC}{Q^*} + \frac{HQ^* (p - r)}{2p}$$

N is typically 250 active workdays per year. However, the user needsto be prompted how many days per year he works. This number must be consistent with the total number of hours that he works per year, which is given in the CUSTOMER_WORKING_HOURS and CUSTOMER_WORKING_WEEKS tables. The lead time L is in calander days. The production rate is p, and r is the demand rate. The demand rate R is a function of the reliability of the item and is the amount in the TOTAL_FAILURES table. The production rate is given by the user in the EMQ_PRODUCTION table. Although the end user can manufacture an item at various locations at the same time, only the total production quantity is considered. Both p and r have the dimensions units-per-day. PROD_RATE and PROD_COST represent the production rate and the unit production cost, both in working days.

EMQ_PRODUCTION

ITEM#	PROD_RATE	PROD_COST
VWX	100	100

If, for simplicity, a demand rate of 10,000 units of item GTX is expected in every year of operation and it has a lead time of 5 days, then the order quantity, order interval, reorder point, and total cost of the item will be calculated as illustrated in the appropriate tables. The EMQ model is assumed. All the other inventory models, as illustrated in the INV_MODEL_LIST table, are described in Appendix A.

4.0 A HEURISTIC PROCEDURE FOR SYSTEM DESIGN

A heuristic procedure is proposed to approach the optimum solution to system and logistic design. This heuristic procedure utilizes a process of enumeration and is used in conjunction with the database management system developed in Chapter 3. This heuristic procedure does not guarantee optimality. However, a solution close to the "optimum" solution will be reached. After reaching this solution, the user can change the value of any parameter listed in Paragraph 2.10 and the resultant effect on the entire system will be made visible.

Relationships are defined between the user requirements, the reliability and maintainability of the system, the number of units deployed, the inventory level, and other logistic requirements of the system. The heuristic procedure is used to interactively manipulate these parameters to obtain a good solution to the problem. Technical performance and cost measures are used as criteria. The output of the heuristic procedure is a specification of:

1. The number of end items to deploy at each location.
2. The inventory level for each item at each location.
3. The reorder point for each item in inventory at each location.
4. The throwaway age for each item of each configuration of prime equipment and inventory. (Items are considered from end items to the lowest level replaceable items.)
5. The identification of all test and support equipment, facilities, personnel, documentation, training, and packaging requirements for each design configuration for each facility at each level of repair.

The heuristic procedure will also determine, under each set of conditions, which items will contribute most to the effectiveness of the system (see Paragraph 4.3) if additional units of those items are added to the inventory. The major assumptions of this heuristic procedure are as follows:

1. All corrective maintenance actions involve the replacement of items. Each repairable item that has been removed due to a failure can be repaired (or replaced) at whatever level of concern. Items that are replaced at one level and the faulty repairable item is sent to another level for repair, will have at least two failures modes. The first failure mode, typically starting with the digit 8, requires the initial replacement of the item. The second failure mode, typically on a lower level item than the original item, will be associated with the relevant level of repair in the REPAIR_LEVEL table.

2. Whenever the inventory level of an item drops to zero and demand still exists, spare parts are ordered immediately. This means that the longest time period that the system can be down due to shortages is equal to the lead time of the item that caused the delay.

3. Time between visits to a repair facility is uniformly distributed.

4. The only difference between the achieved availability and the operational availability is the time that the system is down due to a shortage of spare parts.

5. The total failure rate per year depends on (among other things) the number of units deployed and the time the equipment is operational. The number of units deployed depends on the operational availability of the end item (because of the maintenance requirements of the system). The operational availability again depends on the failure rate

of the system. A loop has now been defined. The assumption made is that the operational availability of the system, as calculated in each iteration, will be used to determine the total failure rate of the system in each subsequent iteration. This is a realistic assumption since the effect of each iteration on the system is very small. When a final solution has been reached, a few more iterations can be run on the same configuration to stabilize the results.

4.1 TOTAL NUMBER OF FAILURES PER YEAR

For time-independent failures and for time-dependent failures, the total number of failures per year for each failure mode (FM) for the j^{th} item ($\Phi_{j:FM}$) is given in [4.1] and [4.2] respectively:

$$\Phi_{j:FM} = (\#\text{ units deployed})_j * A_o * \Phi_{j:FM/hr} * (\text{hours worked per year}) \qquad [4.1]$$

$$\Phi_{j:FM} = \Phi_{j:FM}\{(\#\text{ units deployed})_j * A_o * \text{hours worked per year}\} \qquad [4.2]$$

The $(\#\text{ units deployed})_j$ is the number of units of item j that are deployed. This is calculated from the number of items utilized per end item deployed (in the UNITS_DEPLOYED table), multiplied by the quantity used per end item (in the PRODUCT_STRUCTURE table), multiplied by the fraction of the time the unit is utilized (in the MISSION_FRACTION table). $\Phi_{j:FM/hr}$ is the failure rate per hour for the particular failure mode for the j^{th} item. The values of $\Phi_{j:FM}$ are all the failures that demand replacements and are maintained in the TOTAL_FAILURES table. The total failure rate per item per year, Φ_j, is the summation of all the different failure modes for each item. This is calculated in [4.3]:

$$\Phi_j = \sum_{FM_j=1}^{(FM_j)_{max}} \Phi_{j:FM} \qquad [4.3]$$

The preventive maintenance frequency per hour for the k^{th} item ($fpt_{k/hr}$) is maintained in the PMAINT_FREQ column of the PREVENT_PERSONNEL table. The total number of preventive maintenance actions per item per year (fpt_k) is calculated from [4.4]:

$$fpt_k = (\#\text{ units deployed})_k * A_o * fpt_{k/hr} * (\text{hours worked per year}) \quad [4.4]$$

The "hours worked per year" in both preventive and corrective cases are the total number of hours that the end user would like the equipment to work. These are constant values and are maintainded in the CUSTOMER_WORKING_HOURS and CUSTOMER_WORKING_WEEKS tables, both as a function of time. The values of Φ_j and fpt_k are initially calculated for a system with just enough units deployed (fractions allowed) to fulfill the user requirements for each year, given that the operational availability of the system is 1.0. This number of units is the theoretical number of units deployed in the UNITS_DEPLOYED table. Although not stated specifically, the values of Φ_j and fpt_k are all calculated per location as a result of the user requirements in the DETAIL_REQUIREMENTS table. In order to fulfill the user requirements, sufficient capacity must be made available at each location to meet the demand. This can be calculated from [4.5]:

$$\text{Capacity Available} = (\#\text{ end-items deployed}) * A_o * (\text{Unit capacity}) \quad [4.5]$$

The unit capacity values are maintained in the ITEM_CAPACITY table. Unit capacity is an inherent characteristic of an item and is not a function of the number of units deployed. For the rest of this chapter, all calculations are done on a "per year" basis. The unit capacity in [4.5] is the unit capacity per year, and the available capacity is also per year (in response to capacity required per year).

4.2 OPERATIONAL AVAILABILITY

In order to determine the relationship between the number of units to deploy and the inventory level for each item, the operational availability, A_o, of the system at each deployment location must be calculated. A_o has to be calculated for each deployment location since the number of units to deploy and the inventory level must be calculated for each location. The operational availability of the system is calculated from [4.6]:

$$A_o = \frac{MTBM}{MTBM + M^* + DT_{short}} \qquad [4.6]$$

MTBM is the mean time between maintenance for the system and is calculated from [4.7] to [4.9]:

$$MTBM = \frac{1}{1/MTBM_u + 1/MTBM_s} \qquad [4.7]$$

$$MTBM_u = MTBF = \frac{\text{hours worked per year}}{\Phi} \qquad [4.8]$$

$$MTBM_s = \frac{\text{hours worked per year}}{fpt} \qquad [4.9]$$

Φ is the total number of failures per year for the deployment population, while fpt is the total number of preventive maintenance actions for the deployment population. If there are J items in the system

with failure rates Φ_j, and K items with preventive maintenance requirements fpt_k, then the parameters Φ and fpt can be calculated from [4.10] and [4.11]:

$$\Phi = \sum_{j=1}^{J} \Phi_j \qquad [4.10]$$

$$fpt = \sum_{k=1}^{K} fpt_k \qquad [4.11]$$

M^* is the mean active maintenance time for the system and is calculated from [4.12]:

$$M^* = \frac{(\Phi * M_{ct}^*) + (fpt * M_{pt}^*)}{\Phi + fpt} \qquad [4.12]$$

M_{ct}^* is the mean corrective maintenance time for the system and M_{pt}^* is the mean preventive maintenance time. $(M_{ct})_j$ and $(M_{pt})_k$ are the mean corrective maintenance time for the j^{th} item, and the mean preventive maintenance time for the k^{th} item respectively. These values are maintained in the CORRECT_PERSONNEL and PREVENT_PERSONNEL tables. M_{ct}^* and M_{pt}^* are calculated from [4.13] and [4.14] respectively:

$$M_{ct}^* = \frac{\sum_{j=1}^{J} [\Phi_j * (M_{ct})_j]}{\sum_{j=1}^{J} \Phi_j} \qquad [4.13]$$

$$M_{pt}^{*} = \frac{\sum_{k=1}^{K} [\, fpt_k * (M_{pt})_k \,]}{\sum_{k=1}^{K} fpt_k} \qquad [4.14]$$

DT_{short} is the downtime in the system as a result of the unavailability in spare parts. DT_{short} is the summation of all the downtimes as a result of shortages of all the items in the system. The parameter $downtime_j$ will denote the downtime of the system due to a shortage of the j^{th} item. The end item comprises J different replaceable items. DT_{short} is then calculated from [4.15]:

$$DT_{short} = \sum_{j=1}^{J} downtime_j \qquad [4.15]$$

where $downtime_j$ is the product of 1) the probability of having demand in excess of the number of items (N_j) carried in stock for item j over the period MTBM, and 2) the lead time of the j^{th} item, LT_j. The Poisson distribution can be used to determine the probability of demand for item j over the period MTBM. The amount by which the demand exceeds the available inventory (N_j) for item j during the period MTBM, is denoted by n_j. $downtime_j$ is calculated from [4.16]:

$$downtime_j = \sum_{n_j=1}^{\infty} Prob\,(demand_{j(MTBM)} = N_j + n_j) * LT_j$$

$$= LT_j * \{1 - \sum_{n_j=0}^{N_j} Prob\,(demand_{j(MTBM)} = n_j)\}$$

$$= LT_j * \{1 - \sum_{n_j=0}^{N_j} \frac{(\Phi_j * MTBM)^{nj}}{n_j!} * e^{-(\Phi j * MTBM)}\} \qquad [4.16]$$

The operational availability A_o can now be calculated by substituting equations [4.7] to [4.16] into [4.6]. The relationship between the number of units deployed and the inventory level is now defined.

4.3 THE HEURISTIC PROCEDURE

There are two approaches in using the heuristic procedure. Both approaches utilize a process of enumeration. The difference between the two is in the starting point. The first approach first determines the minimum number of units to deploy that will fulfill the need, assuming a virtually unlimited supply of inventory as a starting point. The deployment population is then progressively increased, and the inventory is each time "loaded" from a zero level to determine the most effective level of inventory that needs to accompany a deployed population to fulfill the requirements at the lowest equivalent cost.

The second heuristic first determines a reasonable solution (not necessarily a feasible solution) of the deployed population and the inventory. It then determines which items can be added to the inventory and which ones can be subtracted to increase the cost effectiveness of the system, while still fulfilling the requirements. Different deployment configurations around the initially suggested configuration are also considered. Each deployment configuration of end-items and inventory is evaluated as in the first heuristic. The second approach, although not as accurate as the first, will demand much less computing time.

4.3.1 The First Heuristic Procedure

The minimum possible number of units to deploy (which will fulfill the requirements) is first determined. Steps 1 through 10 determine the minimum number of units to deploy. The numbers in parenthesis refer to the specific equations. The first heuristic procedure is as follows:

1. Let $A_o = 1.0$.

2. Set the capacity available in [4.5] equal to the required capacity. Calculate the number of units to deploy, using [4.5].

3. Determine the failure rate of each item [4.3], using [4.1] and [4.2], and the failure rate of the system, [4.10].

4. Determine the number of preventive maintenance actions per year for each item [4.4], and for the system, [4.11].

5. Determine the MTBM [4.7], using [4.8] and [4.9].

6. Determine M^* [4.12], using [4.13] and [4.14].

7. Assume $DT_{short} = 0.0$ [4.15].

8. Calculate A_o [4.6].

9. Recalculate the number of units deployed with new A_o, again using [4.5].

10. Repeat steps 3 to 9, using A_o as calculated in step 9. Add one unit to the suggested population to be deployed.

Up to this point, a virtually infinite inventory level was assumed ($DT_{short} = 0$). The inventory is now depleted (in the model) and will now be "loaded" from a zero level. This loading process is described in the following steps:

11. For each component j of the end item, calculate the Gain Ratio as the ratio between the gain in operational availability of the system if an additional unit of item j is added to inventory, and the unit acquisition cost of item j. The true gain ratio would involve the total life-cycle cost. This cost is, for the purposes of determining the most likely items to be added to inventory, approximated by the acquisition cost. The item with the biggest Gain Ratio is the candidate that will have the biggest increase in the cost effectiveness of the system if one unit of that item is added to inventory.

$$\text{Gain Ratio}_j = \frac{\text{Gain in } A_o}{\text{Unit acquisition cost}_j} \qquad [4.17]$$

First, DT_{short} is calculated for each item [4.16] and the system [4.15] with zero inventory ($N_j = 0$). A_o is calculated, using DT_{short} and the results from step 10. This A_o serves as a baseline. DT_{short} is now calculated for each item in the product configuration under consideration if one unit of that item is added to the inventory. For each item added to inventory, the new A_o is calculated. The difference in this newly calculated A_o and the

baseline A_o is the gain in technical effectiveness. Whenever an item is added to inventory, the A_o associated with that addition becomes the baseline A_o. The Gain Ratio is therefore calculated for each item.

12. Add one unit of the item with the biggest Gain Ratio to inventory. If the required capacity has been achieved, go to step 13. Otherwise, recalculate the Gain Ratio for an additional unit to be added to the inventory of the same item that had just been added. Keep on adding units of this item to the inventory until the required capacity has been achieved, or until the second highest Gain Ratio in step 11 is bigger than the Gain Ratio of the item under consideration. In this case, repeat step 11.

13. Calculate the total cost of the system over the anticipated life cycle. The costs include acquisition, operation, and maintenance costs for this system configuration. The following example illustrates how only the test and support equipment quantities and associated costs are determined:

    13.1. Get the failure rates of all the failure modes for all items in the product configuration under consideration from the TOTAL_FAILURES table. (These values are calculated using [4.1] and [4.2].)

    13.2. Divide the failures per year in step 13.1 by 52 to get the weekly demand rate.

    13.3. For each deployment location, divide the failure rate in the proportion outlined in the PERCENT_DISTRIBUTION table and allocate the failure rates to the different levels of repair. The result is the demand rate for test and support equipment at

each level of repair.

13.4. For each failure mode and item, at each repair facility, determine the type and quantity of test and support equipment required as a function of the demand rate, as calculated in step 13.3.

13.5. The requirements for test and support equipment are summarized and rounded up for all the test and support equipment that are commonly used at a repair facility.

13.6. The quantity and type of test and support equipment have now been defined. The quantity of each type of test and support equipment is multiplied by the the unit price of the equipment in the ITEM_PRICE table. The requirements and cost for test and support equipment at each repair facility are now defined. This process is repeated for the other elements of logistics.

14. Add one end item to the system and deplete the inventory. Repeat steps 3 to 6 and 11 to 13. Repeat these steps until the lowest present equivalent life-cycle cost has been obtained. The deployment configuration associated with this cost is the preferred alternative.

The item that will have the biggest positive influence on the cost effectiveness of the system if additional stock of that item is carried, is the item with the biggest Gain Ratio. The optimum throwaway age will be when the ratio of the increase in operational availability to the present equivalent life-cycle cost of the new item exceeds that of the old item. Once the overall system level requirements are established for inventory, local lot sizing technics can be used to determine the

exact order quantities and reorder points.

4.3.2 The Second Heuristic Model

The same enumeration process is followed as in the previous heuristic approach, except that a better starting point is defined. This is done by initially assuming that 1) no more capacity will be utilized than required by the end user; and 2) enough capacity will be made available to fulfill the need. This means that the total number of failures in the system remains constant, regardless of the number of units deployed. The maintenance requirements also remain constant. The local optimum probability of stockout (as defined by Johnson and Montgomery, 1974) is determined for each item:

$$P_s^* = \frac{HQ}{KR}$$

where

H = holding cost

Q = economic order quantity

K = stockout cost

R = demand rate

The downtime of each item, and the system, are calculated directly from these probabilities, using [4.16] and [4.15]. The deployment population can now be estimated (because of the initial assumptions). The Gain Ratio of each item is determined. Inventory is now reduced for the items with the least Gain Ratios, and inventory is added for those with the biggest Gain Ratios until the process stabilizes. If the required capacity had not been achieved when the process had stabilized,

more inventory must be added. Different simulations are also run with different numbers of end items deployed.

4.4 AN EXAMPLE

The following simple example illustrates some of the capabilities of the proposed model. A system, consisting of only two replaceable items, is considered. The primary objective is to determine the number of end-items to deploy, as well as the number of spare parts for each of the two items of the system. One of the items, item A, is then improved by redesign. The resultant impact on the system is subsequently analyzed. Although the procedure illustrated in this example is only one of many different ways of manipulating data within the framework of the proposed model, it shows what will typically be done in analyzing new data. System XYZ is illustrated in Figure 5 and is defined accordingly in the PRODUCT_STRUCTURE table.

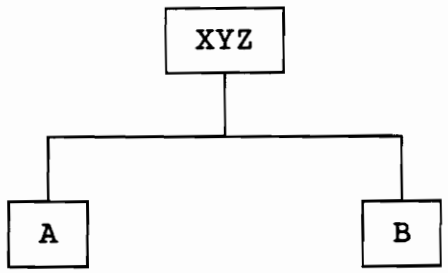

Figure 5 Product structure of system XYZ

PRODUCT_STRUCTURE

PARENT	CHILD	QTY_PER
XYZ	A	1
XYZ	B	1

The user requirements for system XYZ (the end item) are maintained in the DETAIL_REQUIREMENTS table. Only one location will be considered, and only the requirement for the first year, which is 2900 units of capacity code A.

DETAIL_REQUIREMENTS

ITEM#	CUST#	CAP_COD	LOCATN	YR_0	YR_1	....	YR_n
XYZ	C123	A	L01	2900	3100	....	6100

The number of hours per week and the number of weeks per year that customer C123 wants system XYZ to work are maintained in the CUSTOMER_WORKING_HOURS and the CUSTOMER_WORKING_WEEKS tables. Again, only the first year is of concern with 40 hours per week and 45 weeks per year.

CUSTOMER_WORKING_HOURS

ITEM#	CUST#	YR_0	YR_1	...	YR_n
XYZ	C123	40	45	...	40

CUSTOMER_WORKING_WEEKS

ITEM#	CUST#	YR_0	YR_1	...	YR_n
XYZ	C123	45	42	...	40

The unit capacity of an end-item of system XYZ is maintained in the ITEM_CAPACITY table. The actual capacity of an end-item of system XYZ is assumed to be known as 120 units of capacity code A, the same capacity code as in the DETAIL_REQUIREMENTS table.

ITEM_CAPACITY

ITEM#	CAP_CODE	DESIGN_TO	ACTUAL
XYZ	A	130	120

The total number of units that will eventually be deployed, will be maintained in the UNITS_DEPLOYED table. The theoretical number of units deployed (calculated from [4.5], assuming A_o = 1.0) is a very useful feature since the relationship "number of units deployed * A_o" (which is equal to the theoretical number of units deployed) occurs quite frequently.

UNITS_DEPLOYED

ITEM#	CUST#	LOCATN	TH_PRAC	YR_0	...	YR_n
XYZ	C123	L01	T	25	...	56
XYZ	C123	L01	P	38	...	85

Both items A and B are assumed to have time independent failure rates. Item A has two failure modes (1 and 2), while item B has only one failure mode (4). The notation $\Phi_{A:1/hr}$ denotes the failure rate per hour of item A due to the failure mode 1. The failure rates for items A and B are maintained in the CONSTANT_FAILURES table.

CONSTANT_FAILURES

ITEM#	FAIL_MODE	FAIL_RATE
A	1	0.000865
A	2	0.000245
B	4	0.000210

The preventive maintenance frequencies (fpt), as well as the associated maintenance time durations (M_{pt}) are specified in the PREVENT_PERSONNEL table. The values of fpt are maintained in the PMAINT_FREQ column. The preventive maintenance requirements for items A and B are as follows:

PREVENT_PERSONNEL

ITEM#	TYPE	Mpt	PMAINT_FREQ	L&A_DELAY
A	D	12	0.00027	3.0
B	H	6	0.00014	0.5

The corrective maintenance times for items A and B (with the associated failure modes) are maintained in the CORRECT_PERSONNEL table.

CORRECT_PERSONNEL

ITEM#	FAIL_MODE	PERS_TYPE	Mct	L&A_DELAY
A	1	F	15	1.5
A	2	G	3	1.5
B	4	F	4	7.0

The failure rates (for each failure mode) for items A and B for one year are then calculated from [4.1]. For a first estimate, the "(# units deployed)$_j$ * A_o" are approached by the theoretical number of units deployed (the value of 25 in the UNITS_DEPLOYED table). "$\Phi_{j:FM/hr}$" is retrieved from the CONSTANT_FAILURES table, while "(hours worked per year)" is the product of the appropriate values from the CUSTOMER_WORKING_HOURS and CUSTOMER_WORKING_WEEKS tables (40*45=1800 hours for year 1). The values of these failure rates for items A and B are then

determined to be:

$\Phi_{A:1} = 38.3$

$\Phi_{A:2} = 10.8$

$\Phi_{B:4} = 9.3$

The TOTAL_FAILURES table is then updated with these values. This table then looks as follows:

TOTAL_FAILURES

ITEM#	FAIL_MODE	LOCATN	YR_0	YR_1	...	YR_n
A	1	L01	38.3	45.9	...	54.8
A	2	L01	10.8	15.0	...	19.7
B	4	L01	9.3	12.6	...	14.4

The total failure rate per item per year, as well as the total failure rate per year of the end item XYZ, are then calculated from [4.3] and [4.10]. Tables do not exist for these failure rates; it is calculated as needed. These failure rates are then calculated to be:

$\Phi_A = 49.1$

$\Phi_B = 9.3$

$\Phi = 58.4$

The same principles are followed in calculating the preventive maintenance frequencies. The only real difference is that each item has only one "failure mode" for preventive maintenance. The preventive maintenance frequencies are calculated from [4.4] and [4.11] to be:

$fpt_A = 12.0$

$fpt_B = 6.2$

$fpt = 18.2$

In order to calculate the operational availability of the system from [4.6], the MTBM is first calculated from [4.8] and [4.9]. The required parameters are all known at this point. The results are:

$MTBM_u = 1800/58.4 = 30.8$

$MTBM_s = 1800/18.2 = 98.9$

$MTBM = 23.5$

The maintenance times are calculated from [4.12], [4.13], and [4.14]. Again, all the required variables are known. The maintenance times are then calculated to be:

$M_{ct}^* = 11.0$

$M_{pt}^* = 10.0$

$M^* = 10.8$

The achieved availability can now be calculated from [4.6] (where the downtime is initially assumed zero):

$A_a = 0.685$

The operational availability will be less than the achieved availability since the latter assumes an infinite supply of inventory. For simplicity, it is assumed that all spare parts will have inventory levels

such that the probability of having a spare part available upon request is at least 0.90. To have more manageable quantities, the annual failure rates will be converted to monthly failure rates. The operational availability calculation will therefore also be transformed to accommodate an MTBM of 160 hours. The demand for spare parts and the associated probability of occurrence can now be determined from the Poisson distribution in [4.16]. The only unknown in [4.16] is the lead time. If an item is defined to the system, the lead time is a required data field in the ITEM_PRICE table. The lead time is therefore retrieved from the ITEM_PRICE table. The cumulative demand distribution for items A and B are then calculated as follows:

n_A	$Prob_A$	n_B	$Prob_B$
0	0.0167	0	0.4584
1	0.0852	1	0.8160
2	0.2252	2	0.9554
3	0.4161		
4	0.6113		
5	0.7709		
6	0.8797		
7	0.9433		

Assume item A has a lead time of 4 weeks (160 hours) and item B has a lead time of 2 weeks (80 hours). DT_{short} and the operational availability A_o can now be calculated from [4.16] and [4.6] respectively, assuming for simplicity a requirement of 0.90 of having a spare part available upon request. These values are then calculated to be:

$$DT_{short} = \{(1 - 0.9433) * 160\} + \{(1 - 0.9554) * 80\}$$

$$= 12.64$$

$$A_o = 160 / (160 + 73.5 + 12.64)$$

$$= 0.65$$

Since A_o is now known, the actual number of end items to deploy can now be calculated from [4.5] to be:

$$2900 = N_{XYZ} * 0.65 * 120$$

N_{XYZ} = 38 units to deploy of system XYZ

N_A = 7 spares for item A

N_B = 2 spares for item B

From [4.5], the total available capacity is 2964. The UNITS_DEPLOYED table is now updated with the "practical" number of units deployed. Tables for spare parts do not exist; the spare parts are calculated as needed.

Item A is now redesigned and test data reveal the following hourly failure rates, together with the new preventive maintenance requirements:

$\Phi_{A:1/hr}$ = 0.00020

$\Phi_{A:2/hr}$ = 0.00015

fpt_A = 0.00018

(Note that these values are given for the simplicity of the example. Actually, only the test data can be given and the proposed model will calculate these failure rates.) The rest of the information remains the same. The same logic is used as in the first part of the example. Due to the changes in the reliability characteristics, the following values become known:

$\Phi_A = 15.6$

$\Phi = 24.9$

$fpt_A = 8.0$

$fpt = 14.2$

$MTBM_u = 72.3$

$MTBM_s = 126.76$

$MTBM = 46.0$

$M_{ct}^* = 7.7$

$M_{pt}^* = 9.4$

$M^* = 8.3$

The probability of having a spare part available upon request is again calculated as a function of the demand rate. The values are:

n_A	$Prob_A$
0	0.2725
1	0.6268
2	0.8571
3	0.9569

If the same restriction holds that all items must have a probability of meeting demand of at least 0.90, then A_o increases to 0.803 and the available capacity increases to 3660 while only 3 spares of item A is carried (compared to 7 previously). If the restriction of a 0.90 probability of meeting demand does not hold, the most economical system must be designed. Several different combinations of spare parts will be evaluated. For the deploymed population of 38 end items, the following combinations of spare parts will result in the operational availabilities and available capacities exhibited:

Alternative	A	B	A_o	Capacity	Acceptable
1	1	0	0.55	2508	N
2	1	1	0.61	2782	N
3	1	2	0.63	2894	N
4	1	3	0.64	2927	Y
5	2	0	0.63	2872	N
6	2	1	0.71	3221	Y
7	3	0	0.67	3048	Y

For simplicity, the total annual equivalent life-cycle cost of each item is approximated by its unit cost. The following selection criteria hold for the above case: If the unit cost of item A is more than that of item B, choose alternative 4. If B is more expensive than A, choose alternative 7. However, a cost analysis can be done to evaluate the increase in available capacity if alternative 6 is considered.

The number of end items to deploy can now be altered and the inventory can be determined for each deployment configuration. The system that has the lowest annual equivalent life-cycle cost

is the preferred approach. Once the overall inventory requirements are established, the inventory models are used to determine the exact quantities and frequency of procurement.

The user can change any parameter value by entering the new value in the appropriate field and the proposed model will automatically recalculate the desired output. The values that can be changed relevant only to this example include:

1. Product structure (replace item A with another item, or series of items).
2. The number of units that are used in each level of the product structure.
3. Customer requirements (capacity and work time).
4. Item unit capacity.
5. Item failure rate.
6. Maintainability characteristics.
7. Number of units deployed.
8. Number of spare parts deployed.

This is a very simple example that covers only a portion of the capabilities of the proposed relational database management system. When systems become large (consisting of thousands of items) and each item has several parameters that could potentially influence the sytem, the proposed model will still keep track of all changes, as well as the effect of each change on the system.

5.0 SUMMARY, CONCLUSIONS, AND EXTENSIONS

The procedure developed in this research is summarized in this chapter. Also, some conclusions are made as to the strengths of the proposed model and further research opportunities are identified.

5.1 SUMMARY

The objective of this research was to define a relational database management system that will enable the user of it to evaluate different possible design configurations of complex systems in such a way that the required system effectiveness will be achieved at a close-to-minimum life-cycle cost. Also, the logistic requirements are defined for each design configuration. The relational database management system will also provide the user with the capability to test the sensitivity of the system due to changes in input variables. The decision variables are mainly the number of end items to deploy, the inventory level of spare and repair parts, the reorder points and order quantities of inventory, the throwaway age of items, and other logistic requirements for the system.

The methodology utilized is noted in the following steps: Customer requirements are analyzed in functional terms. Feasible design alternatives are considered and defined as product configurations. The reliability characteristics of each product configuration are determined. Initially, these reliability values are allocated from a system-level down to lower level components, and later determined from test and evaluation data. A maintenance analysis is conducted to determine the inventory requirements (using reliability data) and the other logistic requirements for each design configuration.

A vector of effectiveness measures can then be developed for each customer, depending on objectives, constraints, and risks. These effectiveness measures, consisting of a combination of performance and cost measures, are used to aid objectively in deciding which alternative is preferred.

5.2 CONCLUSIONS

The contribution of this research can be summarized as follows: The objective of defining a relational database management system is met. The database management system was not coded (it was not part of the objective). It is therefore not possible to state with certainty that such a database system will definitely fulfill all the requirements stated. However, the flow of logic was tested several times. One such an example was illustrated in Paragraph 4.4. The proposed model attempts to establish the design so that the required effectiveness will be achieved at a minimum life-cycle cost.

The proposed model does not guarantee optimality. However, the heuristic procedure utilized in Chapter 4 gives a practical solution close to the optimum. After reaching this point, the user of the proposed model will be able to change any input parameter listed in Paragraph 2.10, and the effect on the whole system will be made visible. Furthermore, for each design configuration the spare and repair parts are determined that, when added to inventory, will increase the availability of the system most effectively. This is a dynamic process in that the items that will increase the availability of the system most effectively are not only a function of the product configuration, but also of the inventory status. The ability is created to keep track of this dynamic process.

The total life cycle of a system is covered. The proposed model will therefore serve as a central

source of information not only over the life cycle of each specific system, but as a common source of information. Baseline comparisons with other projects are therefore possible. Because a relational database approached is used, any additional information required (which is not covered in this research), can be added onto the proposed model. The modelling capability is therefore very adaptable to changing requirements.

The proposed model will serve as a good management tool since the user will have visibility of the impact on the system over the life cycle if changes are proposed to the system. Any query can be constructed that involves any of the parameters in any logical combination modelled. The user will be able to respond quickly and effectively to customer demands. Another benefit of the proposed model is that changes can be made to any data, and all other data linked to the original data item will be updated accordingly.

5.3 FURTHER RESEARCH

Several future research opportunities exist. These are:

1. A more efficient heuristic procedure should be developed to approach the optimum solution. Although the heuristic procedure proposed herein is effective, it is inefficient since the boundary lines within which it moves in its search for better solutions are very wide. The result is a requirement for high computation capability.

2. A uniform distribution is assumed for the time between visits to repair facilities. Queuing theory should be applied to more effectively determine the actual facility resource requirements. Simulation software, like SLAM and SIMAN, could be used to model

resource requirements.

3. A weakness of this research is that the relationship between the proposed model and Computer-Aided Acquisition and Logistic Support (CALS) is not defined. This interface should be defined in order to accommodate the entire relevant industry in the evaluation of alternatives.

4. Although Appendix B touches on the relationship between the proposed model and Manufacturing Planning and Control, this interface can be refined further. This interface is important since this research covers the entire life cycle of a system and that includes manufacturing.

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APPENDIX A

INVENTORY MODELS

Appendix A is an extension of Paragraph 3.6. The order quantity (Q), order interval (T), reoder point (B), and total cost (TC) for the most important inventory models are given in this appendix. It excludes the economic manufacturing quantity model, which is covered in Paragraph 3.6.

A.1 ECONOMIC ORDER QUANTITY: NO STOCKOUTS

$$Q^* = \left[\frac{2CR}{H}\right]^{\frac{1}{2}}$$

$$T = \left[\frac{2C}{HR}\right]^{\frac{1}{2}}$$

$$B = \frac{RL}{365}$$

$$TC = RP + \frac{RC}{Q^*} + \frac{HQ^*}{2}$$

A.2 ECONOMIC ORDER QUANTITY : STOCKOUTS ALLOWED

The shortage cost, or the stockout cost, K, is the cost incurred in the total system due to that item being short. This shortage cost is maintained in the SHORTAGE_COST table. V is the maximum

inventory level and is equal to the stockout plus the order quantity. The parameters are:

$$Q^* = \left[\left\{ \frac{2CR}{H} \right\} \left\{ \frac{H+K}{K} \right\} \right]^{\frac{1}{2}}$$

$$T = \left[\left\{ \frac{2C}{HR} \right\} \left\{ \frac{H+K}{K} \right\} \right]^{\frac{1}{2}}$$

$$B = \frac{RL}{N} - (Q - V)$$

$$TC = RP + \frac{RC}{Q^*} + \frac{HV^2}{2Q^*} + \frac{K(Q - V)^2}{2Q^*}$$

A.3 ECONOMIC ORDER INTERVAL

For single item purchase, the situation is as follows:

$$T = \left[\frac{2C}{RFP} \right]^{\frac{1}{2}} \quad \text{in years}$$

$$Q = R * T$$

$$TC = RP + \frac{C}{T} + \frac{RFPT}{2}$$

For both the single and the multiple item situations, the order quantity is determined from the difference in the current stock position at time T and the maximum inventory level E. The order

quantity averages out as RT. The reorder point B is not very important since orders are made periodically. The maximum inventory level E is:

$$E = \frac{R * (T + L)}{N}$$

$$= Q + B$$

Both T and L are expressed in days. For the multiple item purchase, there is an extra ordering cost per order, C^*, (consisting of multiple items), apart from the individual item ordering cost. The EOI_MULTIPLE_ITEMS table indicates all the items that are procured together. The column MULT# indicates the unique number that identifies the items that are ordered as a group: all items with the same MULT# are procured together.

EOI_MULTIPLE_ITEM

ITEM#	MULT#
SDF	M45
GHI	M45
OPQ	J32
GGN	M45
G54	J32

The EOI_MULT_COST table indicates the order cost, C^*, per multiple item order in the ORD_COST column.

EOI_MULT_COST

ITEM#	ORD_COST
M45	245.00

The order interval (T) and the maximum inventory level (E) are determined as follows:

$$T^* = \left[\frac{2(C^* + nC)}{n \{F \sum_{i=1} R_i P_i\}} \right]^{\frac{1}{2}}$$

$$E_i = \frac{R_i(T + L)}{N}$$

$$TC = \sum_{i=1}^{n} R_i P_i + \frac{(C^* + nc)}{T} + \{0.5TF * \sum_{i=1}^{n} R_i P_i\}$$

In both cases i is restricted to the items to be procurred together in a multiple purchase order.

A.4 LOT-FOR-LOT

The order quantity is of primary concern since the items are ordered as needed. Every planning period, orders are placed only to satisfy the anticipated demand for the next period. If X is the number of planning periods per year (defined by the user), then Q is:

$$Q = \frac{R}{X}$$

$$T = \frac{N}{X}$$

$$TC = RP + XC + \frac{HQ^*}{2}$$

A.5 PERIODIC ORDER QUANTITY

$$T = EOI = \frac{EOQ}{R_{avg}} = \left[\frac{2C}{R_{avg}Pf}\right]^{\frac{1}{2}}$$

$$Q = \sum_{i=1}^{EOI} r_i$$

$$TC = RP + \left(\frac{X}{T} * C\right) + \left(\frac{Q}{2} * H\right)$$

r_i is the average demand per period. The user is prompted to establish the length of a period (days, weeks, months, etc.). These values are maintained in the PERIOD_LENGTH table. The column PLAN_PERIOD is the planning period in days (D), weeks (W), months (M), or years (Y). The periods are considered seven days per week, 30 days per month, and 365 days per year. The value of X is selected accordingly, and the average demand per period is calculated, using the number of hours per week, weeks per year, and the total number of days per year that the end user wishes to work with the end item. If the system is being used constantly, r_i is simply the average demand per period (i.e., the total annual demand divided by the number of periods per year). The holding cost fraction per period (f) is the annual holding cost fraction (F) divided by the number of periods per year. The reorder point B is not of concern since the orders are placed with regular intervals T. R_{avg} is the average demand rate over the entire planning horizon.

PERIOD_LENGTH

ITEM#	PLAN_PERIOD
KJH	D
GYK	M
KLP	W

A.6 PART-PERIOD ALGORITHM

$$\sum_{k=1}^{T} (k - 1)R_k = \frac{C}{Ph}$$

The order interval is determined by increasing k to the point where the left hand side of the above equation exceeds the right hand side. R_k is the demand rate during the k^{th} period. The reorder point is, again, not of concern, but the order quantity is calculated from:

$$Q = \sum_{k=1}^{T} R_k$$

$$TC = RP + \left(\frac{X}{T} * C\right) + \left(\frac{Q}{2} * H\right)$$

where the ratio X/T follows the same relationship as under the periodic order quantity. The PEROID_LENGTH table is also used in determining the planning period length.

A.7 PROBABLISTIC: VARIABLE DEMAND & CONSTANT LT (K KNOWN)

The objective in the probablistic models is to determine the order size Q, the reorder point B, and the safety stock, S. These parameters are all maintained in the INVENTORY table. The EOQ model is used to determine the order size and is calculated and stored in the ORD_QUANT column of the INVENTORY table (the variables are the same as discussed under the Economic Order Quantity):

$$Q^* = \left[\frac{2CR}{PF}\right]^{\frac{1}{2}}$$

The optimum probability of having a stockout is calculated as:

$$P_s^* = \frac{HQ}{KR}$$

The Poisson distribution is now used to determine the probability of a stockout during the lead time. The lead time is taken from the LEAD_TIME column in the ITEM_PRICE table. Since lead time is in working days, it has to be transformed in the following way to get the actual working time during the lead time:

$$\text{actual working time} = t_{LT} = \frac{LT}{365} * (\text{weeks/yr}) * (\text{hours/wk})$$

The (weeks/yr) and (hours/wk) terms are the total hours that the end user wishes to work during a year and are retrieved from the tables CUSTOMER_WORKING_WEEKS and

CUSTOMER_WORKING_HOURS respectively in the appropriate years. The failure rate Φ (the number of failures per hour) is a function of the annual failure rate in the TOTAL_FAILURES table. The Poisson distribution can now be used to sequentially calculate the probability for the demand of n (n = 0,1,2,...) spares during the lead time:

$$P[D_n = n] = \frac{(\Phi * t_{LT})^n * \exp(-\Phi * t_{LT})}{n!} = P(M)$$

where P(M) is the probability of having a lead time demand of M units. These probabilities are significantly calculated to the third decimal point. These probabilities are sequentially added together and subtracted from 1 until the optimum probability of a stockout is reached. The value of n at that point is the reorder point B. It is calculated as follows:

$$P_s^* = P(M > B) = 1 - \sum_{i=0}^{n} P(M)$$

The probability distribution of demand during lead time follows a Poisson distribution. P(M>B) is the probability of the lead time demand being greater than the quantity at the reorder point B. P(M>B) is, therefore, also equal to the probability of a stockout. These values are maintained in the VARIABLE_DEMAND table. The columns are as follows: M is the lead time demand; P(M) is the probability of having a lead time demand of M units; and P(M>B) is the probability of needing more units during the lead time than the reorder quantity (which is also the probability of a stockout).

VARIABLE_DEMAND

ITEM#	M	P(M)	P(M>B)
CVB	26	0.010	0.990
CVB	27	0.030	0.960
CVB	28	0.070	0.890
...	...	...	...
CVB	34	0.203	0.674
CVB	35	0.248	0.426
CVB	36	0.196	0.230
...	...	...	...
CVB	47	0.003	0.000

This table does not have to exist in reality since all the values can be computed from existing data in other tables. Its existence, like in many other cases, would violate the concept of data independence. On the other hand, its existence would ease the process of data configuration and speed up queries. In the variable demand, variable lead time case, the assumption is made that this table exists. If it doesn't, the values will be calculated accordingly. The reorder point B is the value of M that corresponds to the value of P(M>B) closest to P_s^*. The safety stock S is already built into the definition of the reorder point and is equal to:

$$S = B - M_{avg}$$

where M_{avg} is the average demand during the lead time. This is equivalent to:

$$M_{avg} = \Phi * t_{LT}$$

$$TC = RP + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

The first time that the safety stock is acquired, this total cost formula changes to:

$$TC = (R + S)*P + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

A.8 PROBABLISTIC: VARIABLE LT & CONSTANT DEMAND (K KNOWN)

A probability distribution must be defined for the lead time. This distribution is maintained in the table VARIABLE_LT. Contrary to the VARIABLE_DEMAND table, the VARIABLE_LT table must exist since, in this case, it contains raw data. The columns LT, PROB, and SUPPLIER are the lead times and its associated probabilities of occurance, and the supplier of each item. The lead time in this table is for the exclusive use of the probablistic approach to a constant demand, variable lead time supply situation and does not replace deterministic values of the LEAD_TIME column in the ITEM_PRICE table. An item cannot have a constant lead time in the ITEM_PRICE table as well as a lead time probability distribution in the VARIABLE_LT table; it must have one or the other. The ITEM_PRICE table shows blank values for the lead time if it has a probability distribution, and the user is pointed towards this distribution when the field is queried. For each item and supplier, the probabilities must sum to one.

VARIABLE_LT

ITEM#	SUPPLIER	LT	PROB
XDF	S05	10	0.15
XDF	S05	11	0.20
XDF	S05	12	0.25
XDF	S05	13	0.20
XDF	S05	14	0.15
XDF	S05	15	0.05

The constant demand on a daily basis (LT is in calendar days) is multiplied by the different lead times to obtain the actual lead time demand M corresponding to the probability of occurence. M still corresponds to the probability distribution. Since the demand is constant and the lead time varies, a probability distribution is obtained from the different lead time demands. The table VARIABLE_DEMAND can also be used to save the results of this process. (The table INV_ITEM_MODEL keeps track of the fact that this is a constant demand, variable lead time case.) The average lead time demand M_{avg} is calculated as:

$$M_{avg} = \Sigma\ M * P(M)$$

The summation is for all the probabilities and their associated lead time demand. The reorder point B is further calculated in the same way as in the constant demand, variable lead time case. The safety stock is then calculated as the difference between the newly calculated reorder point B and actual average demand M_{avg}. The total cost is then:

$$TC = RP + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

The first time that the safety stock is acquired, this total cost formula changes to:

$$TC = (R + S)*P + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

A.9 PROBABLISTIC: VARIABLE DEMAND & VARIABLE LT (K KNOWN)

Both the VARIABLE_DEMAND and the VARIABLE_LT tables are utilized in this case. The standard deviation of the demand distribution, σ_D, and the standard deviation of the lead time distribution, σ_L, must be calculated from the tables VARIABLE_DEMAND and VARIABLE_LT respectively. The standard deviation of the lead time is calculated as follows:

$$\sigma_L = \left[\frac{\sum_{i=1}^{n} Freq_i * (LT_i - LT_{avg})^2}{0.99} \right]^{\frac{1}{2}}$$

where $Freq_i$ is the probability of occurence in the VARIABLE_LT table. LT_i is the i^{th} lead time that corresponds to $Freq_i$. LT_{avg} is simply the summation of the product of LT_i and $Freq_i$ for all the values of i. The standard deviation of the demand distribution is obtained in a similar fashion. In the case where the lead time and the demand distributions are independent, the variance of the demand during the lead time, σ^2, can now be calculated as:

$$\sigma^2 = (LT_{avg} * \sigma_D^2) + (D_{avg} * \sigma_L^2)$$

where D_{avg} is the average demand during the lead time, calculated in a similar way as LT_{avg}. For the case where the demand and the lead time are dependent on each other, the variance will be calculated as:

$$\sigma^2 = \{(LT_{avg})^2 * \sigma_D^2\} + \{(D_{avg})^2 * \sigma_L^2\} + \{\sigma_D * \sigma_L\}$$

For both the independent and dependent cases, the mean of the demand during the lead time is approximated by M_{avg} :

$$M_{avg} = D_{avg} * L_{avg}$$

Since the mean and variance are known, and assuming a normal distribution, the reorder point B can now be expressed as:

$$B = M_{avg} + Z * \sigma$$

The value of Z corresponds to the desired probability of having a spare part available upon request (from normal distribution tables). The safety stock S is calculated from:

$$S = B - M_{avg}$$

$$TC = RP + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

The first time that the safety stock is acquired, this total cost formula changes to:

$$TC = (R + S)*P + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

A.10 PROBABLISTIC: STOCKOUT COSTS UNKNOWN

When stockout costs can not be determined with a reasonable amount of certainty or when management does not want to take the risk of estimating it, a service level can be specified. This service level is simply the probability of having a spare part available upon request, P_{avail}. A probability value is specified (typically 0.97) and the number of spares is then calculated, using the Poisson distribution. This value is the reorder point, B. The order quantity is still the Economic Order Quantity. Again, only the lead time is of concern. P_{avail} is then calculated as:

$$P_{avail} = \sum_{n=0}^{B} \frac{(\Phi * t_{LT})^n * \exp(-\Phi * t_{LT})}{n!}$$

The safety stock is the difference between the reorder point and the average lead time demand ($\Phi * t_{LT}$). The inventory table is updated accordingly. The total cost is:

$$TC = RP + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

The first time that the safety stock is acquired, this total cost formula changes to:

$$TC = (R + S)*P + \frac{RC}{Q^*} + (\frac{Q^*}{2} + S)*H$$

APPENDIX B

INTERFACE WITH MANUFACTURING PLANNING AND CONTROL

There is an important interface between the proposed model (as a result of this research) and Manufacturing Planning and Control (MPC). This interface results primarily from the fact that MPC use a fair amount of data that have already been accumulated by the application of the proposed model in the earlier phases of design. Using these data will give MPC a "running start."

MPC also utilizes the concept of product structure, or bill of material. In fact, the product structure is the backbone of MPC. All the important data and functions of MPC are linked together by means of the product structure: production schedules, capacity planning, inventory control, purchasing, and others. The most basic input to MPC is the product structure. The most important output as a result of this research is the product structure; the configuration that will fulfill all the customer requirements at a minimum life-cycle cost. MPC deals with all the activities in a manufacturing context from acquisition of raw materials to delivery of completed products. As the name implies, the purpose of MPC is to plan and control manufacturing activities. MPC neither looks at the design and development phases of a system, nor does it look at the utilization and support phase, other than having bills of material as references. The other important output of the proposed model is the definition of the logistic requirements to effectively support the system throughout its utilization phase. Because the proposed model covers the entire life cycle of a system, and because it utilizes a good portion of the data that are required by MPC (as will be outlined in the rest of Appendix B), there must be an important interface between the proposed model and MPC.

An ideal is to integrate the proposed model and MPC to have a firm control on the product

throughout its life cycle. Such an integrated system will have the following capabilities:

1. The product configuration that will be selected will fulfill the requirements of the end user at a close-to-minimum cost.

2. All important aspects of production will be planned immediately for the selected configuration. This includes production scheduling, material planning, inventory control, cost accounting, budgeting, capital budgeting, resource and capacity requirements, and purchasing. A large percentage of the data that were used to determine the preferred product configuration will be used in MPC.

3. The logistic requirements for the preferred configuration will be determined.

In such an integrated system these capabilities will be interactive: whenever a change in one aspect occurs, the others will be updated accordingly. Eg., when the cost of a maintenance activity for a certain item exceeds a certain limit, another design configuration can be proposed with a detail breakdown of the impact on the system (including cost): new production schedules, new manufacturing and maintenance processes, new material planning, training requirements, resource, capacity, and manpower requirements for manufacturing and support, inventory requirements for manufacturing and for the customer, and more.

The rest of Appendix B is devoted to briefly describing MPC and its interfaces with the proposed model. Figure 6 illustrates the main elements of MPC. The top part, or the front end (FE), is the set of activities and systems for overall direction setting. The front end is used to establish the company objectives for MPC. The middle part, or engine (ENG), is the detailed planning of material

flow and capacity to support the overall plans. The bottom part, the back end (BE), is the execution of the plans, as generated in the engine, in terms of detailed shop scheduling and purchasing actions. Each of the MPC activities outlined in Figure 6 are described in the subsequent paragraphs. The interfaces with the model are also indicated.

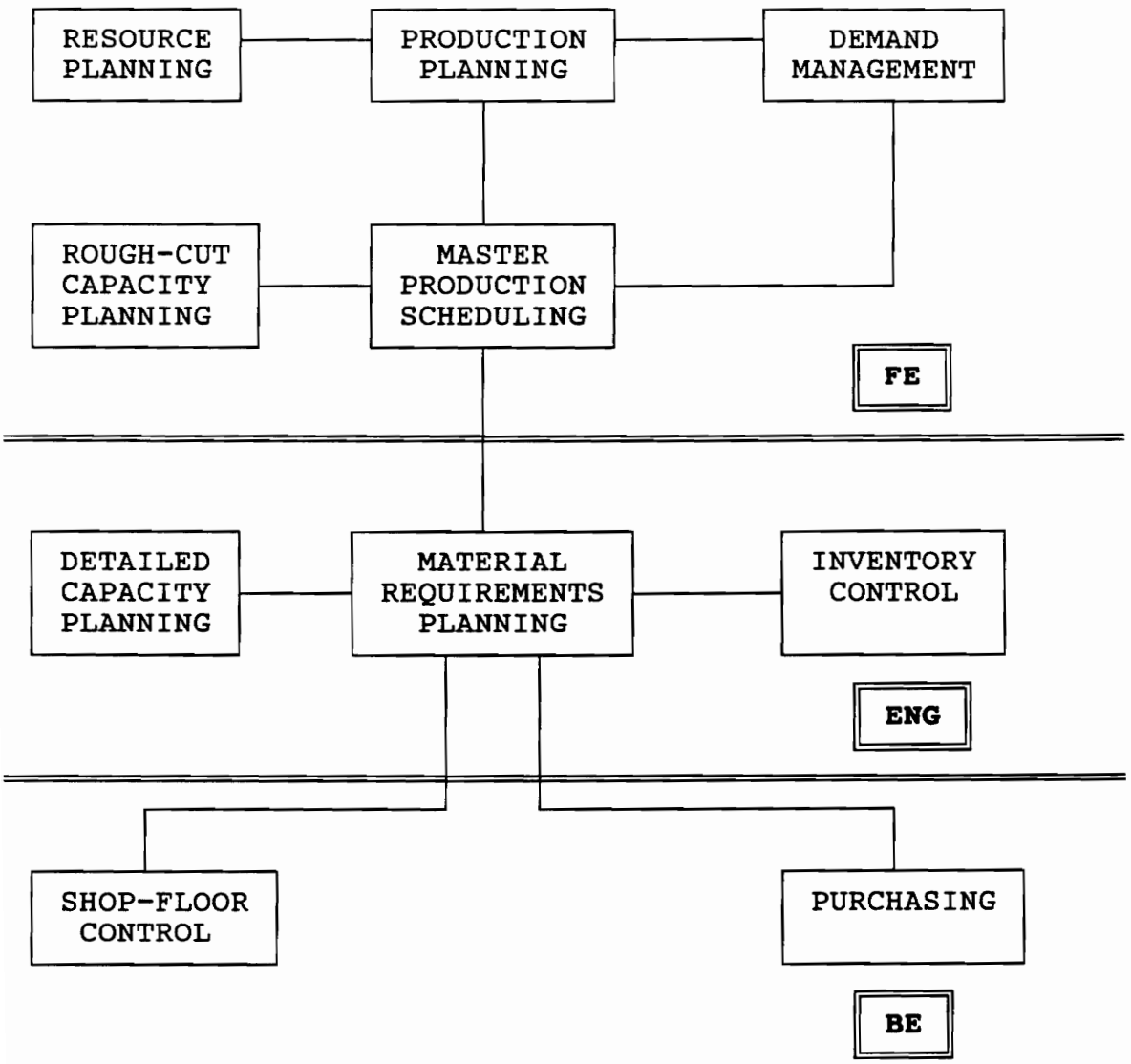

Figure 6 Main elements of MPC

B.1 PRODUCTION PLAN

The production plan provides the key communication (in the form of direct and consistent dialogue) from top management to manufacturing and is derived from, and is consistent with, the strategic plan of the company. It determines the basis for focusing the detailed production resources to achieve the strategic objectives of the firm. The production plan states the mission that manufacturing must accomplish if the overall objectives of the firm are to be met. The production plan is stated in terms of monthly or quarterly sales dollar output (for the company as a whole, or for the individual business units), or in terms of number of units to be produced in each major product line for the next month, quarter or year. How the production plan is to be accomplished in terms of detailed manufacturing and procurement decisions is a problem for manufacturing management. With an agreed-upon game plan, the job of manufacturing is to "hit the production plan." Also, the production plan provides the basis for monitoring and controlling manufacturing performance in a way that provides a much clearer division of responsibilities than is true under conventional budgetary controls.

The production plan is the actual number of units that must be deployed in order to fulfill the user's requirements. This information is received from the UNITS_DEPLOYED table (column TH_PRAC = "P"). This table contains the number of units that must be delivered each year. Manufacturing must add together all the identical items, regardless of where each unit is deployed (LOCATN).

B.2 DEMAND MANAGEMENT IN MPC

Demand management links the marketplace with manufacturing planning and control. It is through demand management that a channel of communication is maintained between the MPC systems

and their "customers." Demand management encompasses forecasting, order entry, order-delivery-date promising, customer order service, physical distribution, and other customer-contact-related activities. Demand management is also concerned with other sources of demand for manufacturing capacity. Included are service-part demands, intracompany requirements, and pipeline inventory stocking. All quantities and timing for demands must be planned and controlled. A primary function of the demand management module is to convert specific day-to-day customer orders into detailed MPC actions. It is through the demand management function that the actual demands consume the planned materials and capacities. Demand management is accomplished by assuring that all the user functional requirements are correctly interpreted. The following tables are the responsibility of those in charge of demand management:

1. DETAIL_REQUIREMENTS
2. TOTAL_REQUIREMENTS
3. CUSTOMER_WORKING_HOURS
4. CUSTOMER_WORKING_WEEKS
5. CAPACITY_DESCRIPTION

B.3 MASTER PRODUCTION SCHEDULING

The master production schedule (MPS) is an anticipated build schedule for manufacturing end products. It is primarily derived from the production plan, with inputs from market demand and rough-cut capacity planning. As such, it is a statement of production and not a statement of market demand. That is, the MPS in itself is not a forecast. An effective MPS provides the basis for:

1. Making customer delivery promises.

2. Utilizing the capacity of the plant effectively.

3. Obtaining the strategic objectives of the firm as reflected in the production plan.

4. Resolving trade-offs between manufacturing and marketing.

The MPS forms the basic communication link with manufacturing. The MPS is stated in part numbers for which bills of materials exist. It cannot be stated in dollar value. The specific products in the MPS can be end-item designations (i.e., complete assemblies or spare parts) or it can be groups of items such as models instead of end-items. The MPS must be stated in such a way that the number of units to be deployed match the values in the UNITS_DEPLOYED table.

B.4 MATERIAL REQUIREMENTS PLANNING

Material requirements planning (MRP) is the central activity in manufacturing planning and control (MPC). The managerial objective of MRP is to provide the right part at the right time to meet the schedules for the completed products. An MRP system ensures that planning is integrated, that is, that the correct number of components and raw material for each component is planned for each end product. A bill of material, or product structure, must exist. Most of this data is received from the following tables:

1. PRODUCT_STRUCTURE

2. ITEM_IDENTIFICATION

3. ITEM_PRICE

4. COMMODITY

Obviously, these tables have data only to the level relevant (or known) during the early stages of design. The data from these tables must be expanded to include the lowest level that requires planning. However, these tables serve not only as an initial source of data, but also as a baseline. All lower level data must add up to the values in these tables. If not, replanning or redesign is required.

MRP takes a period-by-period, or time-phased, set of a master production schedule and produces a resultant time-phased set of component or raw material requirements. Practically, this means that MRP breaks down each requirement in the MPS to the point where it suggests exactly when each raw material part is to be procured (considering lead times, safety stock and re-order quantities). It also prescribes when components should be released to be manufactured or assembled into higher level assemblies. It therefore acts as a translator of the overall plans for production into the detailed individual steps necessary to accomplish those plans. The bill of material (or product structure) serves as a primary input to the material requirement planning activity.

B.5 CAPACITY PLANNING

In order to fulfill a market demand the company must have the necessary resources with sufficient capacity. The objective of capacity planning is to ensure that sufficient capacity is available to accomplish the planned production in order to fulfill the market demand. The benefits of an effective MPC system can only be fully realized with the provision of adequate capacity; too little or too much capacity can be harmful. There are basically four levels in capacity planning:

The Resource planning activity is directly linked to the production planning module. It is the most highly aggregated and longest-range capacity planning decision. Resource planning typically

involves converting monthly, quarterly, or even annual data from the production plan into aggregate resources such as gross labor-hours, floor space, machine-hours, and the like. This level of planning involves new capital expansion, which requires a time horizon of months or years.

Rough-cut capacity planning has the master production schedule as its primary source of information. The capacity requirements of a particular master schedule can be estimated by any of the following techniques: capacity planning using 1) overall planning factors (CPOF), 2) capacity bills, or 3) resource profiles. These techniques provide information with which to modify the resource levels or material plan in the medium range to ensure efficient execution of the master production schedule.

The Capacity Requirements Planning (CRP) is used for detailed capacity planning. The material plans produced by the MRP system serve as the basis for calculating time-phased capacity requirements. The data files used by the CRP technique include work in process, routing, scheduled receipts, and planned orders. The information provided by the CRP technique can be used to determine the short-term capacity needs for both key machine centers and labor skills.

The types of facilities, tools, and labor required to perform manufacturing activities will most probably be the same as those required for logistic repair activities. The unit capacities of each of these elements, as well as the frequency of use, must be considered in estimating the capacity for the manufacturing activity. Costs are estimated accordingly. The following tables provide essential data:

1. GENERAL_FACILITIES
2. FACILITIES

3. GENERAL_TOOLS

4. TOOLS

5. GENERAL_TRAINING

6. TRAINING

7. GENERAL_PERSONNEL

8. ITEM_PERSONNEL

9. CORREC_MAINT_LABOR

10. CORRECT_PERSONNEL

11. PREVENT_MAINT_LABOR

12. PREVENT_PERSONNEL and UNIT_PACKAGE

B.6 INVENTORY

In a production control environment, the primary functions of inventory control are the following:

1. To ensure that the production function is not hampered by lack of required items, or a surplus of them.

2. Minimum cost is expended on the inventory function, provided production is commensurate within acceptable component availability.

Only the inventory at the manufacturing facility is of concern. Determining of desired inventory levels and maintaining inventory at these levels are the heart of the inventory control problem. Lot sizing, order quantities and reorder points are determined for all types of inventory. These types of inventory usually consist of supplies, raw materials, in-process goods, and finished goods.

Supplies are inventory items consumed in the normal functioning of an organization that are not a part of the final product. Typical supplies are pencils, paper, light bulbs, typewriter ribbons, and facility maintenance items. (Factory supplies are called MRO; standing for maintenance, repair, and operating supplies.) Raw materials are items purchased from suppliers to be used as input into the production process. They will be modified or transformed into finished goods. Typical raw materials for a furniture manufacturer are lumber, stain, glue, screws, nails, and varnish. In-process goods are partially completed final products that are still in the production process. They represent both the accumulation of partially completed work and the queue of material awaiting further processing. Finished goods are the final product, available for sale, distribution, or storage.

Although inventory control is limited to the inventory function at the end-user (for the purposes of this study), there must be some form of consistency in principles between the management of inventory at the end-user and for that of manufacturing. Some comparisons can be made between these two types of inventory.

B.7 SHOP FLOOR CONTROL

Shop Floor Control (SFC) manages the detailed flow of materials inside the plant. MRP provides the materials plans that SFC executes: to build the right part at the right time. (The materials plan is derived from MRP and sets performance objectives.) This will result in the ability to fulfill the master production schedule and satisfy the production plan, while at the same time satisfy customer service objectives.

MRP and capacity requirements planning (CRP) together produce capacity plans (what capacity required from what work center, in what time). The capacity plan is especially critical to managing

the detailed shop floor flow of materials. In essence, the capacity provided represents the resource availabilities for meeting the material plans.

Many of the logistic repair activities are approximately the same than the original manufacturing activities. This means that the common information can be shared. Although the model (as a result of this study) does not go down to the level required for shop floor control, many tables can help assessing the required data.

B.8 PURCHASING

Purchasing is at the back end of the MPC system, and has the objective of executing the detailed planning developed by the material and capacity planning techniques. The integration of MPC systems with purchasing (and therefore the vendors) represents one part of an overall program to improve supplier cost and quality performance. The object of the MPC system is to improve the planning and control of vendor capabilities through procurement; thereafter, vendor capabilities are scheduled in ways analogous to those used in shop-floor control. The most important functions of purchasing are (listed from strategic importance to the firm to immediate action activities that effect day to day business): Sourcing, value analysis, contracting, budgeting, purchasing, and monitoring.

Purchasing is a very low level activity and is only touched on during this study. The prices and lead times for items needed for manufacturing should have a close relationship with the prices and lead times promised to the customer in the ITEM_PRICE table. There must be consistency between these two values.

VITA

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